

MSc Chemical Engineering Dissertation



Water Quality Impact on Flotation Response: A Focus on Specific Ions and Temperature

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ABSTRACT

Factors such as water scarcity and environmental restrictions have brought about the need to recycle process water within the mining industry. This recycling however causes an accumulation of ions in the process water which may affect plant processes since processing routes are water-intensive. Seasonal temperature differences affect the water quality through variation of the available recycled water within the plant between the summer and winter seasons.

Literature highlights that flotation efficacy is reliant on the differences in mineral surface properties. Chemical reagents are used to increase the separation of valuable mineral (which is usually hydrophobic) from unwanted gangue (which is usually hydrophilic). Literature also highlights that different ores and different minerals react differently to temperature variation. The presence of certain species in process water with water variation has been seen to impact the flotation response. It stands to reason that simultaneously varying the temperature and specific ions concentrations will affect the interaction of minerals and reagents thus affecting the flotation response of target minerals.

This is a temperature-controlled flotation chemistry study that adopted a three-level-four-factor (3^4) factorial experimental design to evaluate the simultaneous effects of temperature and specific ions; Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$ as well as determined the possible interactive effects between the chosen parameters. A low-grade copper-nickel platinum group element (Cu-Ni-PGE) ore from the Kevitsa Igneous Complex in Lapland, Finland was floated in a complex water matrix that mimics onsite process water. This ore is remarkably similar to the Merensky ore in South Africa, meaning that the results of this study may apply to the South African mining industry. Sequential batch flotation tests were conducted, targeting copper flotation with Aerophine 318A as the copper collector. Consequently, followed by targeting nickel flotation with sodium isopropyl xanthate (SIPX) used as the respective collector. Carboxymethylcellulose (CMC) was the depressant used and Nasfroth 240 was the frother used.

The objective of this study was therefore to investigate the effect of specific ions and temperature, relevant to onsite process water recycling and temperature variations brought about by seasonal changes, on the separation of gangue from valuable minerals in batch flotation of a low-grade Cu-Ni-PGE ore.

The study demonstrated that there are specific ion concentration ranges beyond which flotation performance was adversely affected and other ranges beyond which no observable effect on flotation was visible. Based on this understanding, it may be possible to predict the ideal operating conditions for the number of water recycles in a plant. The effects of single variables and the interactions between variables were reflected in some responses. The higher ionic concentrations and their corresponding ionic strengths resulted in a more stable froth in comparison to lower ionic concentrations and consequently an improvement in the recoveries.

Water and solids recoveries were impacted by the interaction of Ca^{2+} and SO_4^{2-} . At high SO_4^{2-} concentration an increase in Ca^{2+} increased the mass of water and solids recovered. An increase in SO_4^{2-} alone caused an increase in copper recovery whilst decreasing the copper grade. $\text{S}_2\text{O}_3^{2-}$ alone affected the nickel recovery. An increase in $\text{S}_2\text{O}_3^{2-}$ caused an increase in nickel recovery whilst the nickel grade was affected by the interaction of $\text{S}_2\text{O}_3^{2-}$ and temperature. Furthermore, copper showed similar trends as those observed for nickel in the responses for the mineral grade. At high $\text{S}_2\text{O}_3^{2-}$ concentration there was no observable change in the nickel and copper grades when temperature increased. At low $\text{S}_2\text{O}_3^{2-}$ concentration, an increase in temperature decreased the nickel and copper grades. In addition to the interactive effect of temperature and $\text{S}_2\text{O}_3^{2-}$, nickel was more temperature sensitive in comparison to copper. It may thus be concluded that the postulated hypotheses are supported by this work.

GLOSSARY

% w/v	per cent weight per volume
µg/L	micrograms per litre
µm	micrometres
CCD	Charge-coupled device
cm	centimetres
CMC	carboxymethylcellulose
CMR	Centre for Minerals Research
g/t	grams per ton
ICP-OES	Inductively coupled plasma optical emission spectroscopy
IS	ionic strength
kg	kilogram
L/min	litres per minute
L	litres
LEW	Lapland equivalent water
M	molarity
mg/L	milligram per litre
mL	millilitres
mm	millimetre
Ni	nickel
PAX	potassium amyl xanthate
PGE	platinum group element
PGM	platinum group metal
ppm	parts per million

QEMSCAN	quantitative evaluation of materials by scanning electron microscopy
rpm	revolutions per minute
SEX	sodium ethyl xanthate
SIBX	sodium isobutyl xanthate
SPW	synthetic plant water
TDS	total dissolved solids
UCT	University of Cape Town
vs.	versus

TABLE OF CONTENTS

PLAGIARISM DECLARATION.....	ii
ACKNOWLEDGEMENTS.....	iii
FUNDING ACKNOWLEDGEMENTS.....	iv
ABSTRACT.....	v
GLOSSARY.....	vii
TABLE OF CONTENTS.....	ix
LIST OF FIGURES.....	xiii
LIST OF TABLES.....	xviii
1. INTRODUCTION.....	1
1.1 Background.....	1
1.2 Scope of the Study.....	2
2. LITERATURE REVIEW.....	3
2.1 Froth Flotation Fundamentals.....	3
2.1.1 Pulp Phase.....	4
2.1.2 Froth Phase.....	4
2.2 Flotation Reagents.....	5
2.2.1 Collectors.....	6
2.2.2 Frothers.....	8
2.2.3 Modifiers.....	9
2.3 Ore Mineralogy.....	10
2.4 Effect of Temperature on Flotation.....	10
2.5 Process Water and Effect of Ions on Flotation.....	13
2.5.1 Process water recycling and resultant quality variation.....	13
2.5.2 Varying ions and ionic strength.....	14
2.6 Factorial Design Experiments.....	17
3. OBJECTIVES, HYPOTHESES AND KEY QUESTIONS.....	19

3.1	Problem Statement	19
3.2	Objectives.....	19
3.3	Key Questions	20
3.4	Hypotheses	20
3.5	Sustainable Development Goals.....	20
4.	EXPERIMENTAL DETAILS	22
4.1	Ore Mineralogy	22
4.2	Ore Preparation	23
4.3	Plant Water Preparation	23
4.4	Factorial Design	25
4.5	Lab-Scale Milling.....	27
4.6	Reagent Preparation and Storage	28
4.6.1	Collector.....	29
4.6.2	Depressant.....	29
4.6.3	Frother.....	30
4.7	Sequential Batch Flotation Tests.....	30
4.8	Statistical Modelling Using Design Expert 13.....	31
5.	BATCH FLOTATION RESULTS	34
5.1	Key for Graphs	34
5.2	Reproducibility.....	34
5.3	General trends	35
5.4	Solids and Water Recoveries.....	36
5.4.1	Total Cumulative Water Recoveries and Total Cumulative Solids Recoveries	36
5.4.2	Cumulative Water Recoveries vs Time	36
5.4.3	Cumulative Solids Recoveries vs Time	39
5.4.4	Cumulative Solids Recoveries vs Cumulative Water Recoveries	42
5.5	Copper	45

5.5.1	Total Cumulative Copper Recoveries and Final Cumulative Copper Grades ...	45
5.5.2	Cumulative Copper Recoveries vs Time	46
5.5.3	Cumulative Copper Recoveries vs Cumulative Water Recoveries.....	49
5.5.4	Cumulative Copper Grades vs Cumulative Copper Recoveries	52
5.6	Nickel	54
5.6.1	Total Cumulative Nickel Recoveries and Final Cumulative Nickel Grades	54
5.6.2	Cumulative Nickel Recoveries vs Time	56
5.6.3	Cumulative Nickel Recoveries vs Cumulative Water Recoveries.....	58
5.6.4	Cumulative Nickel Grades vs Cumulative Nickel Recoveries	61
5.7	Determination of batch flotation kinetics using the classical model.....	64
5.7.1	Classical model for copper.....	66
5.7.2	Classical model for nickel.....	67
6.	STATISTICAL MODELLING RESULTS.....	69
6.1	Water Recovery	69
6.2	Solids Recovery.....	71
6.3	Copper Recovery	72
6.4	Copper Grade	75
6.5	Nickel Recovery	77
6.6	Nickel Grade	77
6.7	Key findings	79
7.	DISCUSSION.....	80
7.1	The effect of Ca^{2+} and possible interactions with other parameters on flotation performance.....	81
7.2	The effect of SO_4^{2-} and possible interactions with other parameters on flotation performance.....	82
7.3	The effect of $\text{S}_2\text{O}_3^{2-}$ and possible interactions with other parameters on flotation performance.....	82
7.3.1	Copper response to $\text{S}_2\text{O}_3^{2-}$ and possible interactions with temperature.....	83

7.3.2	Nickel response to $S_2O_3^{2-}$ and possible interactions with temperature	84
7.4	The effect of temperature and possible interactions with other parameters on flotation performance.....	85
8.	CONCLUSIONS	87
9.	RECOMMENDATIONS.....	90
	REFERENCES	91
	APPENDICES	98
	Appendix A: Batch flotation data for tests conducted under 25 °C	98
	Appendix B: Batch flotation data for tests conducted under 60 °C	117
	Appendix C: Batch flotation data for tests conducted under 40 °C	136

LIST OF FIGURES

Figure 2-1: Schematic diagram of a flotation cell (Encyclopaedia Britannica, 2021)	3
Figure 2-2: Factors that affect flotation response (Klimpel, 1984)	4
Figure 2-3: Diagram of froth structure at different heights (adapted from Ross, 1998).....	5
Figure 2-4: Adsorption of collector on mineral surface showing general orientation with hydrocarbon chain directed toward the water and making the site hydrophobic (Wills & Finch, 2015).	6
Figure 2-5: Classification of collectors (Adapted from (Wills & Finch, 2015; Bulatovic, 2014; Lovell, 1982).....	7
Figure 2-6: Structures of four common xanthates. Adapted from Bulatovic (2014); Lovell (1982).....	8
Figure 2-7: The molecular structure of sodium dithiophosphate (Aerophine 3418A) (Manenzhe, 2018), adapted from Bulatovic (2007).....	8
Figure 2-8: Structure of Carboxymethyl cellulose (CMC) (Biswal & Singh, 2004).....	10
Figure 2-9: Recovery of Pb from bench scale flotation using tap and process water at 4 °C, 11 °C & 22 °C for Renstrom and Kristineberg ores. Adapted from Ikumapayi (2012).	11
Figure 2-10: [Ca ²⁺] and [SO ₄ ²⁻] in solution from flotation of Renstrom ore at different temperatures using tap water. Adapted from Ikumapayi et al., (2012).....	12
Figure 2-11: [Ca ²⁺] and [SO ₄ ²⁻] in solution from flotation of Renstrom ore at different temperatures using process water. Adapted from Ikumapayi et al. (2012)	12
Figure 3-1: Sustainable development goals (The United Nations, 2022).....	21
Figure 4-1: Bar graph showing the extent of liberation of base metal sulphides. Adapted from Tetlow, S., (2020).	22
Figure 4-2: Cu-Ni-PGM milling curve plotted from milling times of 8, 10 and 14 times. Green line shows time required to achieve 70% passing 75 µm	28
Figure 4-3: (a) Thermostatic temperature controller, (b) 3 L Barker flotation cell front view, (c) 3 L Barker flotation cell side view.	30
Figure 5-1: Graph showing the total water recovered and the total solids recovered for two midpoint conditions.	35
Figure 5-2: Graph showing the total water recovered and the total solids recovered for three temperatures and three levels of ionic concentrations of Ca ²⁺ , SO ₄ ²⁻ and S ₂ O ₃ ²⁻ . Error bars represent standard error between duplicate runs.....	36

Figure 5-3: Graph showing the cumulative water recoveries vs time for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.	37
Figure 5-4: Graph showing the cumulative water recoveries vs time at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.	38
Figure 5-5: Graph showing the cumulative water recoveries vs time at 60 °C and three levels of ionic of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.	39
Figure 5-6: Graph showing the cumulative solid recoveries vs time for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.	40
Figure 5-7: Graph showing the cumulative solid recoveries vs time at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.	41
Figure 5-8: Graph showing the cumulative solid recoveries vs time at 60 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.	42
Figure 5-9: Graph showing the cumulative solid recoveries vs cumulative water recoveries for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.	43
Figure 5-10: Graph showing the cumulative solid recoveries vs cumulative water recoveries at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.	44
Figure 5-11: Graph showing the cumulative solid recoveries vs cumulative water recoveries at 60 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.	44
Figure 5-12: Graph showing the total copper recoveries, final copper grades and average copper recovery for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.	45
Figure 5-13: Graph showing the total copper recoveries, final copper grades and average copper recovery for three temperatures and zero level ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.	46

Figure 5-14: Graph showing the cumulative copper recoveries vs time for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.47

Figure 5-15: Graph showing the cumulative copper recoveries vs time at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. Y-axis has been shortened.48

Figure 5-16: Graph showing the cumulative copper recoveries vs time at 60 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. Y-axis has been shortened. A, B and C show grouped tests according to concentrations of relevant ions.49

Figure 5-17: Graph showing the cumulative copper recoveries vs cumulative water recoveries for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.50

Figure 5-18: Graph showing the cumulative copper recoveries vs cumulative water recoveries at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.51

Figure 5-19: Graph showing the cumulative copper recoveries vs cumulative water recoveries at 60 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.51

Figure 5-20: Graph showing the copper grade vs copper recovery for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. Both axes have been shortened for clarity.52

Figure 5-21: Graph showing the copper grade vs copper recovery at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. X-axis has been shortened for clarity.53

Figure 5-22: Graph showing the copper grade vs copper recovery at 60 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. X-axis has been shortened for clarity. A and B show grouped tests according to IS.54

Figure 5-23: Graph showing the total nickel recoveries, final nickel grades and average nickel recovery for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.55

Figure 5-24: Graph showing the total nickel recoveries, final copper grades and average copper recovery for three temperatures and zero level ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.....55

Figure 5-25: Graph showing the cumulative nickel recoveries vs time for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. Y-axis has been shortened for clarity.56

Figure 5-26: Graph showing the cumulative nickel recoveries vs time at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. Y-axis has been shortened for clarity.57

Figure 5-27: Graph showing the cumulative nickel recoveries vs time at 60 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. Y-axis has been shortened for clarity.58

Figure 5-28: Graph showing the cumulative nickel recoveries vs cumulative water recoveries for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.59

Figure 5-29: Graph showing the cumulative nickel recoveries vs cumulative water recoveries at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.60

Figure 5-30: Graph showing the cumulative nickel recoveries vs cumulative water recoveries at 60 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.61

Figure 5-31: Graph showing the nickel grade vs nickel recovery for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. X-axis has been shortened for clarity.62

Figure 5-32: Graph showing the nickel grade vs nickel recovery at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. X-axis has been shortened for clarity.63

Figure 5-33: Graph showing the nickel grade vs nickel recovery at 60 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. X-axis has been shortened for clarity.64

Figure 5-34: The rate constants for all the test conditions.....65

Figure 5-35: Graph showing the cumulative copper recoveries vs time for kinetics model for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. The

markers represent experimental data with the standard error represented by error bars. The solid lines in the corresponding colours represent the modelled data.67

Figure 5-36: Graph showing the cumulative nickel recoveries vs time for kinetics model for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. The markers represent experimental data with the standard error represented by error bars. The solid lines in the corresponding colours represent the modelled data.68

Figure 6-1: 3D surface graph showing the effects of Ca^{2+} and SO_4^{2-} on water recovery for all tests.70

Figure 6-2: 2D linear graph showing the interaction effects of Ca^{2+} and SO_4^{2-} 70

Figure 6-3: 3D surface graph showing the effects of Ca^{2+} and SO_4^{2-} on solids recovery for all tests.71

Figure 6-4: 2D graph showing the effects of Ca^{2+} and SO_4^{2-} on solids recovery for all tests..72

Figure 6-5: 2D linear graph showing the effects of SO_4^{2-} on copper recovery for all tests.....73

Figure 6-6: 3D surface graph showing the effects of temperature and $\text{S}_2\text{O}_3^{2-}$ on copper recovery for all tests.....74

Figure 6-7: 2D linear graph showing the effects temperature and $\text{S}_2\text{O}_3^{2-}$ on copper recovery for all tests.74

Figure 6-8: 2D linear graph showing the effects of SO_4^{2-} on copper grade for all tests.....75

Figure 6-9: 3D surface graph showing the effect of temperature and $\text{S}_2\text{O}_3^{2-}$ on copper grade for all tests.76

Figure 6-10: 2D linear figure of the effect of temperature and $\text{S}_2\text{O}_3^{2-}$ on copper grade for all tests76

Figure 6-11: 2D linear graph showing the effect of $\text{S}_2\text{O}_3^{2-}$ on nickel recovery for all tests. ...77

Figure 6-12: 3D surface graph showing the effect of temperature and $\text{S}_2\text{O}_3^{2-}$ on nickel grade for all tests.78

Figure 6-13: 2D surface graph showing the effect of temperature and $\text{S}_2\text{O}_3^{2-}$ on nickel grade for all tests78

LIST OF TABLES

Table 2-1: Frother classification at different pulp pH (Khoshdast & Sam, 2011).....	9
Table 2-2: Synthetic LEW-Zero recipe comparison for summer and winter (Schreithofer & Hannu, 2019).....	13
Table 4-1: Percentage of minerals by mass in the bulk feed sample (Tetlow, S., 2020).....	22
Table 4-2: Total ion concentrations in LEW-Zero level.....	23
Table 4-3: Tap water analysis report 1 July- 31 December 2021. Adapted from www.capetown.gov.za. UCT falls under Blackheath Supply shown.	24
Table 4-4: Level values of Factorial design variables.	25
Table 4-5: Total compositions of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$ for all test conditions.	27
Table 4-6: Mill Specifications.	27
Table 4-7: Summary of the Sequential batch flotation procedure.	29
Table 5-1: Total ionic strength of each test condition. Tests are listed in ascending IS values.	35
Table 5-2: Summary of the flotation kinetics rate constant (k) and maximum recovery (R_{\max}) for copper and nickel for all tests.....	66
Table 6-1: Key findings from Chapters 5 and 6	79
Table 7-1: IS values for Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$	80

1. INTRODUCTION

1.1 Background

Flotation is the primary method used to separate valuable minerals from gangue however it is the most water-intensive unit in mining operations (Wills & Finch, 2015; Gunson et al., 2012). Owing to worldwide water scarcity and environmental restrictions, process water recycling within the mining industry has become crucial. The recycling however causes the accumulation of ions such as Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. There are some environmental advantages to recycling process water such as minimising the amount of freshwater usage in areas with limited freshwater supplies such as the South African mining regions (Manono et al., 2013; Carlson et al., 2002; Peters & Meybeck, 2000) and reducing effluent discharged into the environment. Some countries, such as Finland, have environmental restrictions on discharge water, such that process water recycling is advantageous (Katko et al., 2005).

Local climate is one of the influencers of the temperature in a flotation circuit whilst there is usually a temperature increase during the milling process. Different ores have been seen to have different flotation responses depending on the ore type, water composition and onsite temperature (Ikumapayi et al., 2012).

Froth flotation is a physicochemical process which relies on the differences in mineral surface properties which are enhanced by reagents, with collectors being used to enhance the hydrophobicity of valuable minerals by adsorbing onto their active sites (Wills & Finch, 2015; Bulatovic, 2014). The simultaneous variation of the temperature and specific ions has been seen to influence collector adsorption ions which may increase or decrease the floatability of sulphide minerals dependent on the water chemistry as well as the mineral type. Some collectors have been seen to decompose at high temperatures in the presence of oxidation by-products of certain ions (Mhonde et al., 2021). In such a water-intensive process, using recycled water for flotation has been seen to affect the separation of valuable minerals from each other and valuable minerals from unwanted minerals.

A recipe was developed at the University of Cape Town for standard synthetic plant water (UCT SPW). Ions can be spiked to represent the accumulation of those certain ions while maintaining a complex background process water matrix (Dzingai et. al 2021). This study, therefore, aims to evaluate the impact of recycling process water and temperature within flotation, with a specific focus on selected ions whilst simultaneously considering the effect of varying temperature on the flotation response of a low sulphide Cu-Ni-PGE ore. A factorial

design was done and thereafter temperature-controlled batch flotation tests were conducted. In experiments with more than one independent variable, factorial experimental designs are commonly used. The effects of reagents on flotation responses of various ore types have been examined using various factorial designs in previous studies (Moimane et al., 2016; Nanthakumar & Kelebek, 2007; Somasundaran & Prickett, 1969).

Despite recycling consequences, studies are underway to determine the best flotation conditions for efficient flotation separation. Prior studies have shown that large seasonal variations affect the flotation response within given limits. Most have studied the effect of single ions on the flotation response, few have investigated the complex matrix mimicking on site process water and even fewer have simulated both complex water matrix and temperature variation.

1.2 Scope of the Study

There are several factors which affect the flotation process which include but are not limited to reagents, circuit design, solids suspension, pulp viscosity, ions present and temperature (Klimpel 1984). This study focused on specific ions namely Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$ at temperatures of 25 °C, 40 °C and 60 °C. For these variables, the flotation responses were evaluated for both single variables as well as interactive effects. Different concentration values were tested for the specific ions through spiking whilst the other ions were kept at constant values. There was no collector analysis done for this study. The flotation performance was evaluated through the recovery of valuable minerals, the recovery of solids from which concentrate grades were determined, and the recovery of water which was used with total solids recovery as an indicator for froth stability and entrainment.

2. LITERATURE REVIEW

2.1 Froth Flotation Fundamentals

Froth flotation is a physicochemical process by which valuable minerals are separated from non-valuable (gangue) minerals based on the differences in their surface properties (Bulatovic, 2014). The valuable minerals are typically hydrophobic while the gangue minerals are typically hydrophilic (Kawatra, 2011; Warren, 1985). Froth flotation occurs in two distinct phases namely the pulp phase and the froth phase. The pulp phase is made up of finely ground minerals mixed with process water to which flotation reagents (activators, depressants, frothers and collectors) and air are added. The hydrophobic minerals are collected from the froth phase while hydrophilic gangue remains in the pulp phase and is collected as tailings (Wiese et al., 2007; Kawatra, 2012). Figure 2-1 shows a schematic diagram of a flotation cell. More detail is given on the pulp and froth phase in sections 2.1.1 and 2.1.2 respectively.

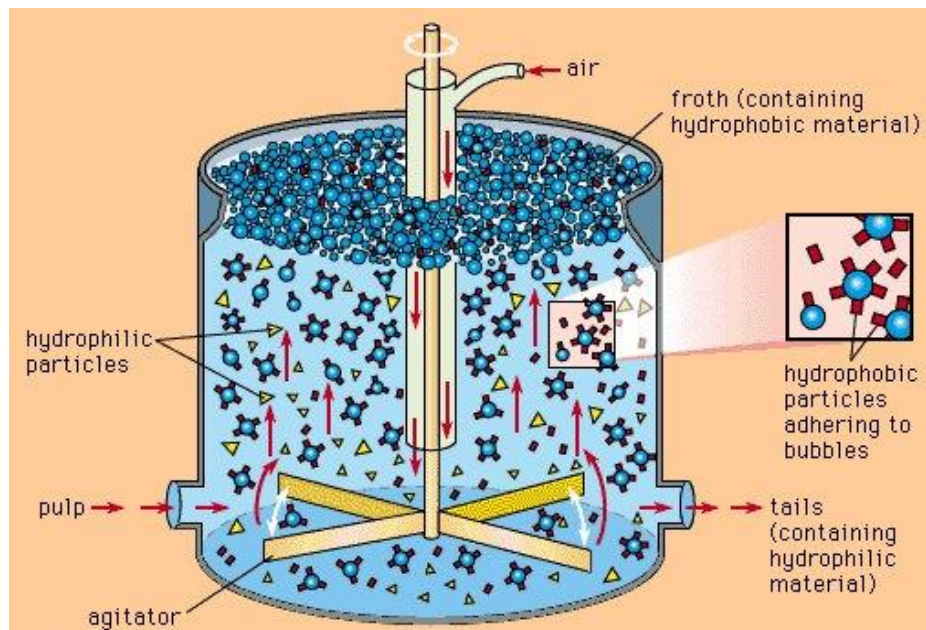


Figure 2-1: Schematic diagram of a flotation cell (Encyclopaedia Britannica, 2021)

There are three main aspects which affect flotation efficiency as depicted in Figure 2-2 namely the chemistry parameters, equipment or hydrodynamic parameters as well as operating parameters. Ions and temperature are highlighted as they are the main key factors that this study focuses on and as such will be discussed in further details in Sections 2.4 and 2.5 respectively.

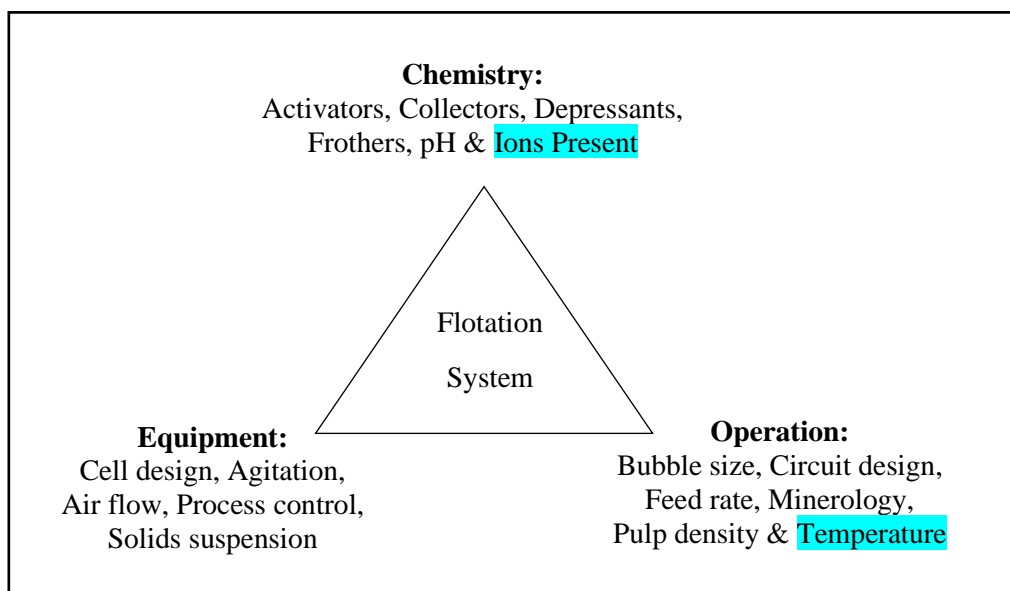


Figure 2-2: Factors that affect flotation response (Klimpel, 1984)

2.1.1 Pulp Phase

There are three mechanisms by which material from the pulp is recovered by flotation namely true flotation, entrainment and entrapment (Wills & Finch, 2015). True flotation is a selective process by which hydrophobic minerals attach to the air bubbles as they rise through the slurry. Entrainment is a non-selective mechanical mass transfer process whereby the particles suspended in the water between bubbles enter the froth phase from the top pulp region and are transferred to the concentrate (Wang, L. et al., 2015). Both hydrophobic and hydrophilic mineral particles suspended in water can experience entrainment hence the use of flotation reagents to increase the flotation selectivity. Entrapment is when particles aggregate and physically trap other particles in-between them thus carrying them to the froth phase (Yianatos et al., 1988).

2.1.2 Froth Phase

Valuable minerals are collected from the froth phase as concentrate which then undergoes further processing. Froth stability impacts mineral recovery. A froth that is too stable hinders the flotation process efficiency due to high water and gangue recoveries owing to inadequate drainage. When the froth is not stable, bubble bursting and coalescence occurs which in turn

causes valuable minerals to drain back into the pulp phase (Wiese et al., 2010). The structure of froth at different froth heights is depicted in Figure 2-3.

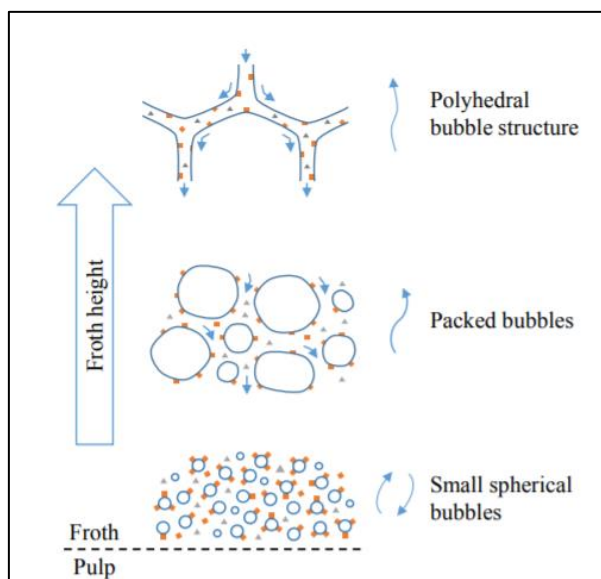


Figure 2-3: Diagram of froth structure at different heights (adapted from Ross, 1998)

There are several factors which may affect froth stability; some of these are solid particle shape and size (Bulatovic, 2014). Sharply-edged particles may cause bubble bursting as opposed to spherical particles (Aktas et al., 2008). Smaller particles may be trapped in the polyhedral bubble structure increasing the viscosity which in turn slows down the water drainage thus helping to stabilize the froth (Farrokhpay, 2011; Aktas et al., 2008). Furthermore, smaller particles although less likely to collide with rising bubbles, are easily carried to the froth layer in comparison to bigger particles. Bigger particles are more likely to collide with rising bubbles but may detach from the bubble if they are too heavy (Wills & Finch, 2015). To increase froth stability and reduce bubble coalescence, surfactants may be used as explained in Section 2.2.

2.2 Flotation Reagents

Flotation reagents are added to the pulp to enhance the differences between the surface properties of the valuable and gangue minerals. Flotation reagents are broadly classified into three groups namely collectors, frothers and modifiers with modifiers comprising of activators and depressants (Lovell, 1982). The following subsections will highlight some of the main reagents as well as their mechanisms and roles during froth flotation.

2.2.1 Collectors

Collectors adsorb onto mineral surfaces rendering them hydrophobic thus facilitating bubble attachment (Wills & Finch, 2015). Collectors consist of a hydrophilic polar functional group and a hydrophobic non-polar portion which is commonly a hydrocarbon. The polar functional group attaches to the mineral as shown in Figure 2-4 whilst the non-polar portion is orientated towards the bulk solution and subsequently attaches to an air bubble (Lovell, 1982).

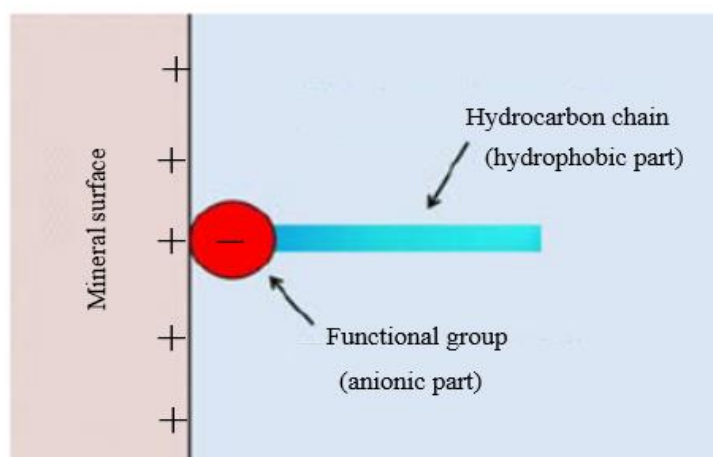


Figure 2-4: Adsorption of collector on mineral surface showing general orientation with hydrocarbon chain directed toward the water and making the site hydrophobic (Wills & Finch, 2015).

The hydrophilic polar functional groups vary and as such collectors can be classified into three main categories namely non-ionic, cationic and ionic as shown in Figure 2-5. These categories depend on the extent of collector dissociation when dissolved in water. Non-ionic collectors can either be non-polar hydrocarbon oils or may contain bivalent sulphur. Cationic collectors are made up mostly of amines. The ionic collectors are heteropolar organic molecules which may have anionic or cationic properties in the presence of water. Furthermore, anions more suited for silicates, oxides and carbonate mineral flotation are classified as oxhydroxyl whilst those suited for sulphide mineral flotation are classified as sulfhydryl (Wills & Finch, 2015; Bulatovic, 2014; Lovell, 1982).

Sulfhydryl collectors are commonly known as thiols. In PGM industrial operations, xanthates are the most commonly used collectors whilst dithiophosphinates have been recently added to the list of common reagents thiol group (Cytex Solvay Group, 2020).

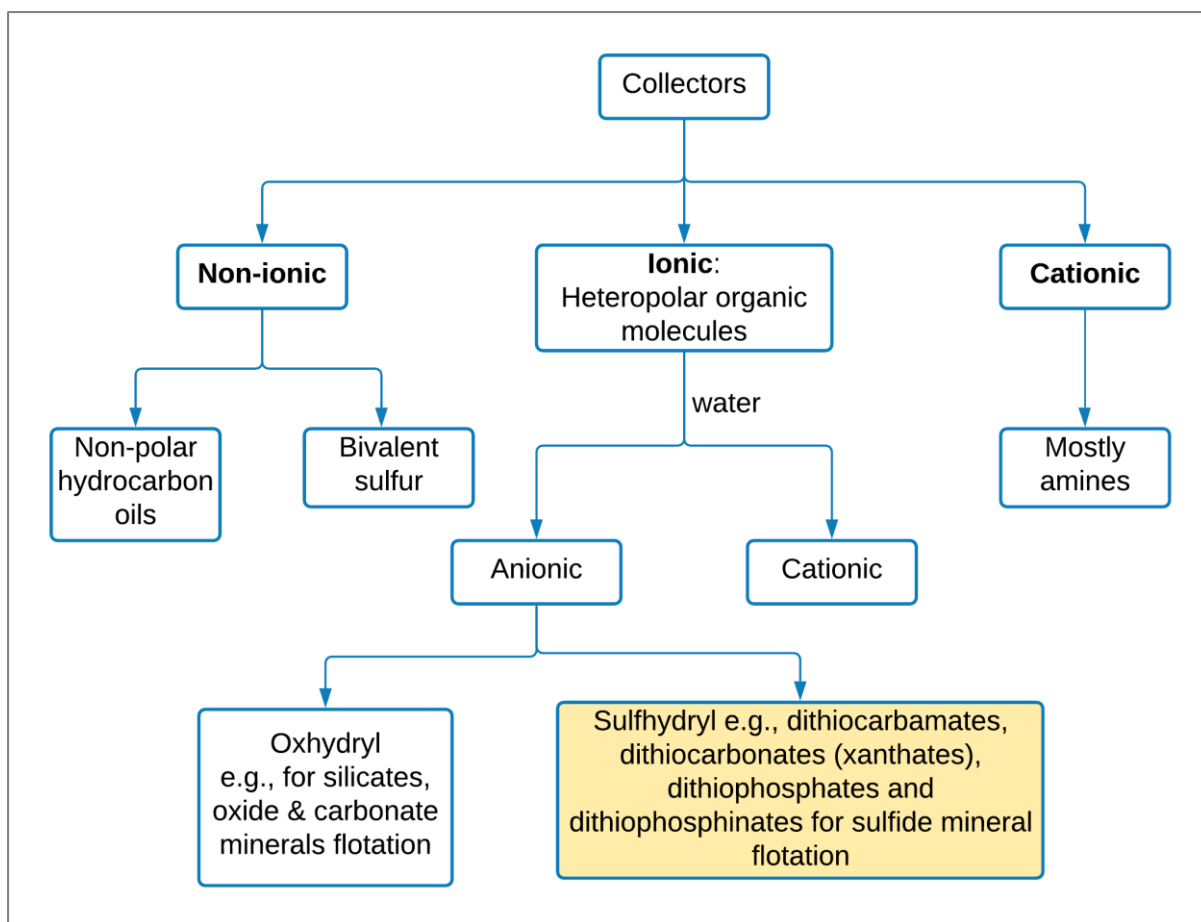
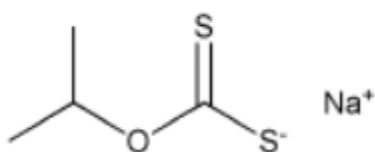


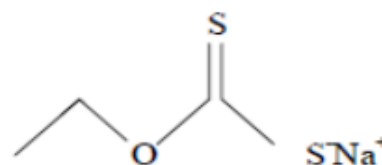
Figure 2-5: Classification of collectors (Adapted from (Wills & Finch, 2015; Bulatovic, 2014; Lovell, 1982))

2.2.1.1 Xanthates

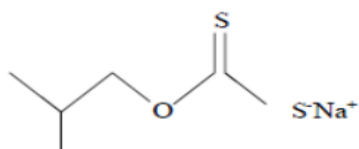
Xanthates are low-cost and efficient in mineral collection and are therefore commonly used in sulphide mineral flotation (Wiese et al., 2005). Industrially, xanthates are prepared from aliphatic alcohol, an alkali hydroxide and a carbon disulphide. Xanthates operate within a pH range of 8 – 13 (Fuerstenau et al., 2007). Sodium isopropyl xanthate (SIPX) is a xanthate collector that can be used to target pentlandite. The structure of SIPX is shown in Figure 2-6(a) along with structures of some of the other commonly used xanthates.



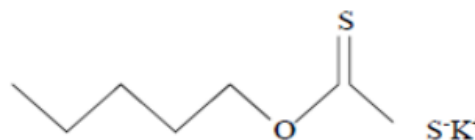
(a) Sodium isopropyl xanthate (SIPX)



(b) Sodium ethyl xanthate (SEX)



(c) Sodium isobutyl xanthate (SIBX)

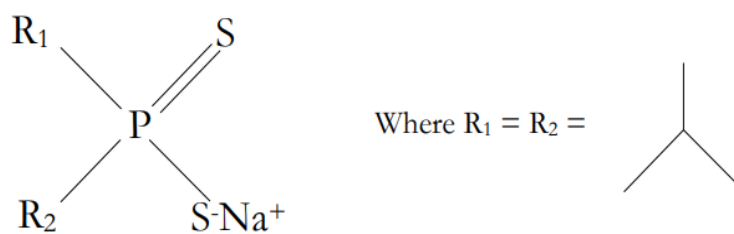


(d) Potassium amyl xanthate (PAX)

Figure 2-6: Structures of four common xanthates. Adapted from Bulatovic (2014); Lovell (1982)

2.2.1.2 Dithiophosphinates

Dithiophosphinates are preferred for their selectivity and are thus used in the flotation of complex sulphide ores. Dithiophosphinates operate within a pH range of 4 – 12 (Gray et al., 2016). Sodium dithiophosphate (Aerophine 3418A) is commonly used to target galena in the presence of other gangue minerals (Tercero et al., 2019). Figure 2-7 shows the structure of Aerophine 3418A.

**Figure 2-7: The molecular structure of sodium dithiophosphate (Aerophine 3418A) (Manenzhe, 2018), adapted from Bulatovic (2007)**

2.2.2 Frothers

Frothers are added to the pulp to stabilize air bubbles by lowering the surface tension of water by acting at the air-liquid interface thus controlling the stability of the froth phase (Wills & Finch, 2015). As these bubbles rise to the surface of the cell, they collide with mineral particles. The particles considered hydrophobic enough will attach (true flotation) and then be collected as concentrate. Frothers reduce bubble coalescence in the pulp phase ensuring that floated particles do not fall back into the pulp phase before they can be collected. They also increase the possibility of bubble-particle contact by decreasing the rate at which bubbles rise to the froth phase (Lovell, 1982).

Frothers may be categorized by pH sensitivity as shown in Table 2-1, where certain frothers are effective in a particular pulp pH range. The effectiveness of acidic frothers decreases as the pulp pH increases from acidic to alkaline and vice versa for alkaline frothers. The performance

of neutral frothers however does not depend on pulp pH (Hearn et al., 2015; Khoshdast & Sam, 2011) making neutral frothers the most commonly used frothers in sulphide mineral flotation operations specifically polyglycol ethers (Sweet et al., 1997). Triethylene glycol butyl ether (Nasfroth 240) is an example of a neutral polyglycol ether.

Table 2-1: Frother classification at different pulp pH (Khoshdast & Sam, 2011)

Acidic	Neutral	Basic
Phenols	Aliphatic alcohols	Pyridine base
Alkyl sulphonates	Cyclic alcohols and natural oils	
	Alkoxy paraffins	
	Propylene glycol ethers	
	Polyglycol ethers	
	Polyglycol glycerol ethers	

2.2.3 Modifiers

Chemicals referred to as modifiers influence the surface character of the minerals and therefore allow the collector to act. In cases where collectors do not adequately adsorb onto the valuable mineral particles, activators are added to increase the adsorption of collectors onto valuable mineral. In cases where collectors adsorb onto valuable mineral particles as well as onto the gangue minerals, depressants are added to enhance the gangue hydrophilicity thus ensuring that only the valuable minerals float. Additionally, depressants are used to reduce the floatability of naturally floating gangue (NFG) (Becker et al., 2009; Lovell, 1982).

2.2.1.1 Depressant

Depressants may enhance gangue hydrophilicity or reduce the floatability of NFG. Depressants achieve such effects by adsorbing onto the mineral surface without chemical alteration (Kawatra, 2011). Depressants can either be organic or inorganic, however, inorganic depressants are less popular as they tend to be toxic e.g., cyanide must be used at a pH greater than 10 to avoid the release of HCN (Hilson & Monhemius, 2006). Of the organic depressants, guar gum and carboxymethylcellulose (CMC) are the most commonly used ones (Wiese & Harris, 2012).

CMC is a derivative of cellulose and is formed by its reaction with chloroacetic acid and sodium hydroxide. CMC has several carboxymethyl groups (CH_2COONa) which promote water solubility (Biswal & Singh, 2004). CMC operates best withing a range of pH 7 – 9 (Klimpel, 1984). Figure 2-8 shows the structure of CMC.

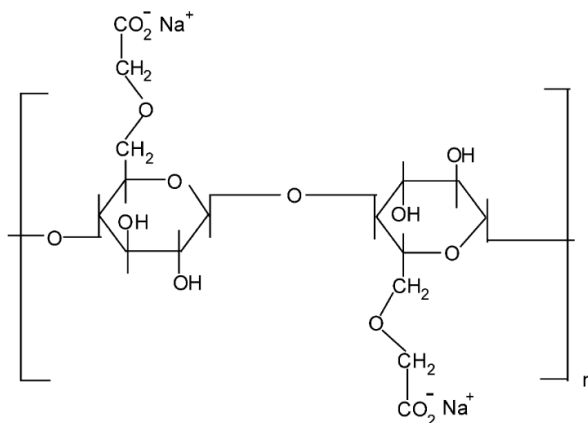


Figure 2-8: Structure of Carboxymethyl cellulose (CMC) (Biswal & Singh, 2004)

2.3 Ore Mineralogy

A low-grade copper-nickel ore was sourced from the Kevitsa Igneous Complex in Lapland, Finland. This ore is remarkably similar to the Merensky ore in South Africa, meaning that the results of this study may apply to the South African mining industry. Up to 10% of the copper and up to 20% of the nickel is often contained in the non-sulphide minerals and the total sulphides make up less than 5% of the deposit's mineralogy. The most abundant gangue mineral in the non-sulphide minerals is pyroxene. The primary copper and nickel bearing minerals are chalcopyrite and pentlandite respectively (Gray et al., 2016; Musuku et al., 2016). Details of a QEMSCAN analysis on the ore is given in Chapter 4.1.

2.4 Effect of Temperature on Flotation

Ambient temperature is one of the influencers of the temperature in the flotation circuit. It may increase or decrease the overall temperature of a flotation circuit. A temperature increase is also brought about during the milling process. Different ores can have different flotation responses depending on the water type and the temperature, as was the case in a study carried out by Ikumapayi et al. (2012). Flotation was carried out at 4 °C, 11°C and 22°C using tap and process water. Each flotation test was carried out in triplicate and the data presented was the average result of the three flotation tests. The Renstrom ore showed an increase in recovery as temperature increased for both the tap and process water. On the other hand, the Kristineberg ore did not show any clear relationship between the temperature and the different types of water (tap and process water) as shown Figure 2-9. Ikumapayi et. al. (2012) also considered the change in $[Ca^{2+}]$ and $[SO_4^{2-}]$ in the pulp during the flotation of the Renstrom and Kristineberg ores. The changes in $[Ca^{2+}]$ and $[SO_4^{2-}]$ in the flotation of the Renstrom ore at different

temperatures using both tap and process water are depicted in Figure 2-10 and Figure 2-11 respectively. $[\text{Ca}^{2+}]$ decreased with tap water at all three temperatures yet had little variation with process water at all temperatures. The $[\text{Ca}^{2+}]$ decrease was attributed to their adsorption on the mineral surfaces and/or precipitated as CaCO_3 . $[\text{SO}_4^{2-}]$ increased at all temperatures with process water but however decreased at 4 °C and 11 °C with tap water showing little variation at 22 °C. The excess of $[\text{SO}_4^{2-}]$ was attributed to ore dissolution. The extent to which $[\text{Ca}^{2+}]$ decreases and $[\text{SO}_4^{2-}]$ increases with variation in temperature is impacted by the overall composition of the water as depicted by the differences in recovery with the tap and process water.

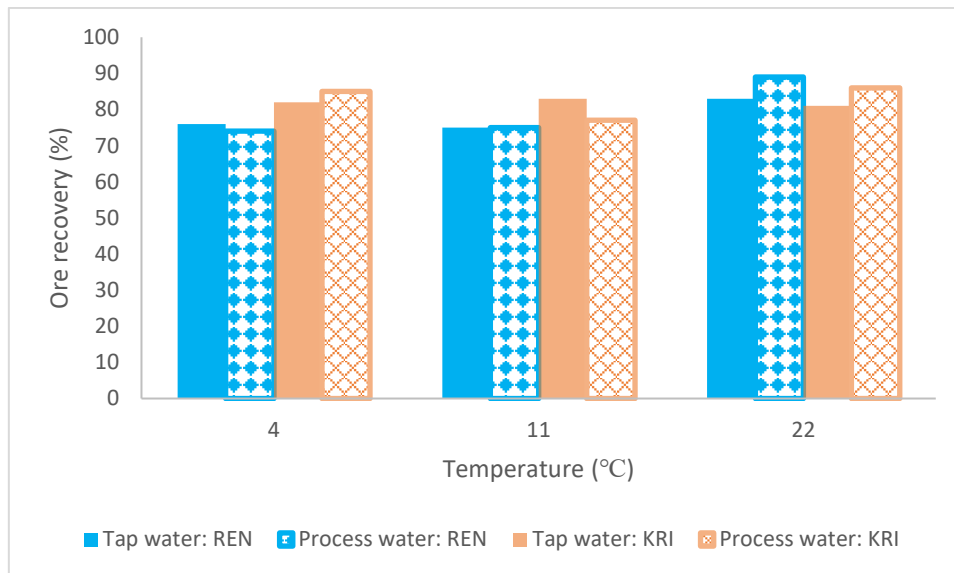


Figure 2-9: Recovery of Pb from bench scale flotation using tap and process water at 4 °C, 11 °C & 22 °C for Renstrom and Kristineberg ores. Adapted from Ikumapayi (2012).

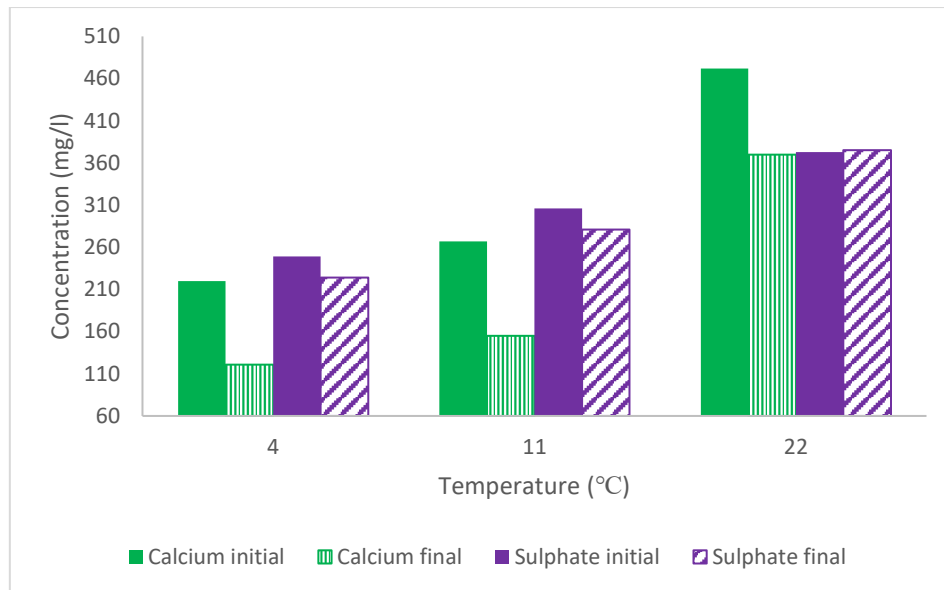


Figure 2-10: $[Ca^{2+}]$ and $[SO_4^{2-}]$ in solution from flotation of Renstrom ore at different temperatures using tap water. Adapted from Ikumapayi et al., (2012)

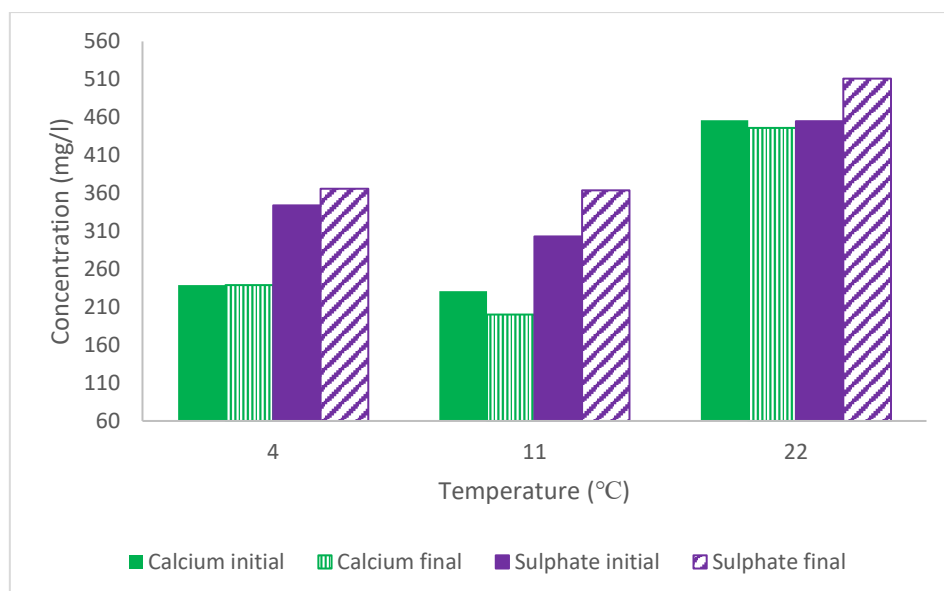


Figure 2-11: $[Ca^{2+}]$ and $[SO_4^{2-}]$ in solution from flotation of Renstrom ore at different temperatures using process water. Adapted from Ikumapayi et al. (2012)

In addition to ambient temperature, seasonal variation may affect the flotation response especially in regions where the variation is large and persistent. In Finland, winter temperatures are low enough such that tailing dams freeze over. This locks a significant amount of the water that would have been recycled and consequently causes an elevation of residual reagents which then changes the quality of the recycled water (Muzinda & Schreithofer, 2018). With the seasonal change from winter to summer, the warmer temperatures melt the ice which in turn causes a large flush of water which then again changes the recycled water quality. Ion

concentration measurements were conducted for summer and winter campaigns (Schreithofer & Hannu, 2019). The differences are shown in Table 2-2. The winter campaigns values are used as the basis of Lapland Equivalent Water which is termed LEW-Zero. The LEW-Zero mimicked the water quality at the Lapland operation in Northern Finland with an ionic strength (IS) of 0.0868 M. More detailed explanation is given in Section 2.5 on how the LEW was adjusted to simulate the varying ion concentration. It should be noted that there is no CaCl_2 present in the LEW-Zero recipe. It has however been added to the recipe table as it is used for spiking as explained in Section 2.5.

Table 2-2: Synthetic LEW-Zero recipe comparison for summer and winter (Schreithofer & Hannu, 2019)

	Summer (mg/L)	Winter (mg/L)
CaSO_4	546	599
Na_2SO_4	198	279
$\text{Na}_2\text{S}_2\text{O}_3$	61	79
* CaCl_2	0	0
NaCl	254	254
MgCl_2	276	317
KCl	105	125
Na_2CO_3	43	40
Total Solids	1482	1693

2.5 Process Water and Effect of Ions on Flotation

Valuable minerals are most commonly recovered through froth flotation (Wills & Finch, 2015) which is the most water-intensive unit in mining operations (Gunson et al., 2012). Some challenges faced in mining operations with process water include environmental regulations and limited fresh water supplies (Manono et al., 2013; Carlson et al., 2002; Peters & Meybeck, 2000). South African mines are generally located in water scarce regions whilst the Finnish mines have varied seasonal changes and water restrictions that require process water recycling which affects the flotation response.

2.5.1 Process water recycling and resultant quality variation

Finnish seasonal variation has been described in Section 2.4. In addition to this, Finland has tight restrictions on discharge water. One of the reasons for this was the exponential increase in suspended solids that were disposed to the environment alongside paper production until the early 1970s (Katko et al., 2005). There has therefore been a need to recycle process water within mining operations with advantages such as a reduction in the usage of potable water and

effluent. Additionally, some reagents may be retained which could lower the quantities of reagents needed (Slatter et al., 2009). Similar to how reagents are retained, ion accumulation occurs during recycling which alters the properties of the pulp and froth phases (Fornasiero & Ralston, 2006; Schwarz & Grano, 2005).

2.5.2 Varying ions and ionic strength

The varying quantities of ions directly affects the ionic strength of the solution which in turn influences the interaction of collectors and depressants with mineral particles (Manono et al., 2018b; Corin et al., 2011; Levay et al., 2001). Collectors and depressants are described in more detail in Section 2.2.1. The ionic strength of a solution is a measure of the concentration of ions in that solution and is defined by the following equation:

$$I = \frac{1}{2} \sum_i^n (c_i z_i^2)$$

Where the: I - ionic strength

c - molarity of ion i

z - charge of ion i

i – specific ion at which the ionic strength is evaluated

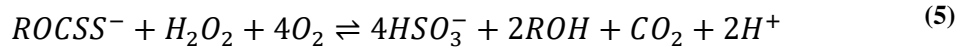
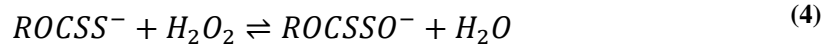
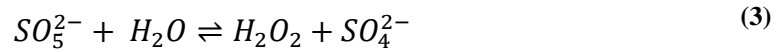
n – number of ions present in a system

90 – 95 % of water from the Cu-Ni-PGM concentrator of the New Boliden Kevitsa Mining Oy is recycled. It should be noted that some ions may be found naturally in water. The water from the tailings is usually used for the recycling which may result in accumulation of ions such as Ca^{2+} , Mg^{2+} , K^+ , SO_4^{2-} , NO_3^- and other species such as thiosalts, residual reagents and base metals (Wiese et al., 2007; Shortridge et al., 1999; Smith & Hertzog, 1985).

It has been suggested that the presence of certain ions at high concentrations beyond a certain concentration modifies the pulp viscosity which leads to entrainment thus reducing the grade of the recovered sulphide mineral (Kirjavainen et al., 2002). The presence of ions may increase or decrease the floatability of sulphide minerals. This, however, is dependent on the water chemistry as well as the type of mineral (Ikumapayi et al., 2012; Slatter et al., 2009).

Ca^{2+} and SO_4^{2-} are very common ions in process water from sulphide mineral flotation. Ca^{2+} originates from the pulp as lime which is used as a pH modifier as well as gangue dissolution

and SO_4^{2-} originates from the ore (Rao et al., 2017; Broman, 1980). Previous studies have shown that in the presence of sulphoxy compounds, there is xanthate decomposition and at high temperatures, the xanthate decomposition is significant in comparison to lower temperatures. When dithionite ions are generated through oxidation of tetrathionates or when added as reagents to flotation waters, their intermediate oxidation products decompose xanthate (Mhonde et al., 2021). Furthermore, the aforementioned study showed that reducing the concentration of dithionites in solution resulted in a decline in the overall xanthate decomposition. A summary of the reactions of sulphoxy compounds was therefore described as follows. The decomposition of SO_2 and dithionite produces unstable bisulphite which decomposes to sulphite ions (Equation 1). The sulphite ion reacts with oxygen in solution to form peroxymonosulphate ion (Equation 2). The peroxymonosulphate ion reacts to form peroxide when in contact with water, (Equation 3). The xanthate ion reacts with hydrogen peroxide thus forming an intermediate perxanthate ion which further reacts with hydrogen peroxide to form bisulphite ions, alcohol and carbon dioxide, (Equation 4) and (Equation 5).



In a sulphide flotation study by Gaudin & Charles (1953), the increase of $[Ca^{2+}]$ in process water resulted in increased adsorption of Ca^{2+} onto valuable mineral surfaces thus hindering collector adsorption and resulting in the gangue floating by entrainment (Konopacka & Drzymala, 2010). Other studies however proposed that increased Ca^{2+} and $S_2O_3^{2-}$ improves xanthate adsorption onto sulphide minerals (Boujounoui et al., 2015; Corin & Wiese, 2014; Wang, B. & Peng, 2014). Some studies have shown an interactive effect of ions in process water. In a study by Hirajima et al. (2016), Ca^{2+} was seen to have a marginal decreasing effect on chalcopyrite flotation at low pH owing to the presence of other ions in the process water that caused the preferential attachment of collector to the sulphide mineral. Chalcopyrite recovery decreased as pH increased beyond 9 as both $[Ca^{2+}]$ and $[Mg^{2+}]$ increased. This was due to the formation of $CaCO_3$ and $Mg(OH)_2$ which precipitate onto mineral surfaces therefore reducing the hydrophobicity of the mineral surface (Hirajima et al., 2016).

Manono et al. (2016) investigated the influence of typical electrolytes present in process water; Na^+ , Ca^{2+} , Mg^{2+} , NO_3^- , SO_4^{2-} and Cl^- on the flotation behaviour of a Cu-Ni sulphide ore. UCT standard synthetic plant water (SPW) (Wiese et al., 2005) with a total dissolved solids (TDS) concentration of 1 023 mg/L was used alongside single salts at an ionic strength of 0.0213 M which is the same ionic strength of the SPW. The ionic strength was kept constant for all electrolyte solutions. SPW was used as the basis for comparison for the cationic and anionic effects. The spiking of SPW recipes with selected ions was done by Dzingai et al. (2020), in a study to simulate the effect of water recirculation on flotation through ion-spiking with a focus on Ca^{2+} and Mg^{2+} .

Accumulation of species in recycled water may become apparent after years of operation. $[\text{Ca}^{2+}]$ and $[\text{SO}_4^{2-}]$ have been seen to exceed 1000 ppm and 2500 ppm respectively in mills with recycled water (Grano, 1995). Recycled water at Pb-Zn operations could contain TDS as high as 4000 ppm (Deng et al., 2013). Studies have shown that water recovery increased with increasing ionic strength owing to the bubble diameter decrease as ionic strength increases, i.e. smaller bubbles recover more water (Dzingai et al., 2020; Manono et al., 2016). SPW that was spiked with cations resulted in higher water recoveries and therefore more stabilised froth compared to SPW that was not spiked (Dzingai et al., 2020). Other studies showed the same effect of polyvalent cations on froth stability (Hirajima et al., 2016; Manono et al., 2016; Corin & Wiese, 2014; Craig et al., 1993). As water recovery increases with ionic strength, the solids recovery may decrease as a result of entrainment per gram of water decreasing as shown in a study by Corin et al., (2011).

Copper recovery was generally unaffected by a change in ionic strength in sulphide flotation studies (Dzingai et al., 2020; Corin et al., 2011). The observed invariant copper recovery whilst total solids increased was attributed to an increase in natural floatable gangue as the ionic strength increased (Corin et al., 2011). An increase in ionic strength has been seen to increase froth stability and naturally floating gangue recovery which would decrease the observed grade (Manono et al., 2018a; Corin & Wiese, 2014; Manono et al., 2012). Nickel recovery was generally unaffected by a change in ionic strength, although it was found to increase slightly in a study by Corin & Weise (2014). Although copper and nickel grades generally decreased with an increase in ionic strength, nickel grade remained the same in a study by Manono et al. (2012). The slight increase in nickel recoveries (Corin & Wiese, 2014) and invariant nickel grade (Manono et al., 2012) might be a result of the presence of electrolytes increasing the floatability of nickel-gangue composites since some of the nickel is contained in unliberated

pentlandite (Liu et al., 2013; Chandra & Gerson, 2009; Finkelstein, 1997). Studies by Dzingai et al. (2020) suggested that there existed a threshold of 400 mg/L for $[Ca^{2+}]$ for copper grade and beyond this $[Ca^{2+}]$, the copper grade may be negatively affected.

2.6 Factorial Design Experiments

The standard experimental approach used in the investigation of process variables is one variable at a time. This method however does not consider that some variables may alter the responses through interactions between or among other independent variables being investigated (Dean et al., 2015; Nanthakumar & Kelebek, 2007). Factorial experimental designs are commonly used for experimental designs with more than one independent variable. In complex processes such as flotation, it is necessary to understand how a certain independent variable can alter flotation responses in the presence of other independent variables.

Various factorial designs have been used in some studies to understand interactive and multivariable effects of reagents on the flotation responses of various ore types (Moimane et al., 2016; Nanthakumar & Kelebek, 2007; Somasundaran & Prickett, 1969). A factorial experimental design consists of two or more factors. Each of these factors has discrete possible levels or values.

Response surface methodology (RSM) is the development of an empirical relationship between a response variable and a set of control variables that represent levels of the quantitative factors believed to affect the response values (Dean et al., 2015). The traditional response surface designs can be categorized according to the degree of the models. Some common main designs for first-degree models are 2^k factorial design, Plackett-Burman design and Simplex design (k is the number of considered control variables). The three most common designs for second degree models are 3^k factorial design, Central composite design and the Box-Behken design (Dean et al., 2015).

Two-level factorial designs are used to fit simple models in the initial stages of the experiment. Three-level factorial designs are used to fit second-degree models that are useful in determining optimal response values. If the number of factors is large, fractions of factorial designs can be used (Dean et al., 2015; Box et al., 2005; Hinkelmann & Kempthorne, 2005; Khuri, Andre I. & Cornell, 1996). For this study, a 4-factor, 3-level custom factorial design with four centre points and two repeats was generated. Centre points are defined as experimental runs where numeric factors are set midway between their low and high levels (Minitab.com, 2019).

As this project was not intended to investigate different experimental designs, further information can be found in the literature (Dean et al., 2015; Khuri, André I. & Mukhopadhyay, 2010; Hinkelmann & Kempthorne, 2005; Box et al., 2005; Khuri, Andre I. & Cornell, 1996)

3. OBJECTIVES, HYPOTHESES AND KEY QUESTIONS

3.1 Problem Statement

Owing to environmental concerns as well as the availability of water resources, the recycling of process water on site is a necessity for many mining operations. Certain ions from Cu-Ni-PGE ores, such as Ca^{2+} and sulphur species accumulate in the process water as the water undergoes recycling. This change in water quality affects the flotation response, hence understanding the impacts will help in optimizing the flotation circuits. While the ore used within this study originated in Finland, it has a composition like Cu-Ni-PGE ores found in South Africa. Temperature variation between South Africa and Finland is high and thus worthy of investigation within the context of onsite process water recycling.

The proposed research will focus on the effect of temperature, $[\text{Ca}^{2+}]$, $[\text{SO}_4^{2-}]$ and $[\text{S}_2\text{O}_3^{2-}]$ in a sequential Cu-Ni batch flotation process. These ions were selected based on site surveys which showed them to be accumulated during recycling (Thi Minh Khanh, 2021). Although the study of individual ions is common in literature, this study intends to maintain the complex water matrix found within process water. This will be done by maintaining all the other water ions at constant values while simultaneously varying the ions of interest and the slurry temperature.

3.2 Objectives

In line with the problem statement, the main aim of this study is to investigate the effect of specific ions and temperature, relevant to onsite process water recycling and temperature variations brought about by seasonal changes, on the separation of gangue from valuable minerals in batch flotation of a low-grade Cu-Ni-PGE ore. The specific objectives are:

1. To investigate the effect of spiking $[\text{Ca}^{2+}]$ on the water, solids, mineral recoveries and mineral grade, whilst maintaining a complex process water background.
2. To investigate the effect of spiking $[\text{SO}_4^{2-}]$ and $[\text{S}_2\text{O}_3^{2-}]$ on the mineral grade and recovery, whilst maintaining a complex process water background.
3. To investigate the effect of temperature on the flotation response of a Cu-Ni-PGE ore.
4. To statistically analyze the flotation data by means of intentional experimental design so as to understand whether there are any interactive effects between the varied factors on flotation performance.

3.3 Key Questions

1. What is the impact of spiking Ca^{2+} on the water, solids, mineral recoveries and mineral grade, whilst maintaining a complex process water background?
2. What is the impact of spiking SO_4^{2-} on the water, solids, mineral recoveries and mineral grade, whilst maintaining a complex process water background?
3. What is the impact of spiking $\text{S}_2\text{O}_3^{2-}$ on the water, solids, mineral recoveries and mineral grade, whilst maintaining a complex process water background?
4. Is there a temperature effect on the water, solids, mineral recoveries and mineral grade, whilst maintaining a complex process water background?
5. Are there any interactive effects between the varied factors on flotation performance?

3.4 Hypotheses

The following is hypothesized:

1. For select ions Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$, there exist optimal concentration ranges beyond which flotation performance is adversely affected. This is because some ions have been shown to be deleterious whilst others are beneficial to the flotation process.
2. Temperature variation with ion concentration variation affects the flotation response. This is because temperature affects the valuable mineral flotation rate. Some ions have been seen to react with flotation reagents and some of these reactions may be affected by temperature thus affecting the flotation response.

3.5 Sustainable Development Goals

Figure 3-1 shows the sustainable development goals as set by the United Nations general assembly (The United Nations, 2022). There are several goals that will be supported by this project. Sustainability goal 6 is addressed by increasing the amount of potable water for human consumption owing to recycling on site. This also addresses sustainability goal 12 as there is responsible use of water by mining operations. Additionally, sustainability goals 11, 14 and 15 are addressed as the communities around mining operations become more sustainable if mining operations do not use their valuable water resources as well as reduce environmental discharge to groundwater, rivers and oceans.



Figure 3-1: Sustainable development goals (The United Nations, 2022)

4. EXPERIMENTAL DETAILS

4.1 Ore Mineralogy

The Kevitsa ore is low-grade with sulphides (S^{2-}) contributing less than 5 % of the total mineralogy. In the plant feed, about 10 % of the Cu and 20 % of Ni is contained in non-sulphide minerals. Chalcopyrite ($CuFe^{2+}S_2$) is the main Cu mineral while pentlandite ($Fe^{2+}_{4.5}Ni_{4.5}S_8$) is the main Ni mineral (Musuku et al., 2016). A QEMSCAN analysis for Kevitsa ore was done by Tetlow (2020). Table 4-1 shows the percentage of minerals in the bulk feed sample. Figure 4-1 shows the extent of liberation of base metal sulphides.

Table 4-1: Percentage of minerals by mass in the bulk feed sample (Tetlow, S., 2020).

Cu-sulphides	1,14
Ni-sulphides	0,76
Pyrrhotite	1,97
Olivine	7,74
Enstatite (OPX)	7,78
Augite (CPX)	28,08
Tremolite	33,76
Serpentine	1,52
Talc	0,23
Chlorite	6,79
Biotite/Phlogopite	0,77
Plagioclase Feldspar	2,38
K-Feldspar	0,05
Quartz	0,26

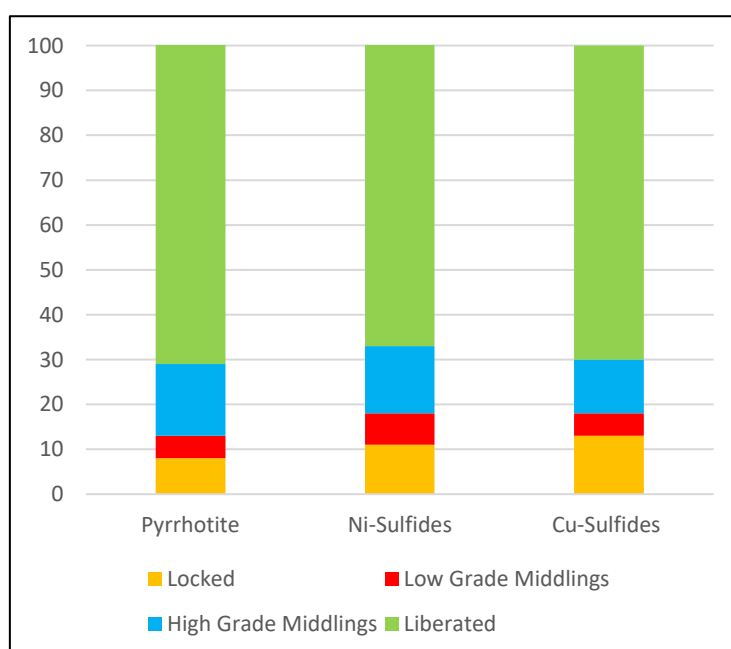


Figure 4-1: Bar graph showing the extent of liberation of base metal sulphides. Adapted from Tetlow, S., (2020).

4.2 Ore Preparation

A Cu-Ni-PGM ore was sourced from Lapland, Northern Finland. The bulk sample was fan dried in an open rack. After drying the bulk sample, it was crushed using a TM Engineering Terminator JLT1AL jaw crusher to a particle size of -1 mm. The sample was homogenized by blending and riffing. A rotary splitter was used to make 1 kg portions which were placed in airtight plastic bags and stored in a sealed drum at room temperature.

A Spectro Arcos Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) equipped with Charge-Coupled Device (CCD) detectors was used for elemental analysis of the ore samples. The ICP-OES is based at Scientific Services Geological Laboratories in Cape Town, South Africa (scientificservices.co.za).

4.3 Plant Water Preparation

The synthetic process water, termed Lapland Equivalent water (LEW) was prepared by dissolving selected inorganic salts in Cape Town tap water to mimic the process water on site as closely as possible within the laboratory. All salts were in powder or crystal form supplied by Merck. LEW zero level had ionic concentrations representing those of measured onsite water with an ionic strength (IS) of 0.086 M, the average of summer and winter sampling campaigns (Schreithofer & Hannu, 2019). Table 4-2 shows the total concentrations of various ions in LEW zero level (i.e., without spiking any ion in LEW).

Table 4-2: Total ion concentrations in LEW-Zero level

Ion	Ca ²⁺	Na ⁺	Mg ²⁺	K ⁺	SO ₄ ²⁻	S ₂ O ₃ ²⁻	Cl ⁻	CO ₃ ²⁻
Concentration (mg/L)	352	166	160	65	377	112	332	49

The recycling of LEW increases the concentrations of all ions, however the ions considered to be most of interest in this study were Ca²⁺, SO₄²⁻ and S₂O₃²⁻. To consider the increase in concentration of specific ions while maintaining a complex background process water matrix (LEW), certain ions were spiked to represent the accumulation of those certain ions over and above all other present ions. The salts CaCl₂, Na₂SO₄ and Na₂S₂O₃ were used to adjust the concentrations of Ca²⁺, SO₄²⁻ and S₂O₃²⁻ respectively. Na⁺ and Cl⁻ were the counter ions for the anions and cations under study. Na⁺ and Cl⁻ were shown to have minimal impact on the system since they do not compete with the ions of interest in this study (Manono et al., 2016). All other ions were maintained at the LEW Zero level concentration values. Table 4-3 shows the tap

water analysis report with the concentration of the macro-determinands being <29.3 mg/L (City of Cape Town, 2021).

Table 4-3: Tap water analysis report 1 July- 31 December 2021. Adapted from www.capetown.gov.za. UCT falls under Blackheath Supply shown.

PARAMETERS	BLACKHEATH SUPPLY (Typical analysis max 430 ML/day)
CHEMICAL - MACRO DETERMINANDS	mg/L
Free Chlorine as Cl ₂	1,3
Nitrate as N	0,2
Nitrite as N	<0,1
Combined nitrate plus nitrite	0,1
Sulphate as SO ₄ ²⁻	11
Fluoride as F ⁻	<0,1
Ammonia as N	<0,4
Chloride as Cl ⁻	11
Sodium as Na	5
Zinc as Zn	<0,1
CHEMICAL - MICRO DETERMINANDS	µg/L
Antimony as Sb	<1
Arsenic as	<1
Barium as Ba	<50
Boron as B	<0,1
Cadmium as Cd	<3
Chromium (total) as Cr	<5
Copper as Cu	<10
Cyanide as CN	16
Iron as Fe	74
Lead as Pb	<10
Manganese as Mn	7
Mercury as Hg	-
Nickel as Ni	<5
Selenium as Se	<1
Uranium as U	-
Aluminium as Al	161
OTHER	mg/L
Hardness (total) as CaCO ₃	35
Alkalinity as CaCO ₃	21
Calcium as Ca	13
Potassium as K	0,4
Magnesium as Mg	0,9

4.4 Factorial Design

An overview of factorial design is given in section 2.6. For this study, a 4-factor, 3-level custom factorial design with four centre points and two repeats was generated resulting in 20 tests. The variables were temperature and three ions: Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$ at low, medium, and high levels. Tests at LEW Zero level were carried out at 25 °C, 40 °C and 60 °C. All the spiking tests were carried out with the baseline of the complex background process water matrix at the LEW Zero level. Table 4-4 shows the values of the factorial variables where the ionic concentrations are the final total concentration for each corresponding ion.

Table 4-4: Level values of Factorial design variables.

Target ion	Generator salt	Concentration of ion (mg/L)		Mass of salt (g) in $V_{\text{water}}=20$ L
Ca^{2+}	$\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$	LEW Zero		0
		Low	LEW+136	4,96
		Medium	LEW+486	17,82
		High	LEW+836	30,69
SO_4^{2-}	Na_2SO_4	LEW Zero		5,58
		Low	LEW+1 124	22,19
		Medium	LEW+2 624	44,38
		High	LEW+4 124	66,56
$\text{S}_2\text{O}_3^{2-}$	$\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$	LEW Zero		2,48
		Low	LEW+89	4,43
		Medium	LEW+339	9,96
		High	LEW+589	15,5
Temperature	-	Low	25°C	-
		Medium	42°C	-
		High	60°C	-

The weight of each salt of the target ion was determined using the formula

$$mass_{\text{salt}} = [(V_{\text{H}_2\text{O}} \times C_{\text{solution}})] + mass_{(\text{water of crystallisation})}$$

Where

$V_{\text{H}_2\text{O}}$: Volume of water to be prepared in L

And

$$mass_{(\text{water of crystallisation})} = moles_{\text{water of crystallisation}} \times M_{r(\text{water of crystallisation})}$$

Moles of water of crystallisation are calculated using the degree of hydration of the specific compound e.g., $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$:

$$\begin{aligned} \text{moles}_{(\text{water of crystallisation})} &= [\text{moles}_{\text{CaCl}_2} \times \text{degree of hydration}] \times M_r(\text{water of crystallisation}) \\ &= [\text{moles}_{\text{CaCl}_2} \times 2] \times M_r(\text{water of crystallisation}) \end{aligned}$$

C_{solution} : Concentration in mg/L of the ion concerned in the prepared water. LEW Zero values were found from onsite measurements as described in section 4.3 as well as in the following paragraph. Goal seek was used to calculate the values of the other test values.

The spiking values of Ca^{2+} were obtained from onsite water analysis, the average of which was determined from site surveys conducted both in summer and winter (Schreithofer & Hannu, 2019). SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$ spiking values were based on water sampled from a massive sulphide ore in Portugal. The spiking values were kept high so the two data sets would be comparable.

Table 4-5 shows the number of tests and their corresponding test conditions for the variables under study. All other ionic concentrations are maintained at the value stated in the LEW- Zero level in Table 4-4. The ionic concentration values are the total concentration for each corresponding ion.

Table 4-5: Total compositions of Ca²⁺, SO₄²⁻ and S₂O₃²⁻ for all test conditions.

Test	Ca ²⁺ (mg/L)	SO ₄ ²⁻ (mg/L)	S ₂ O ₃ ²⁻ (mg/L)	Temperature (°C)
1	1187	4500	700	60
2	487	4500	200	25
3	1187	1500	700	60
4	1187	4500	700	25
5	487	4500	700	60
6	487	1500	700	60
7	1187	4500	200	60
8	487	1500	700	25
9	487	4500	700	25
10	650	3000	450	40
11	1187	1500	700	25
12	1187	1500	200	60
13	487	4500	200	60
14	837	3000	450	40
15	837	3000	450	40
16	837	3000	450	40
17	1187	4500	200	25
18	487	1500	200	60
19	487	1500	200	25
20	1187	1500	200	25
21	352	377	112	25
22	352	377	112	40
23	352	377	112	60
Key: LEW zero level				

4.5 Lab-Scale Milling

A 1 kg sample of Cu-Ni-PGM ore was milled with 500 mL of the LEW of interest in a stainless-steel rod mill. The mill specifications are outlined in Table 4-6.

Table 4-6: Mill Specifications.

Parameter	Quantity	Dimensions (mm)
Mill diameter	-	200
Mill depth	-	297
Rod diameter	6	25
Rod diameter	8	20
Rod diameter	6	16

Figure 4-2 shows the milling curve achieved by grinding three ore samples for 8, 10 and 14 minutes respectively before being passed through two screens, with mesh sizes 106 μm and 75 μm . For each test, the ore was milled at a speed of 47 rpm for 11.2 min to achieve a particle size of 70 % passing 75 μm .

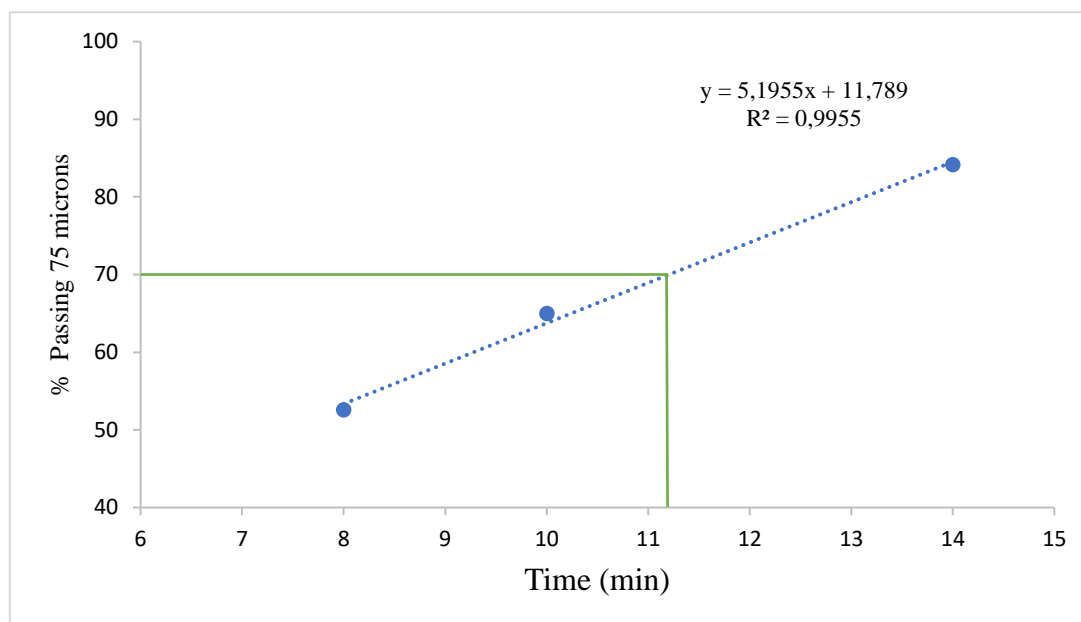


Figure 4-2: Cu-Ni-PGM milling curve plotted from milling times of 8, 10 and 14 times. Green line shows time required to achieve 70% passing 75 μm

4.6 Reagent Preparation and Storage

Reagents were provided by the Finnish Lapland operation. Table 4-7 shows a summary of the sequential batch flotation procedure, detailed in Section 4.7. The reagent properties and additional information are stated in Table 4-7. C1 and C2 refer to the first and second concentrates where copper flotation was targeted. C3-C6 refer to concentrates three through six, where nickel flotation was targeted. The order and concentration of reagents added as well as the conditioning times used were based on the sequential batch flotation procedure carried out onsite (Schreithofer & Hannu, 2019).

Table 4-7: Summary of the Sequential batch flotation procedure.

Action	Reagent name	Chemical formula	Molecular weight (g/mol)	Purity (%)	Dosage (g/t)	Time (min)
Collector	Aerophine 318A	$(C_4H_9)_2PS_2Na$	232	50	5	0
Depressant	Depramin 267	$C_8H_{15}NaO_8$	323 000	100	35	2
Frother	Nasfroth 240	$C_4H_9(OC_2H_4)_3OH$	206	100	20	4
C1	-	-	-	-	-	6
C2	-	-	-	-	-	11
Collector	SIPX	$(CH_3)_2CHOCS_2Na$	158	90	50	16
Depressant	Depramin 267	$C_8H_{15}NaO_8$	323 000	100	15	18
Frother	Nasfroth 240	$C_4H_9(OC_2H_4)_3OH$	206	100	10	20
C3	-	-	-	-	-	22
C4	-	-	-	-	-	29.5
Collector	SIPX	$(CH_3)_2CHOCS_2Na$	158	90	30	37
C5	-	-	-	-	-	39
C6	-	-	-	-	-	51.5

Key

Cu Flotation
Ni Flotation

4.6.1 Collector

Sodium dithiophosphate in liquid form (Aerophine 3418A, Solvay) was used as a Cu collector. A dosage of 5 g/t was added prior to C1 and used for each run without correction for active content. The aerophine was stored in a sealed bottle in a refrigerator at a temperature of 4 °C. Sodium Isopropyl Xanthate, received in powder form, (SIPX, Nasaco) was used as a Ni collector. SIPX easily decomposes hence it was prepared fresh daily as a 1% (w/v) solution in distilled water. A dosage of 50 g/t was added prior to C3 whilst a dosage of 30 g/t was added prior to C5. All the unused xanthate solutions were discarded daily as outlined by the material safety data sheet and the laboratory rules.

4.6.2 Depressant

Depramin 267, a carboxymethyl cellulose (CMC) in powder form from AKZO Nobel, was used as depressant. A 1 % w/v CMC solution was prepared every 5 days by dissolving the CMC granules in distilled water and mixing with a magnetic stirrer for two hours for complete hydration. A dosage of 35 g/t was used for copper flotation and 15 g/t was used for nickel flotation. The prepared CMC solution was stored in a sealed container and refrigerated at a temperature of 4°C. Depressant solutions were used within 5 days, all unused depressant

solutions were discarded daily as outlined by the material safety data sheet and the laboratory rules.

4.6.3 Frother

Nasfroth 240, Nasaco, is a triethylene glycol butyl ether. It was received in liquid form and used without any dilution. A dosage of 20 g/t was used for copper flotation and 10 g/t for nickel flotation. The frother was stored at room temperature.

4.7 Sequential Batch Flotation Tests

A 3 L Barker cell was used for the sequential batch flotation tests. A retort stand was used to support an immersion heater from the top of the cell. The heater was connected to a thermostatic temperature controlling device. There are two markings on the side of the cell, one indicating the 3 L volume and a second marking indicating the 2 cm froth height. Six collection dishes of known weight, and six wash bottles of known weight, were used respectively to each of the six concentrates, such that both water and solids recoveries could be monitored throughout. Figure 4-3 shows the apparatus set up.

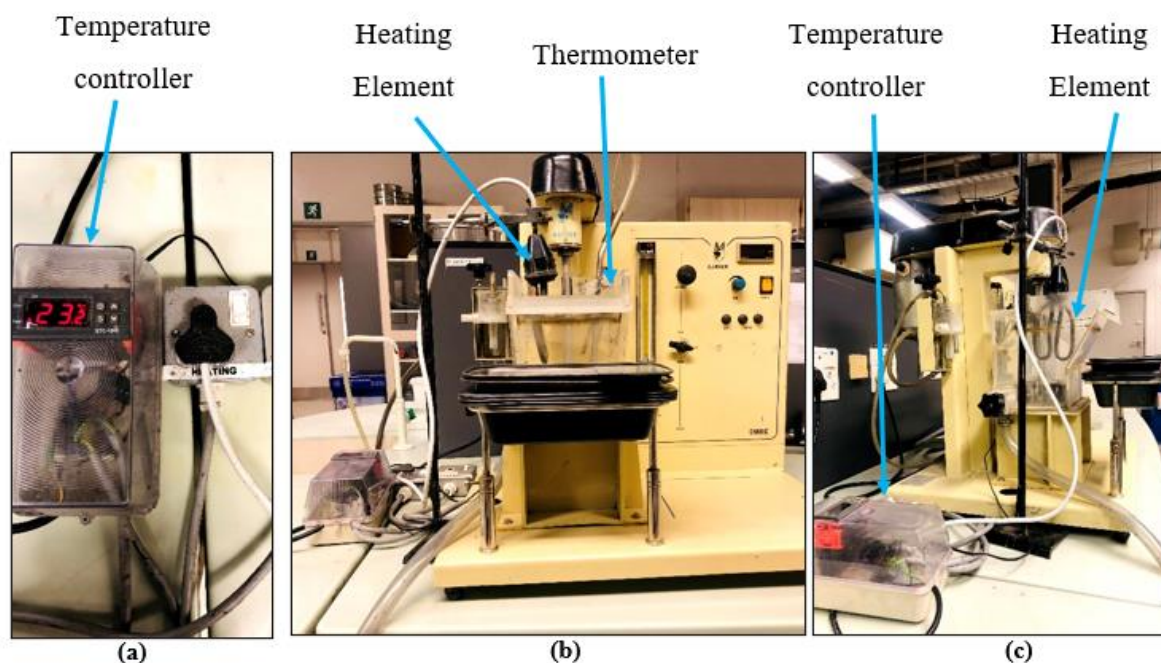


Figure 4-3: (a) Thermostatic temperature controller, (b) 3 L Barker flotation cell front view, (c) 3 L Barker flotation cell side view.

For each test condition 20 L of the relevant plant water was prepared as outlined in Section 4.3. The conditions, the sequential addition of reagents as well as the conditioning times were selected to mimic plant operation conditions. The ore was milled as outlined in Section 4.5. Standard UCT operating parameters were used to enable the comparison of the results obtained

with other such studies. The milled slurry was transferred to the flotation cell. LEW specific to the test was used to top up the slurry volume to the 3 L mark and to achieve 35 % solids. The pH of the slurry was ~9; owing to the gangue mineralogy of the ore, self-buffering occurs. The impeller speed was set to 1200 rpm. A 50 mL feed sample was taken before each flotation test. Table 4-7 shows the sequence and conditioning times for the reagents. The air was switched on to a flow rate of 7 L/min, the froth was scraped into the collection pan at 15 second intervals. The corresponding wash water bottle was used to rinse the flotation cell lip and scraper into the same collection pan for that concentrate. The froth height was maintained at the 2 cm mark by topping up with the corresponding LEW every minute. At the end of flotation, the air was switched off. Two tailing samples of 50 mL each were taken before the impeller was turned off. Water usage and solids recovery was monitored throughout. The feed, concentrates and tailings samples were vacuum filtered using a Buchner funnel and dried overnight in an oven at 75 °C. The dried samples were weighed and analysed for copper and nickel by ICP-OES using a Spectro Arcos ICP-OES as outlined in Section 4.2. The tests were carried in duplicate to ensure reproducibility keeping the standard error less than 5 % and 10 % for solid and water recoveries respectively.

4.8 Statistical Modelling Using Design Expert 13

Design Expert 13 (Anderson & Whitcomb, 2017) was the statistical program used to analyse the data and generate a series of plots and models to visualise the effects of the interaction of the factors under investigation. The four variables; temperature, Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$ were entered as nominal factors. The responses chosen were solids recovery, water recovery, nickel recovery, copper recovery, nickel grade and copper grade. Each response was determined using the average value from each duplicate experiment. The program assigned the terms A, B, C and D to temperature, Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$ respectively. A model hierarchy was then completed to consider the interactive effects; AB, AC, AD, BC, BD, CD, ABC, ABD, ACD, BCD and ABCD.

The following are some of the equations from which the test statistic, F may be calculated as presented by Navidi (2008). The treatment means for I samples each from a different treatment are denoted

$$\mu_1, \dots, \mu_I$$

The sample sizes are denoted

$$J_1, \dots, J_I$$

The total number in all the combined samples is denoted by N

$$N = J_1 + J_2 + \cdots + J_I$$

The hypotheses are $H_0: \mu_1 = \cdots = \mu_I$ versus H_1 : two or more of the μ_i are different. When there is more than one sample, a one-way analysis of variance (ANOVA) method is used. The notation for the sample observations is expressed as follows

$$\bar{X}_i = \frac{\sum_{j=1}^{J_i} X_{ij}}{J_i}$$

where the sample mean of the i th sample is denoted \bar{X}_i and X_{ij} denotes the j th observation in the i th sample. The sample grand mean is the average of all the sampled items taken together and can be expressed as a weighted average of the sample means

$$\bar{X}_{..} = \frac{\sum_{i=1}^I J_i \bar{X}_i}{N}$$

The treatment sum of squares (SSTr) is the variation of the sample means around the sample grand mean and is computed as

$$SSTr = \sum_{i=1}^I J_i (\bar{X}_i - \bar{X}_{..})^2 = \sum_{i=1}^I J_i \bar{X}_i^2 - N \bar{X}_{..}^2$$

The error sum of squares (SSE) is a measure of the variation in the individual sample points around their respective sample means. It is computed as

$$\begin{aligned} SSE &= \sum_{i=1}^I \sum_{j=1}^{J_i} (\bar{X}_{ij} - \bar{X}_i)^2 = \sum_{i=1}^I \sum_{j=1}^{J_i} X_{ij}^2 - \sum_{i=1}^I J_i \bar{X}_i^2 \\ &= \sum_{i=1}^I (J_i - 1) s_i^2 \end{aligned}$$

where s_i^2 denotes the sample variance of the i th sample. A mean square is obtained when a sum of squares is divided by its degrees of freedom. $I - 1$ and $N - I$ are the degrees of freedom for SSTr and SSE respectively. The treatment mean square (MSTr) and the error mean square (MSE) are defined by the equations

$$MSTr = \frac{SSTr}{I-1} \quad \text{and} \quad MSE = \frac{SSE}{N-I}$$

The test statistic F is then defined as

$$F = \frac{MSTr}{MSE}$$

The p-value can be found by consulting an F distribution table with $I - 1$ and $N - 1$ degrees of freedom. In the Design Expert software, the statistical modelling was computed as follows. Initially, all terms were selected for graphical modelling. ANOVA assigned each term a p-value, also known as a Prob > F value. The p-value tests the hypothesis that data from all groups are drawn from populations with identical means. The F value is a ratio of how much variability there is between the groups relative to how much there is within the groups (Navidi, 2008). For a 95 % confidence interval, a term was described as significant if the p-value was less than 0.05. The non-significant terms and their corresponding hierarchal components were deselected for the graphical modelling.

5. BATCH FLOTATION RESULTS

5.1 Key for Graphs

The following convention is used to describe the conditions for each test:

Temperature [Ca²⁺] [SO₄²⁻] [S₂O₃²⁻]

A number represents the temperature at which the test was run. The total ion concentrations of Ca²⁺, SO₄²⁻ and S₂O₃²⁻ are represented by the letters L (low), M (medium) and H (high). The values for the concentrations were obtained from the factorial design as shown in Table 4-4. An example is 25 LHH representing a test run at 25 °C, low Ca²⁺ concentration, high SO₄²⁻ concentration and high S₂O₃²⁻ concentration.

For each temperature set, control tests were run where the concentrations of Ca²⁺, SO₄²⁻ and S₂O₃²⁻ were maintained at zero level without any spiking. These runs are written as Temperature [Zero]. An example is 60 Zero representing a test run at 60 °C at zero level concentrations of Ca²⁺, SO₄²⁻ and S₂O₃²⁻.

5.2 Reproducibility

To determine and minimise the standard error associated with experimental results, each batch flotation test was carried out in duplicate for each of the test conditions. The solids recoveries, water recoveries, concentrate assays and metal recoveries are the variables that were used to determine reproducibility of the tests. The presented values are the calculated average values. The standard error between the duplicate tests is represented by the error bars. The sample standard error was calculated by dividing the sample standard deviation by the square root of the sample size. The standard error for the UCT standard batch flotation procedure is considered acceptable if it is at most 5 and 10% of the total recovered solids and water, respectively. The calculated standard error for all the batch flotation data presented in this thesis was found to be within acceptable limits.

The experimental factorial design resulted in two midpoint tests. As shown in Figure 5-1, there is little variation in the midpoint water and solid recoveries showing reproducibility.

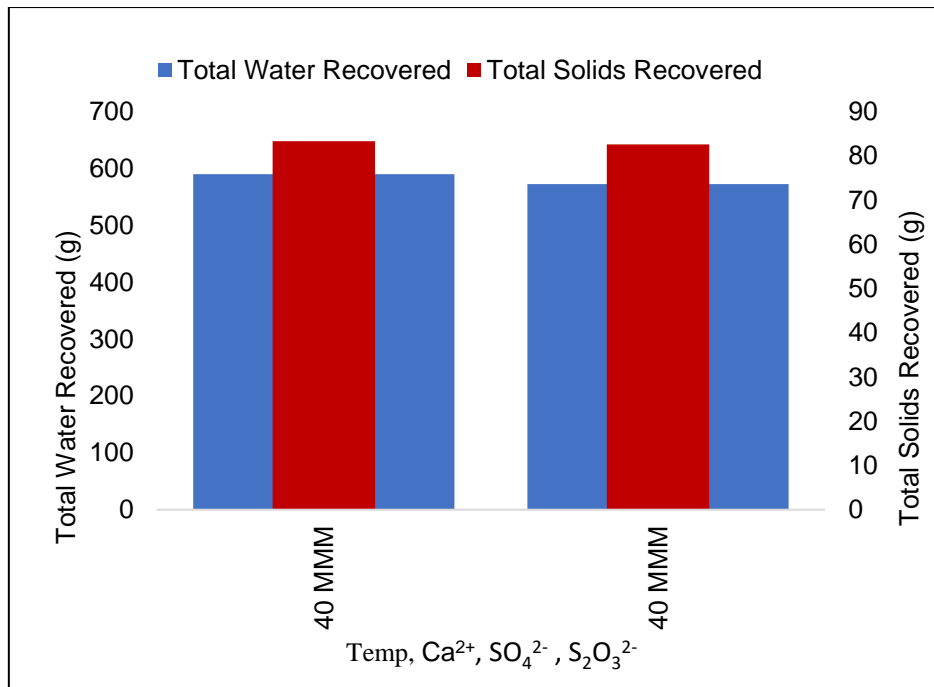


Figure 5-1: Graph showing the total water recovered and the total solids recovered for two midpoint conditions.

5.3 General trends

For each test condition at 25 °C, there is a corresponding test with the same ionic concentrations at 60 °C as shown in Table 5-1. The results in the subsequent sub sections show that the group trends observed at 25 °C do not necessarily match those observed at 60 °C.

Table 5-1: Total ionic strength of each test condition. Tests are listed in ascending IS values.

Run	IS (M)	Run
25 Zero, 40 Zero & 60 Zero	0,0858	-
25 LLL	0,178	60 LLL
25 HLL	0,217	60 HLL
25 LLH	0,241	60 LLH
25 HLH	0,281	60 HLH
40 MMM	0,327	40 MMM
25 LHL	0,373	60 LHL
25 HHL	0,412	60 HHL
25 LHH	0,437	60 LHH
25 HHH	0,476	60 HHH

5.4 Solids and Water Recoveries

5.4.1 Total Cumulative Water Recoveries and Total Cumulative Solids Recoveries

Figure 5-2 shows the total cumulative water recoveries and total cumulative solids recoveries for the conditions tested. The blue bars represent total water recoveries in grams on the left y-axis. The red bars represent total solids recoveries in grams on the right y-axis. Generally, an increase in temperature and ionic strength shows higher recoveries of solids. This graph alone however does not give much detail on the differences arising from the different test variables.

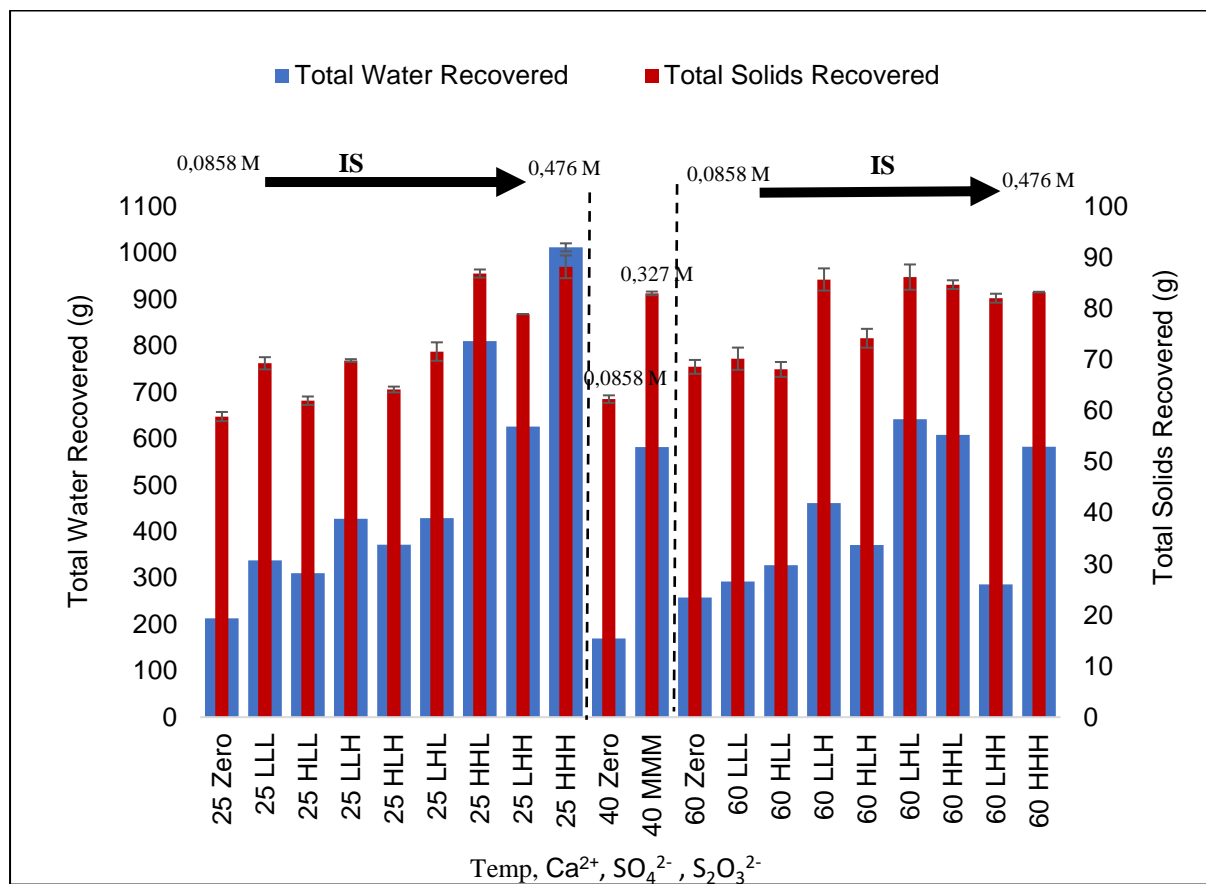


Figure 5-2: Graph showing the total water recovered and the total solids recovered for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

5.4.2 Cumulative Water Recoveries vs Time

Figure 5-3 shows the cumulative water recoveries vs. time for the conditions tested. The recoveries at 25 °C had a wider range (213–1012 g) in comparison to those at 60 °C

(286–642 g). A similar trend can be seen for the cumulative solids recoveries as shown in Figure 5-6.

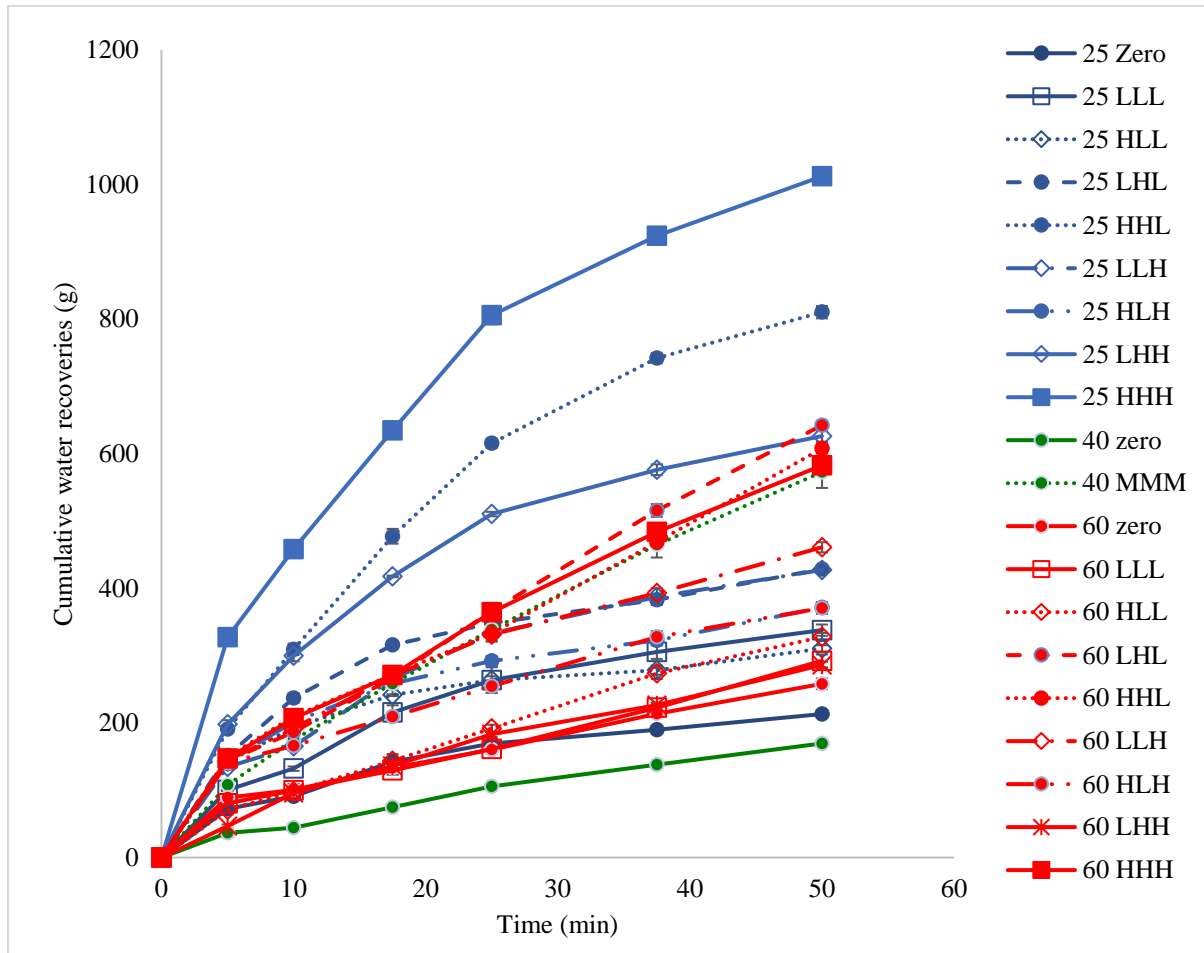


Figure 5-3: Graph showing the cumulative water recoveries vs time for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

Figure 5-4 shows the observations for the tests at 25 °C which can be split into two general regions according to ionic strength. Higher water recoveries were observed at $\text{IS} > 0.4 \text{ M}$. The tests which fell in this region all have a high concentration of SO_4^{2-} . Lower water recoveries were observed at $\text{IS} < 0.4 \text{ M}$. The tests which fell in this region had a low concentration of SO_4^{2-} except for one outlier 25 LHL which had a high concentration of SO_4^{2-} at $\text{IS} 0.373 \text{ M}$ which is not too far off from 0.4 M. A similar trend is observed for the solid recoveries as shown in Figure 5-7.

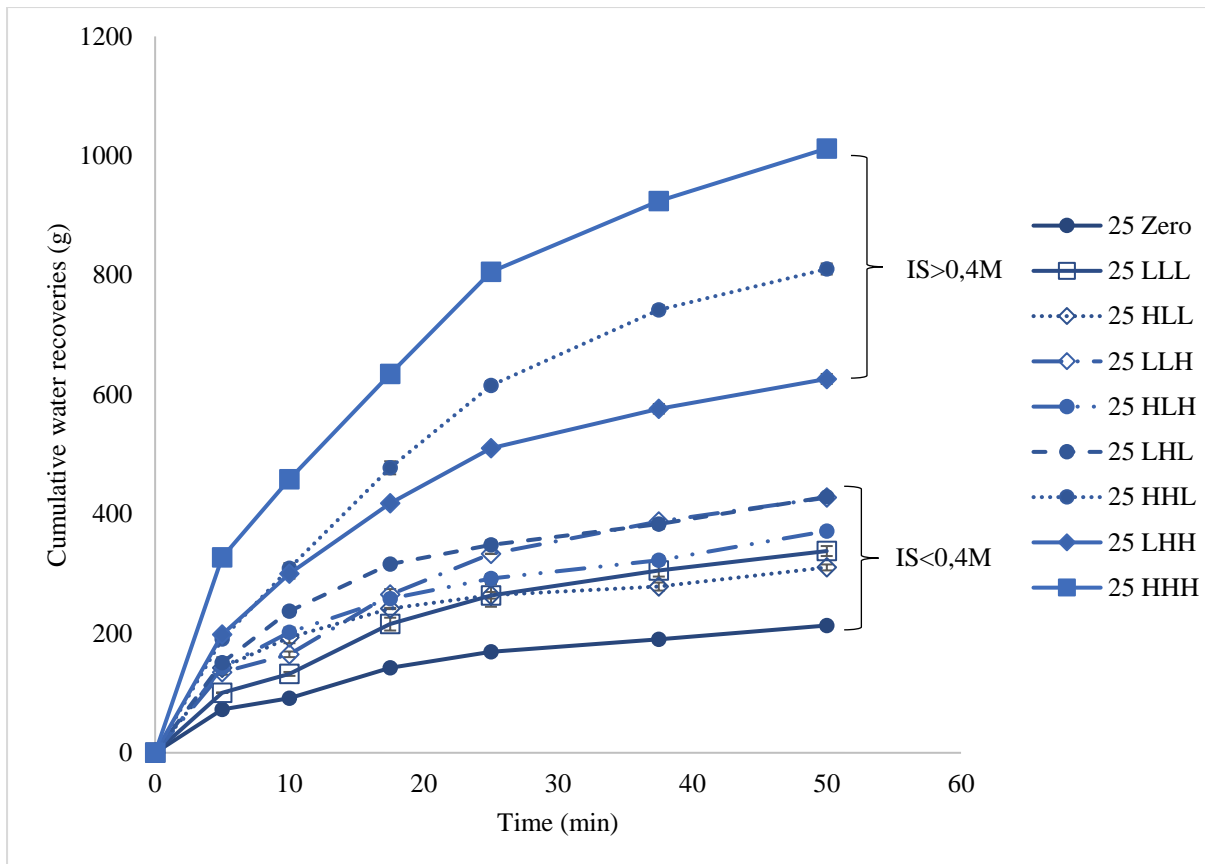


Figure 5-4: Graph showing the cumulative water recoveries vs time at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

Figure 5-5 shows the observations for the tests at 60 °C. There were no distinct group trends observed. The lowest water recoveries were observed at 60 LHH (0.437 M) followed by 60 LLL (0.178 M) both with low Ca^{2+} concentration. The highest water recoveries were observed at 60 LHL (0.373 M) followed by 60 HHL (0.412 M). Both these observations have high SO_4^{2-} and low $\text{S}_2\text{O}_3^{2-}$ concentrations.

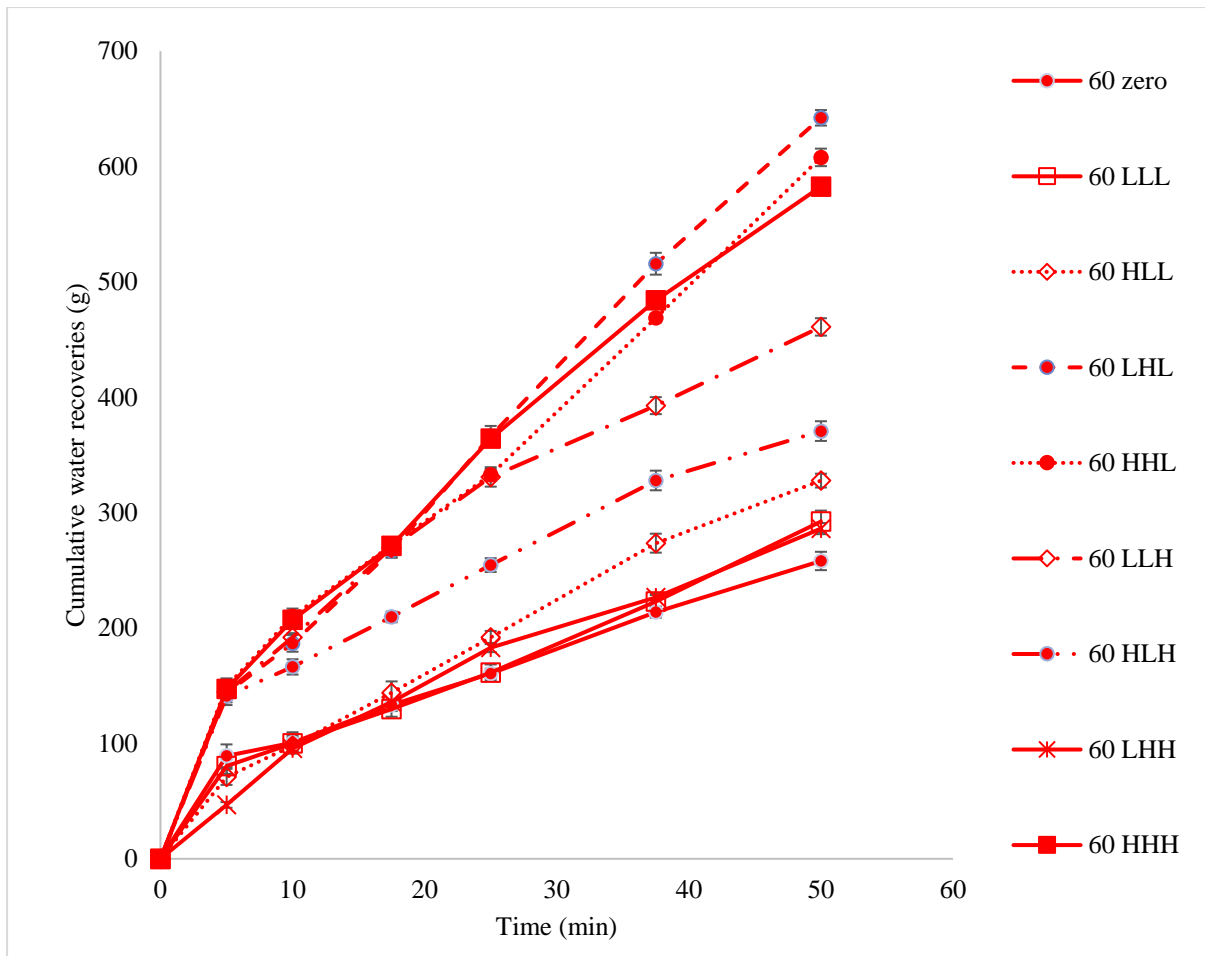


Figure 5-5: Graph showing the cumulative water recoveries vs time at 60 °C and three levels of ionic of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

5.4.3 Cumulative Solids Recoveries vs Time

Figure 5-6 shows the cumulative solid recoveries vs. time for the conditions tested. As aforementioned in 5.4.2, the recoveries at 25 °C had a wider range than those at 60 °C.

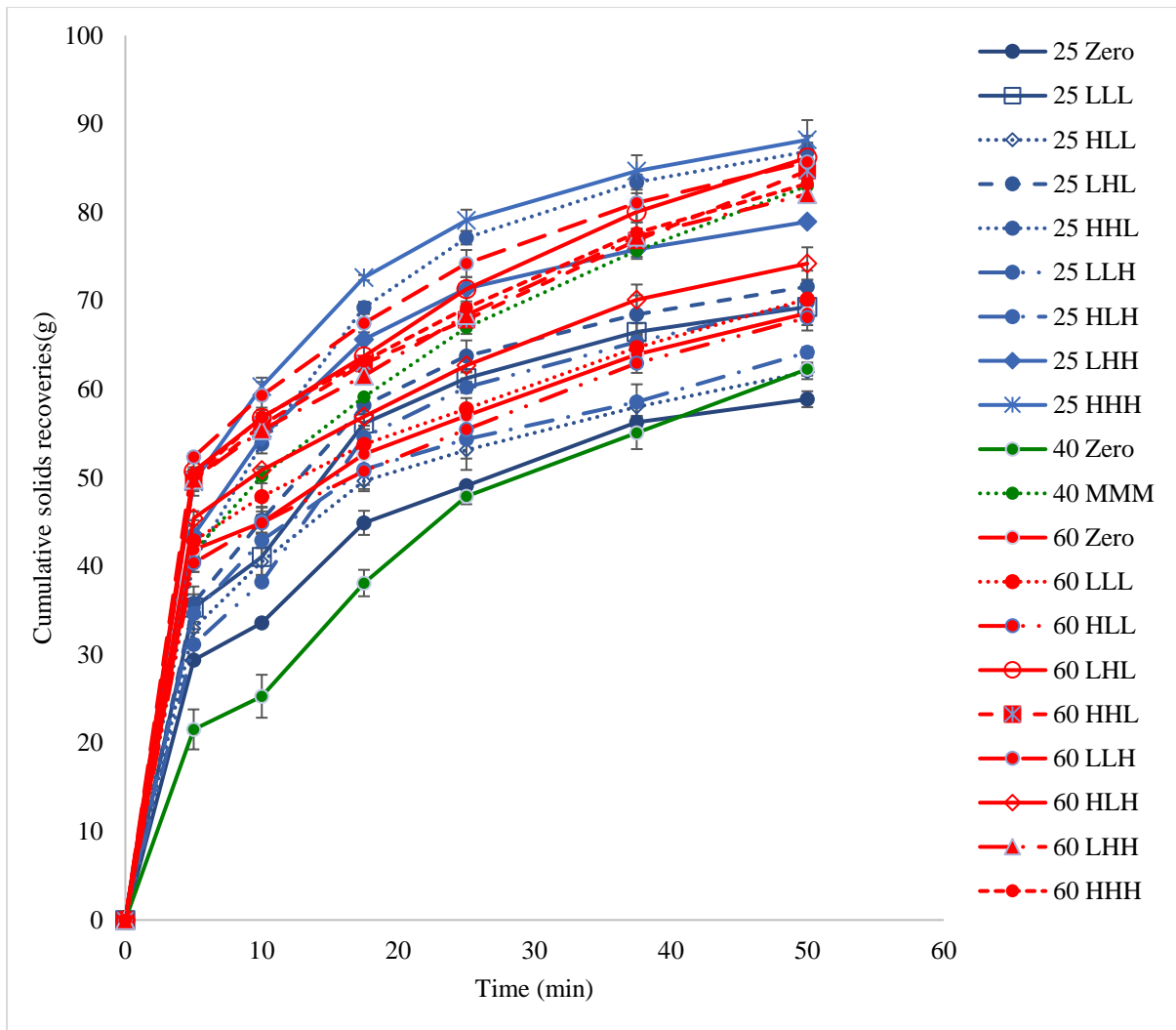


Figure 5-6: Graph showing the cumulative solid recoveries vs time for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

Figure 5-7 shows the observations for the cumulative solids tests at 25 °C as a function of time. There are two main regions with the same trends according to ionic strength as those seen with the water recoveries at 25 °C. Additionally, at 10 min there is a distinctive increase in the flotation rate for some of the tests. Copper flotation was targeted within the first 10 min after which nickel flotation was targeted. The dotted vertical line at 10 min distinguishes the copper and nickel regimes.

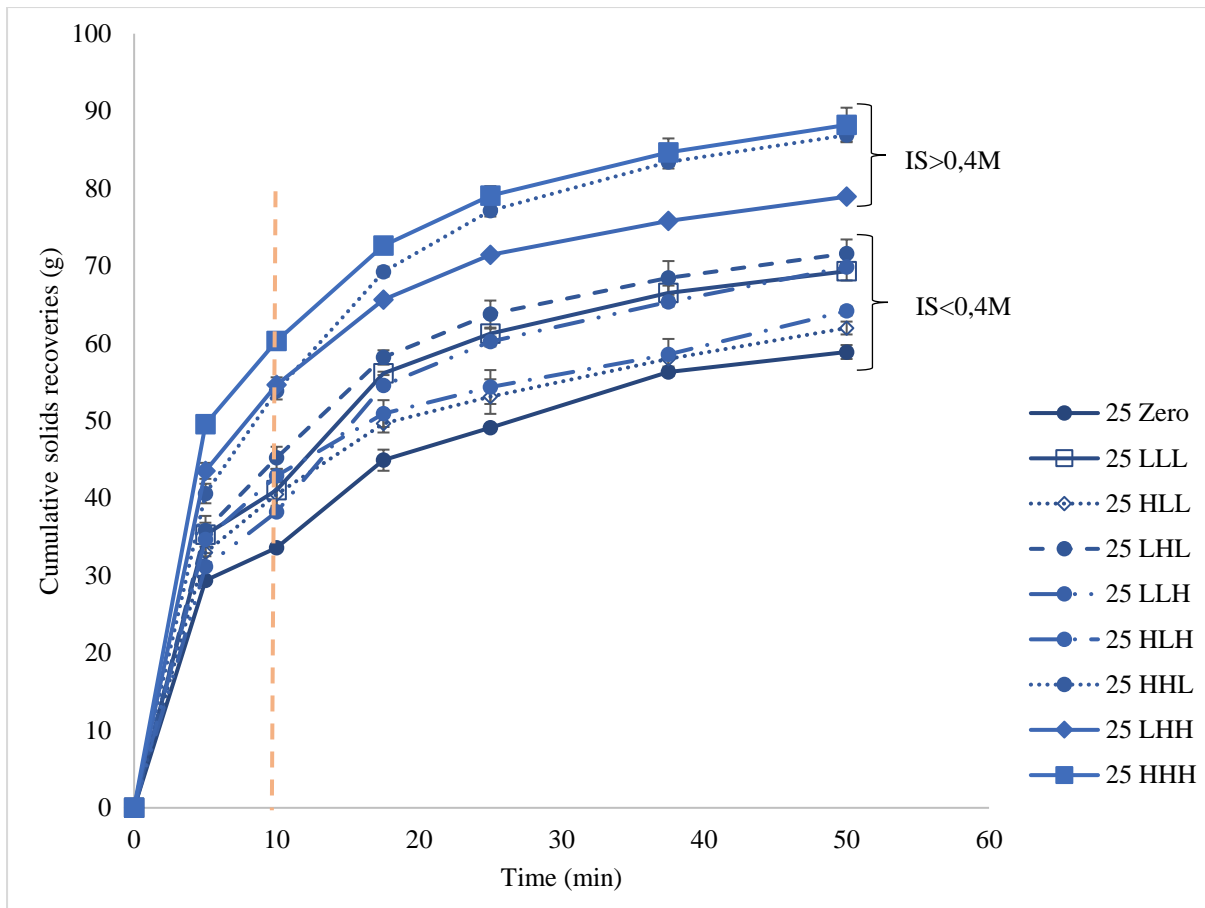


Figure 5-7: Graph showing the cumulative solid recoveries vs time at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

Figure 5-8 shows the cumulative solids recoveries vs. time for the tests at 60 °C. The highest solids recoveries were observed at $\text{IS} > 0.3 \text{ M}$. There was one outlier of the tests in this region, 60 LLH (0.241 M). The general observation of the tests which fell in this region is that they have a high SO_4^{2-} concentration. The lower solids recoveries were observed at $\text{IS} < 0.3 \text{ M}$ and low SO_4^{2-} concentration.

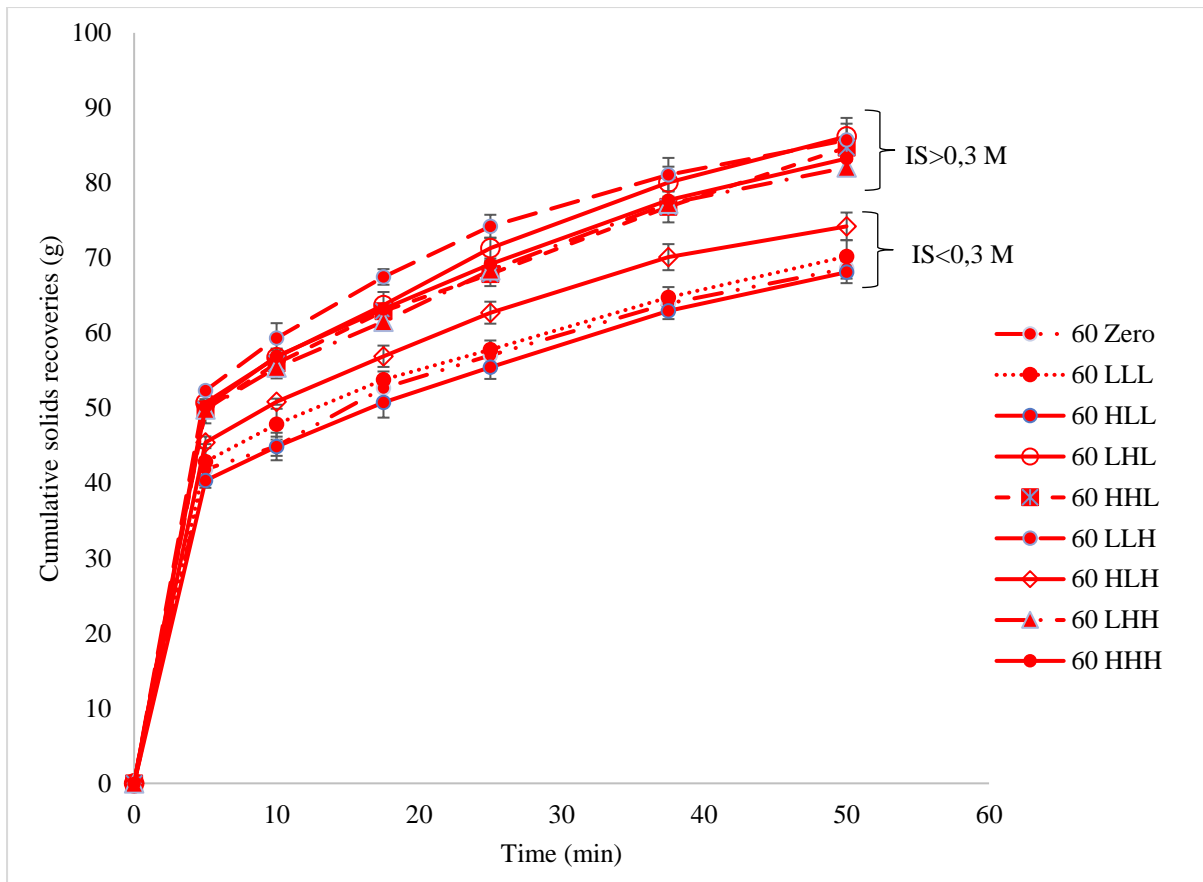


Figure 5-8: Graph showing the cumulative solid recoveries vs time at 60 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

5.4.4 Cumulative Solids Recoveries vs Cumulative Water Recoveries

Figure 5-9 shows the cumulative solid recoveries vs. cumulative water recoveries for the conditions tested. There is a distinction between tests ran at 25 °C and 60 °C. The lower temperature results in less solids per unit water while the higher temperature results in more solids per unit water. At both temperatures, the highest water recoveries gave the highest solids recoveries.

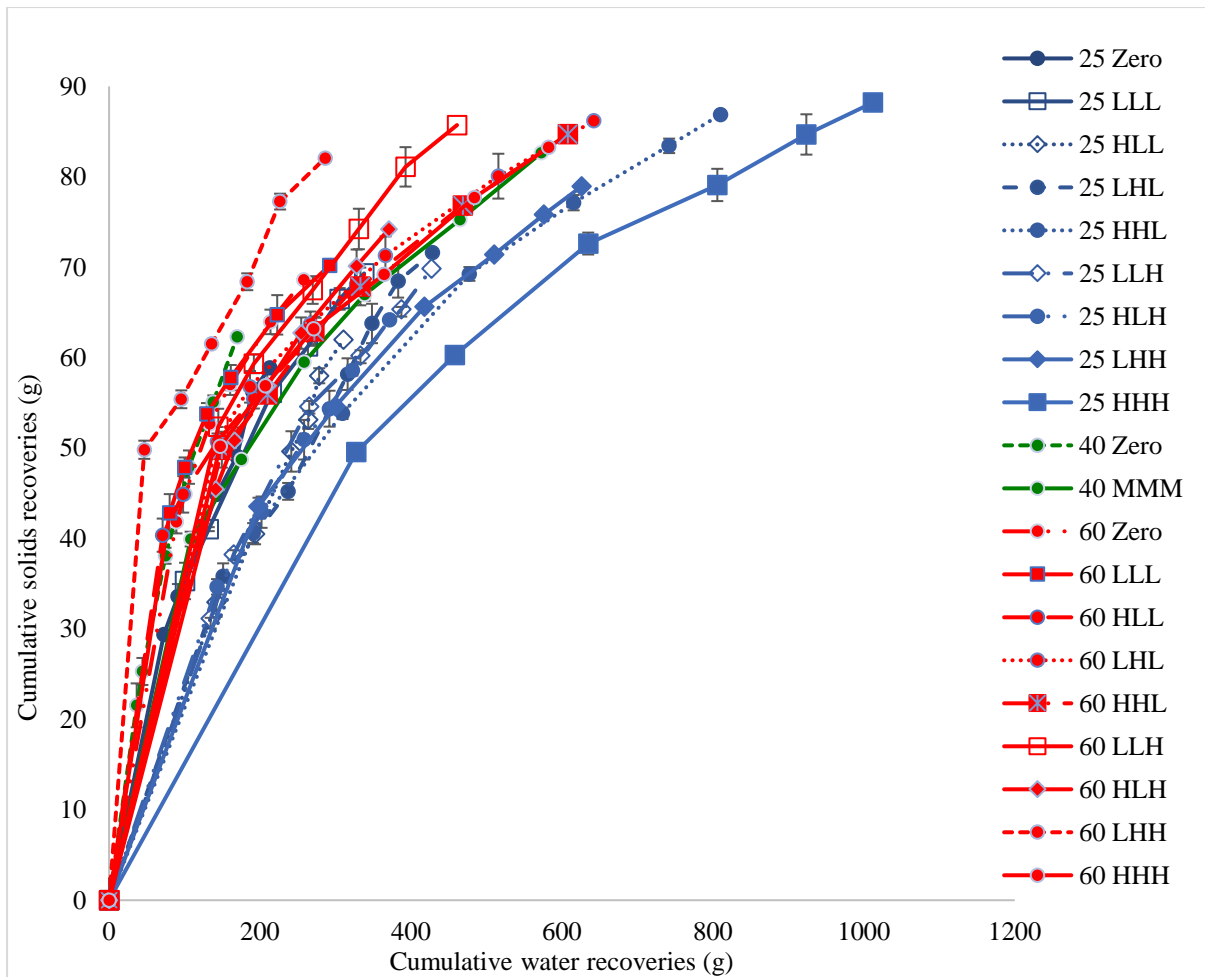


Figure 5-9: Graph showing the cumulative solid recoveries vs cumulative water recoveries for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

Figure 5-10 shows the cumulative solids recoveries vs. cumulative water recoveries at 25 °C. The highest water recoveries gave the highest solids recoveries at 25 HHH (0.476 M). Tests with $\text{IS} > 0.4$ M fell in the same range of values for the solids recovered per unit water. Similarly, test with $\text{IS} < 0.4$ M fell within their own range. A similar trend is observed for tests ran at 60 °C as shown in Figure 5-11. At $\text{IS} > 0.37$ M the tests fell into two different ranges of the solids recovered per unit water.

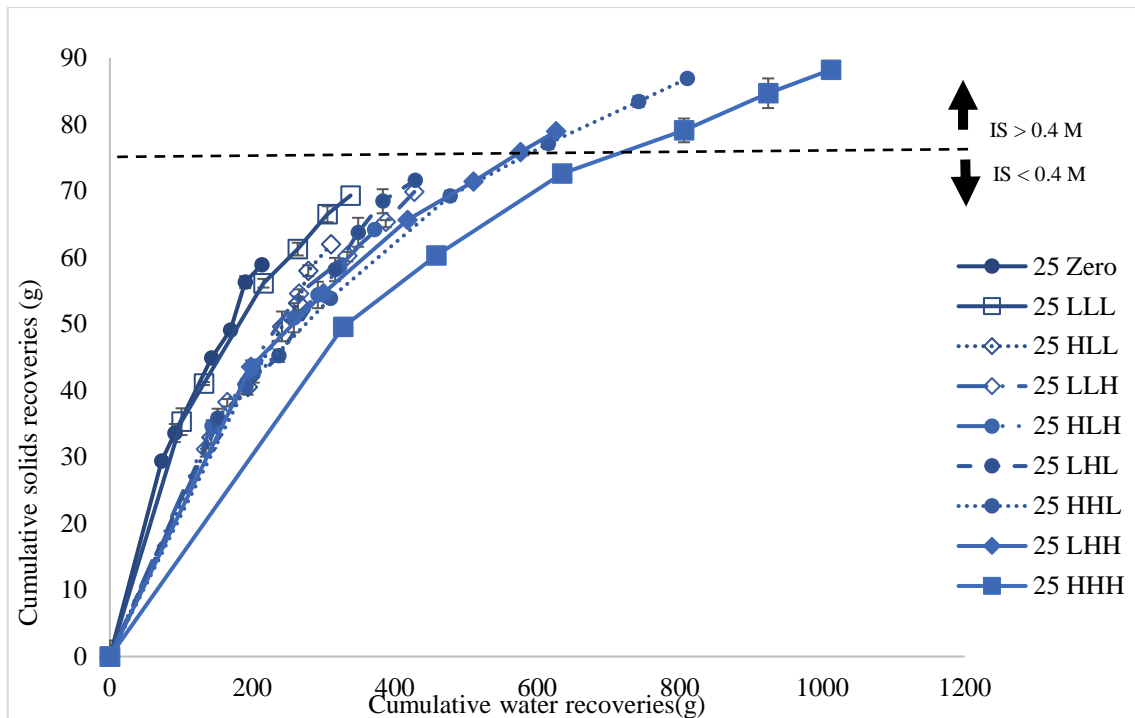


Figure 5-10: Graph showing the cumulative solid recoveries vs cumulative water recoveries at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

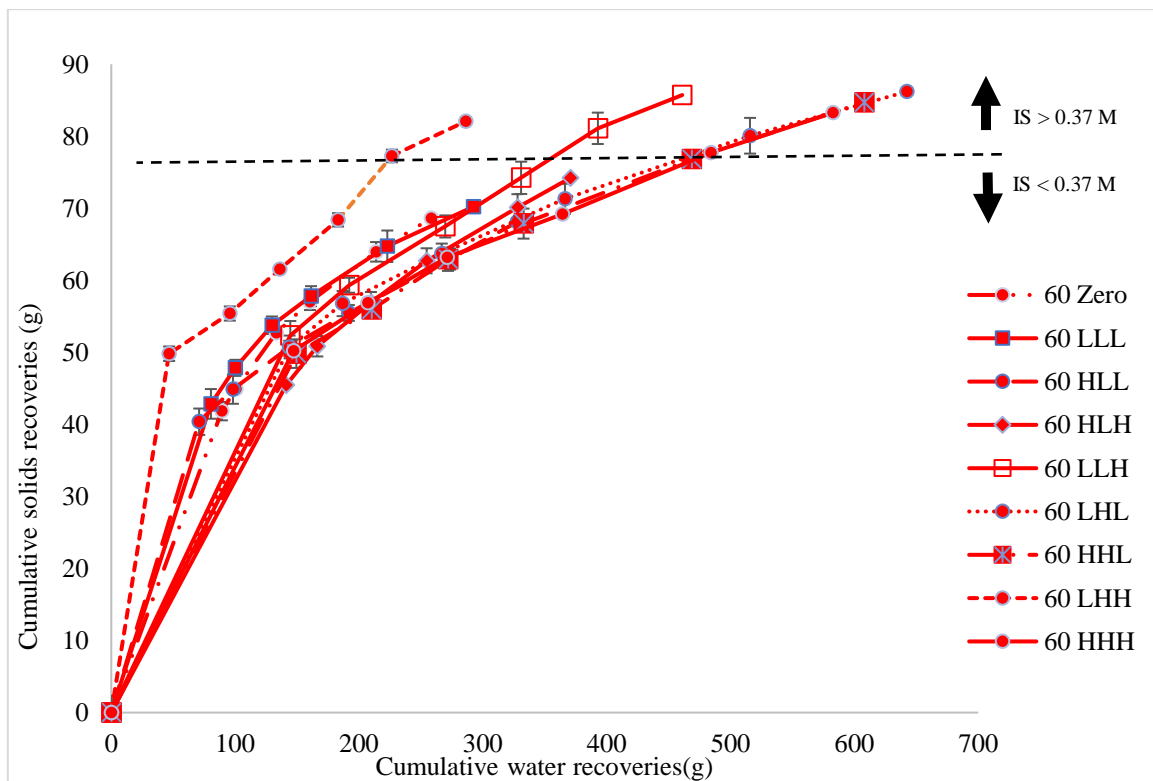


Figure 5-11: Graph showing the cumulative solid recoveries vs cumulative water recoveries at 60 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

5.5 Copper

5.5.1 Total Cumulative Copper Recoveries and Final Cumulative Copper Grades

Figure 5-12 shows total cumulative copper recoveries and final cumulative copper grades for the conditions tested. The brown bars represent the total copper recovered on the left axis. The yellow bars represent the final copper grades on the right axis. The average copper recovery is shown by a blue line. Figure 5-12 shows that there is little variation in the total copper recoveries. Generally, at 25 °C it appears that the copper grade decreases as the ionic strength increases. However, this is not the case at higher temperatures.

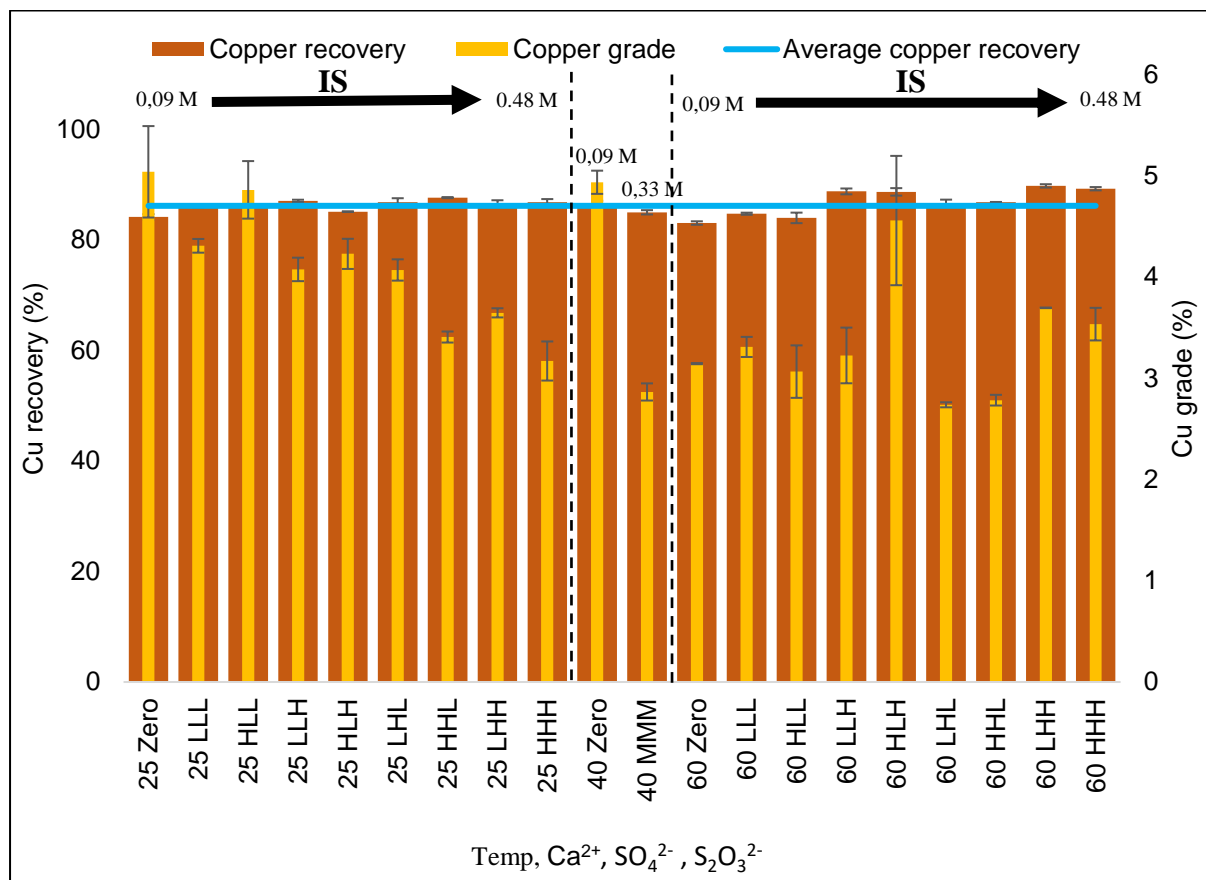


Figure 5-12: Graph showing the total copper recoveries, final copper grades and average copper recovery for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

Figure 5-13 shows that as the temperature increases, there is a decrease in the copper grade.

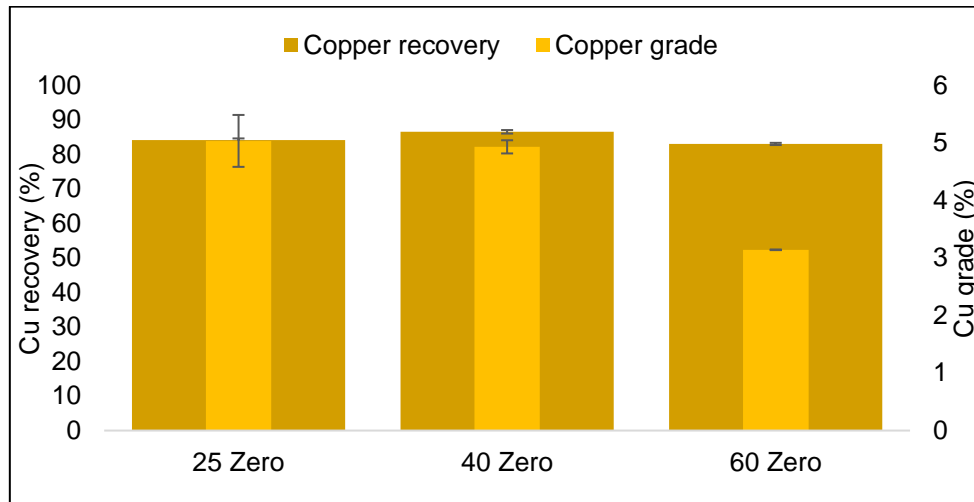


Figure 5-13: Graph showing the total copper recoveries, final copper grades and average copper recovery for three temperatures and zero level ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

5.5.2 Cumulative Copper Recoveries vs Time

Figure 5-14 shows the cumulative copper recoveries vs. time for the tested conditions. Most of the copper seems to be collected within the first 5 minutes with the final copper recoveries varying between 80–90 % overall.

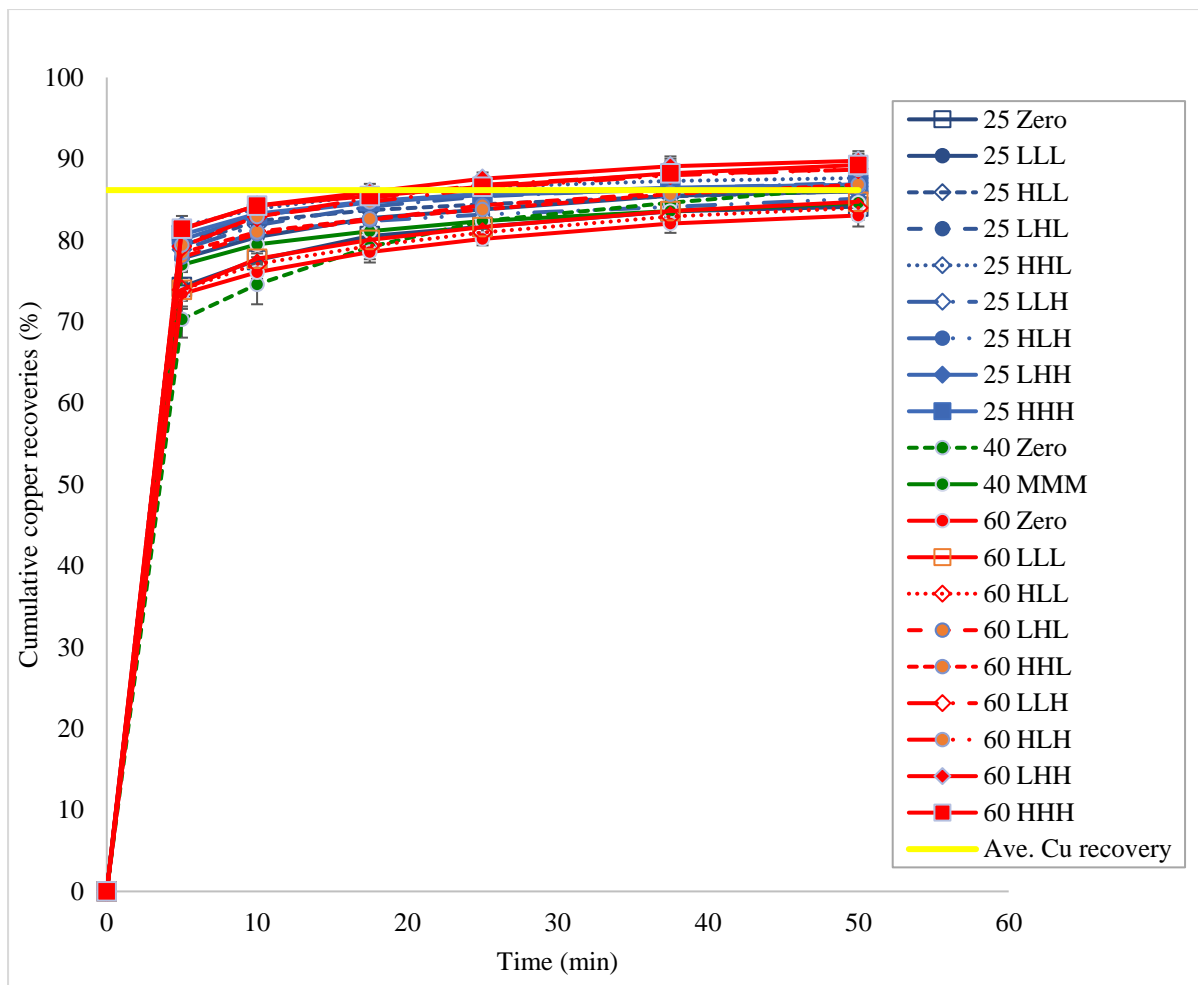


Figure 5-14: Graph showing the cumulative copper recoveries vs time for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

At 25 °C the final copper recoveries had a variation of only 3 % across all the runs. There was no distinct variation within the tests.

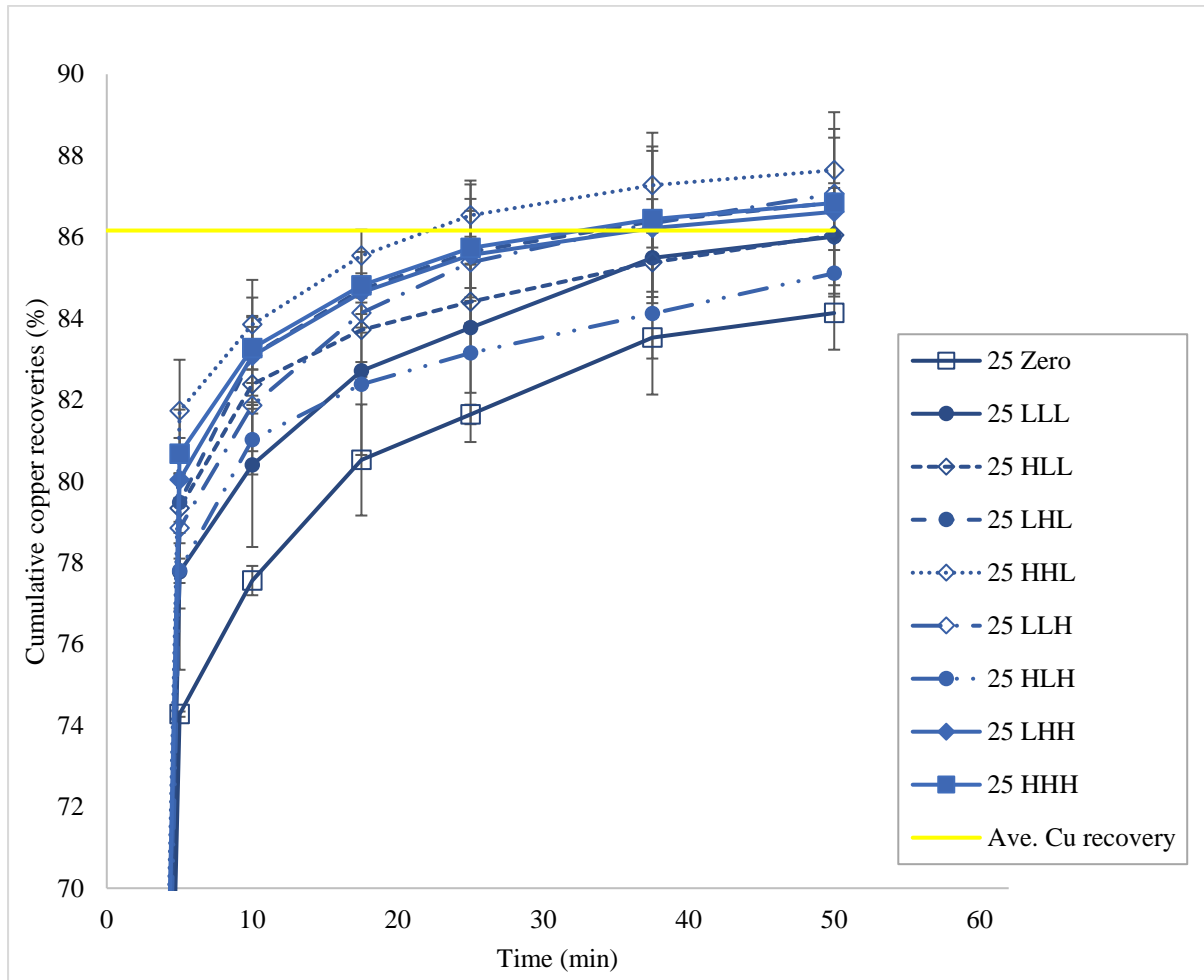


Figure 5-15: Graph showing the cumulative copper recoveries vs time at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. Y-axis has been shortened.

Figure 5-16 shows three distinct variations across the 60 °C tests. The y-axis has been shortened to start at 70 % for better visualisation. **A** represents the three lowest cumulative copper recoveries. The spiked tests in **A** both have low concentrations of SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. **B** shows two middle tests which have final cumulative recovery values that are not too far apart. Both tests have high SO_4^{2-} and low $\text{S}_2\text{O}_3^{2-}$ concentrations. **C** shows the four highest cumulative copper recoveries. The tests in **C** all have high $\text{S}_2\text{O}_3^{2-}$ concentrations. The regions **A**, **B** and **C** are the same presented with the corresponding models in 5.7.1.

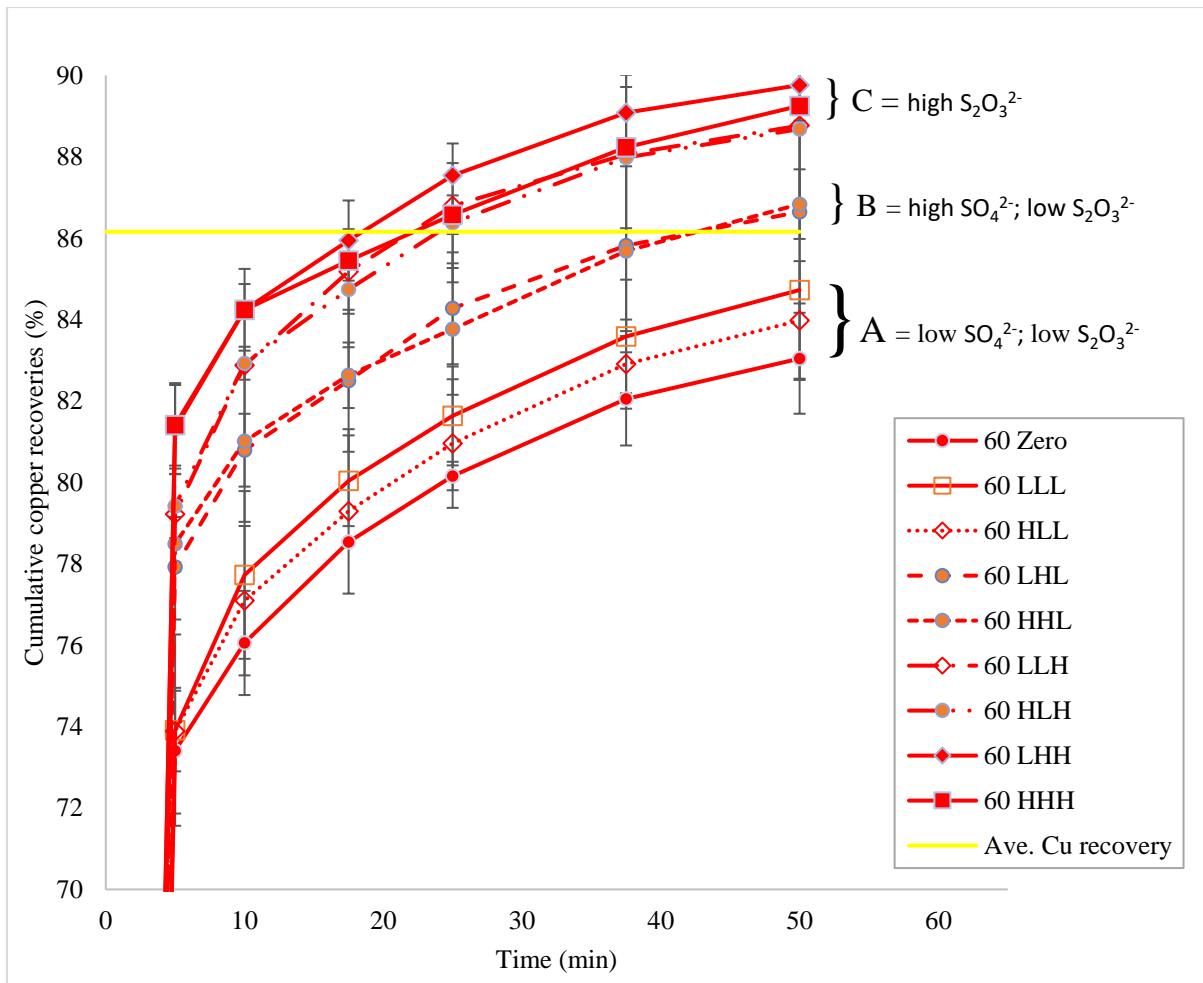


Figure 5-16: Graph showing the cumulative copper recoveries vs time at 60 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. Y-axis has been shortened. A, B and C show grouped tests according to concentrations of relevant ions.

5.5.3 Cumulative Copper Recoveries vs Cumulative Water Recoveries

Figure 5-17 shows the cumulative copper recoveries vs the cumulative water recoveries for the conditions tested. Generally, it appears that the higher temperature (60 °C) recovers less water while recovering a similar amount of copper as lower temperatures (25 °C and 40 °C).

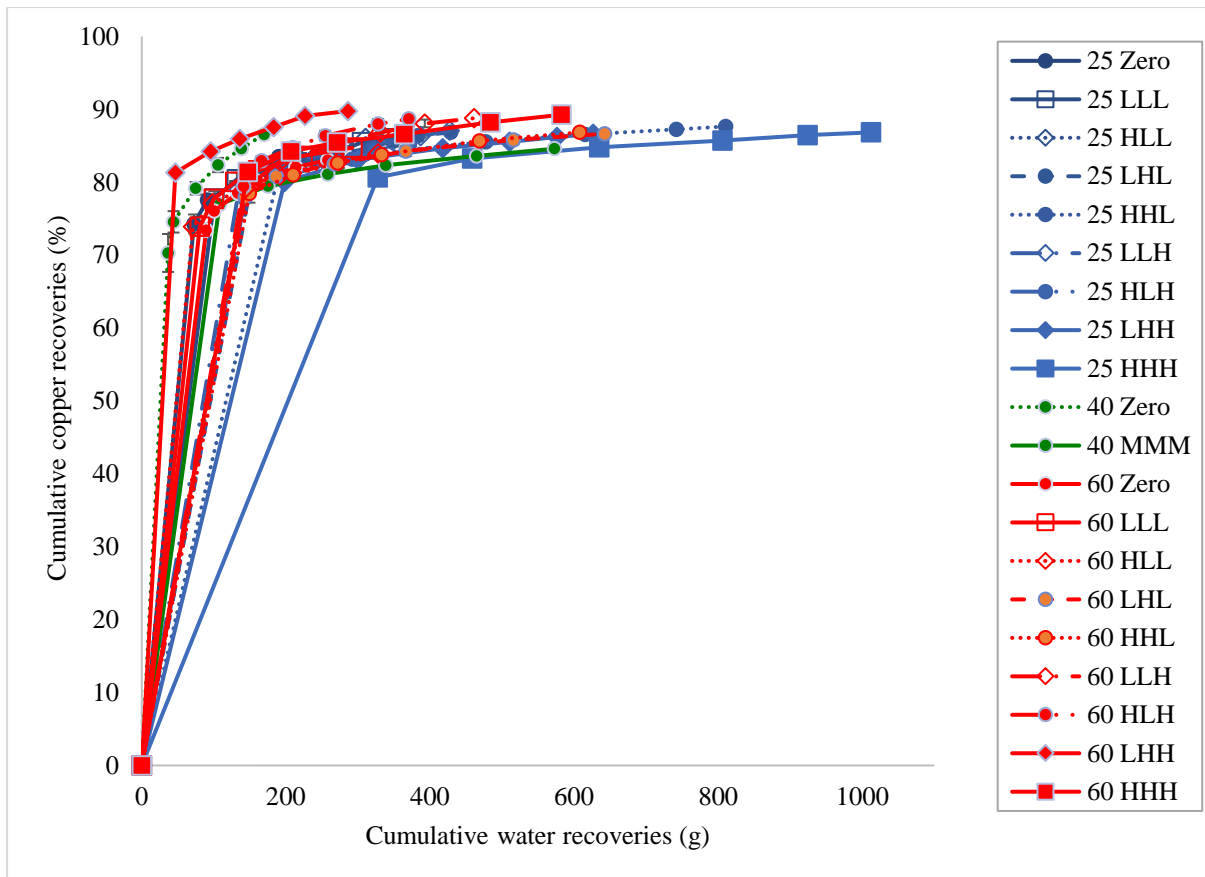


Figure 5-17: Graph showing the cumulative copper recoveries vs cumulative water recoveries for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

Figure 5-18 and Figure 5-19 both show that there were no distinct variations within each temperature group.

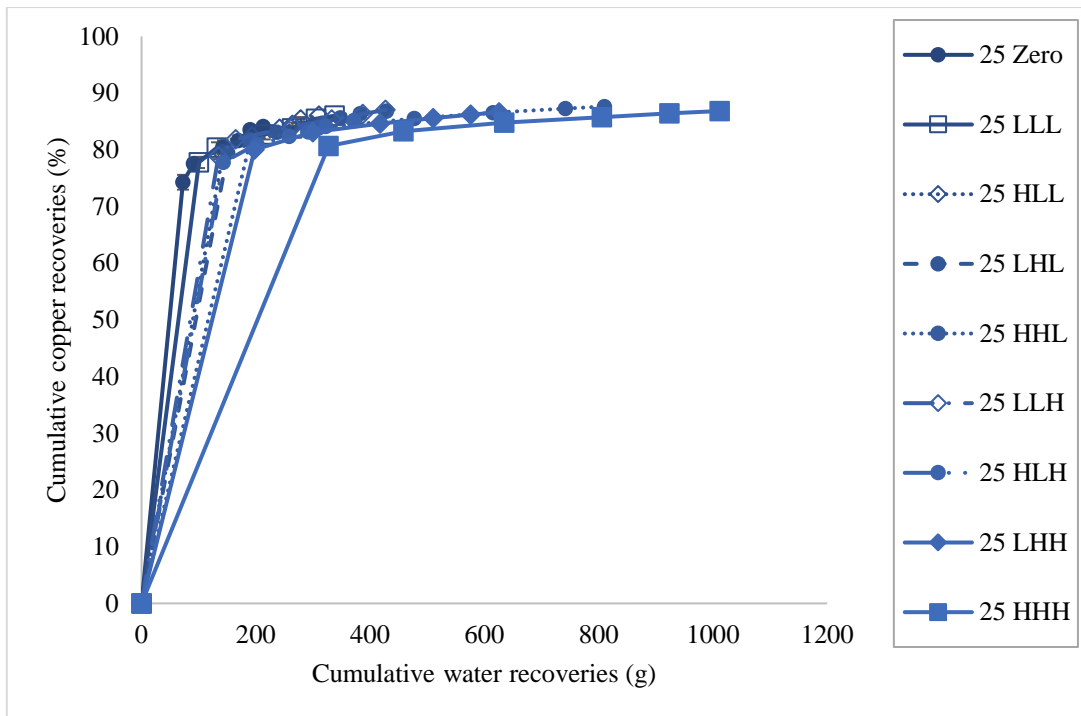


Figure 5-18: Graph showing the cumulative copper recoveries vs cumulative water recoveries at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

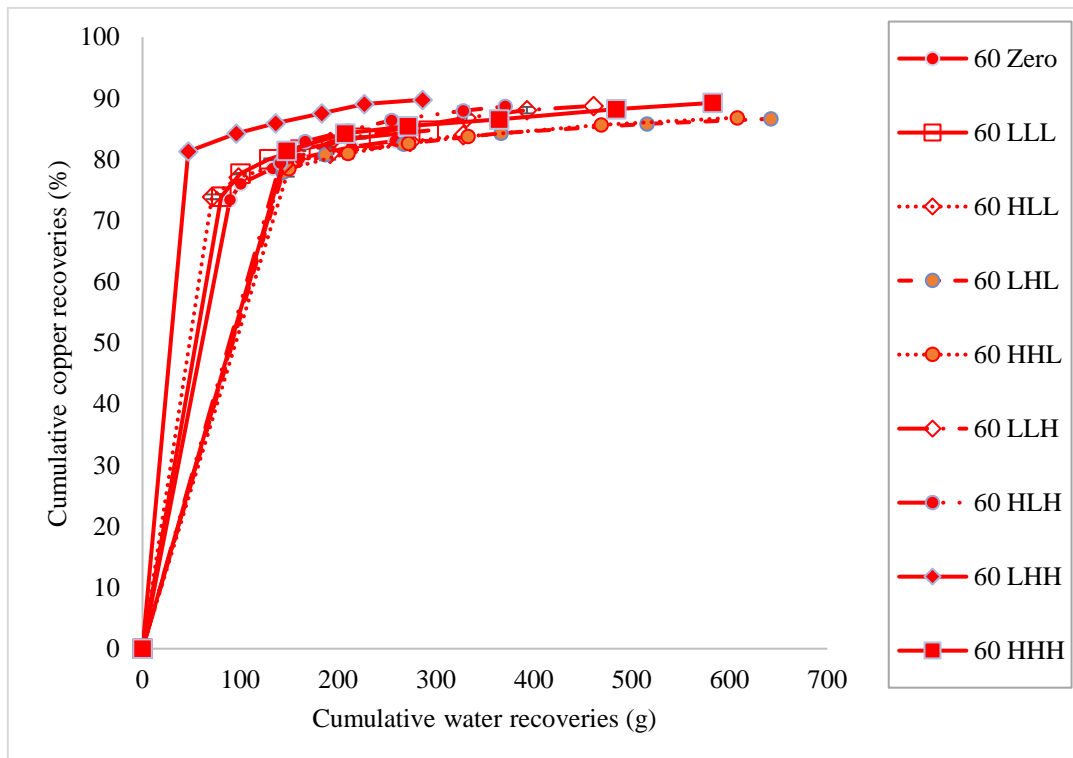


Figure 5-19: Graph showing the cumulative copper recoveries vs cumulative water recoveries at 60 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

5.5.4 Cumulative Copper Grades vs Cumulative Copper Recoveries

The horizontal axes for all the graphs in 5.5.4 have been adjusted to start at 70 % for better visualisation. Figure 5-20 shows the cumulative copper grades vs. the cumulative copper recoveries for the conditions tested. Within each temperature group, the copper grade decreases as the recovery increases. An increase in temperature appears to decrease the extent to which the grade decreases as the recovery increases. A similar trend was also observed for nickel as presented in 5.6.4.

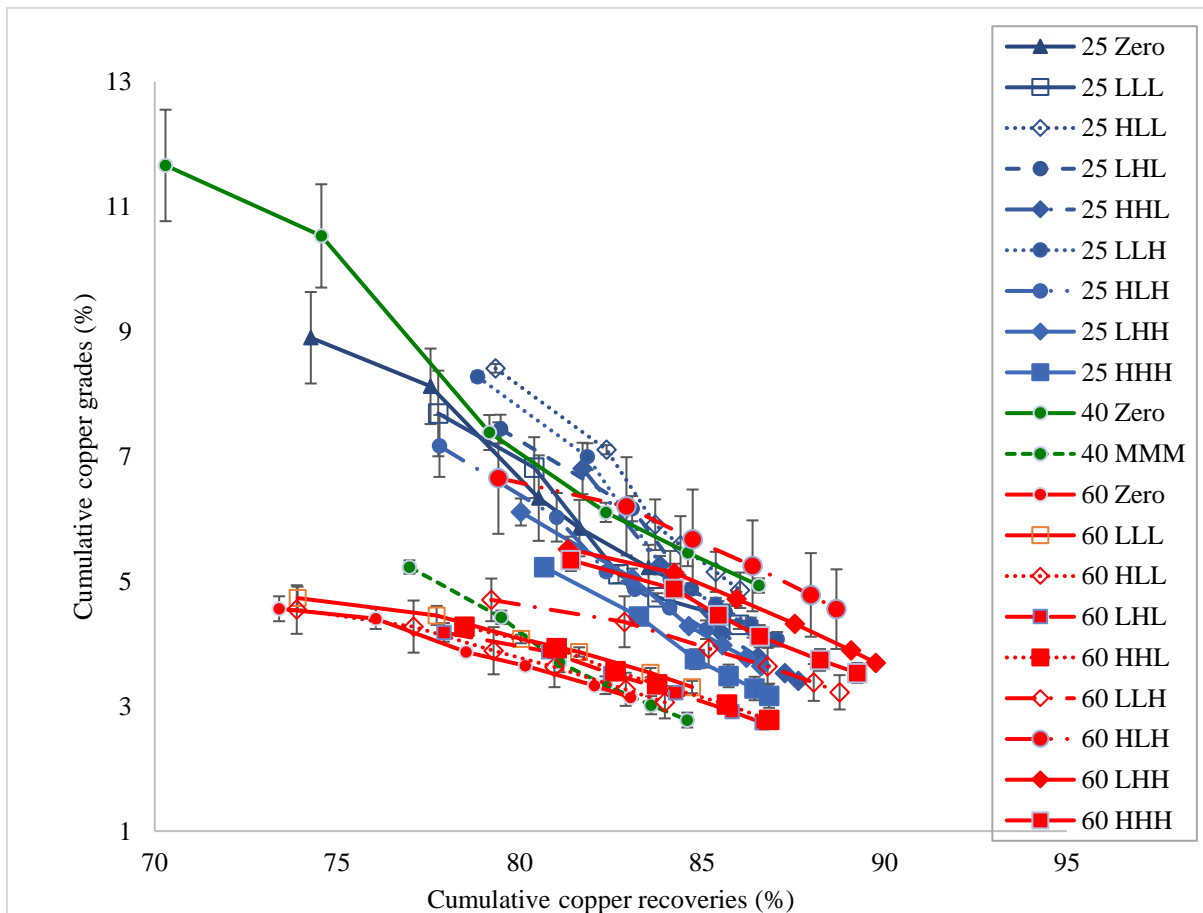


Figure 5-20: Graph showing the copper grade vs copper recovery for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. Both axes have been shortened for clarity.

The tests at 25 °C are shown in Figure 5-21. It can be observed that the tests were distributed within a narrower region in comparison to the tests at 60 °C in Figure 5-22.

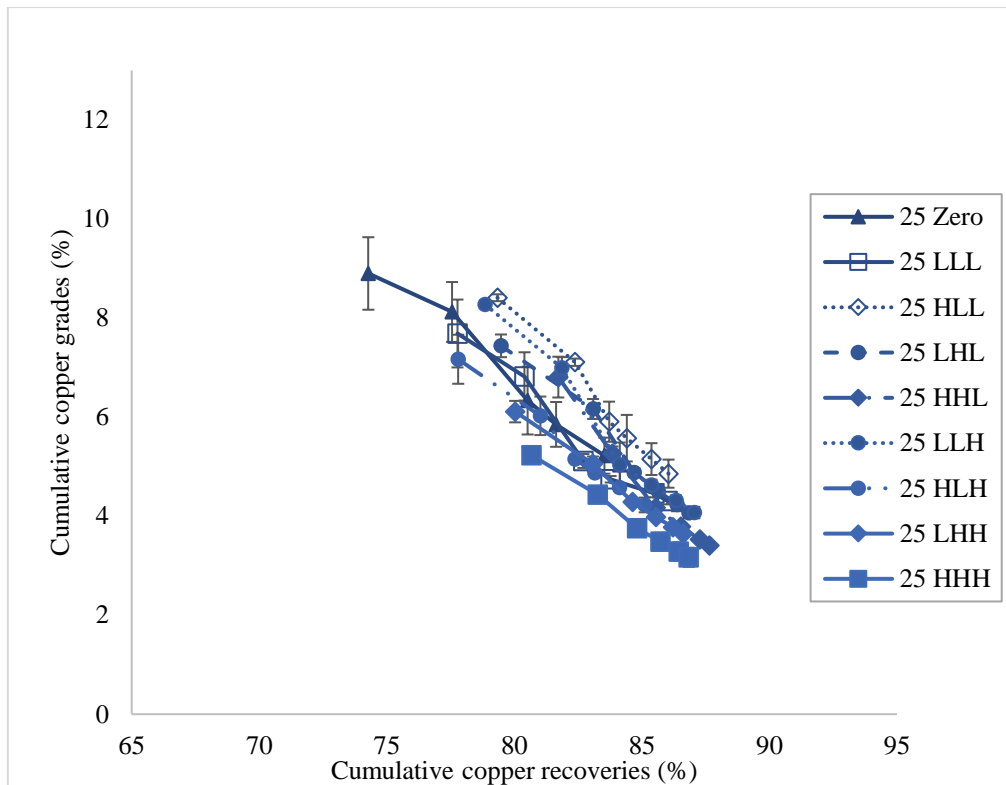


Figure 5-21: Graph showing the copper grade vs copper recovery at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. X-axis has been shortened for clarity.

Figure 5-22 shows the tests at 60 °C. The tests seem to fall within two regions defined by ionic strength. The tests with lower copper grade per unit copper recovery have $\text{IS} < 0.43 \text{ M}$, whilst those with $\text{IS} > 0.43 \text{ M}$ have higher copper grade per unit copper recovery. The exception is 60 HLH (0.281 M) with high Ca^{2+} and $\text{S}_2\text{O}_3^{2-}$ concentrations. Similar trends can be seen for nickel in Section 5.6.4.

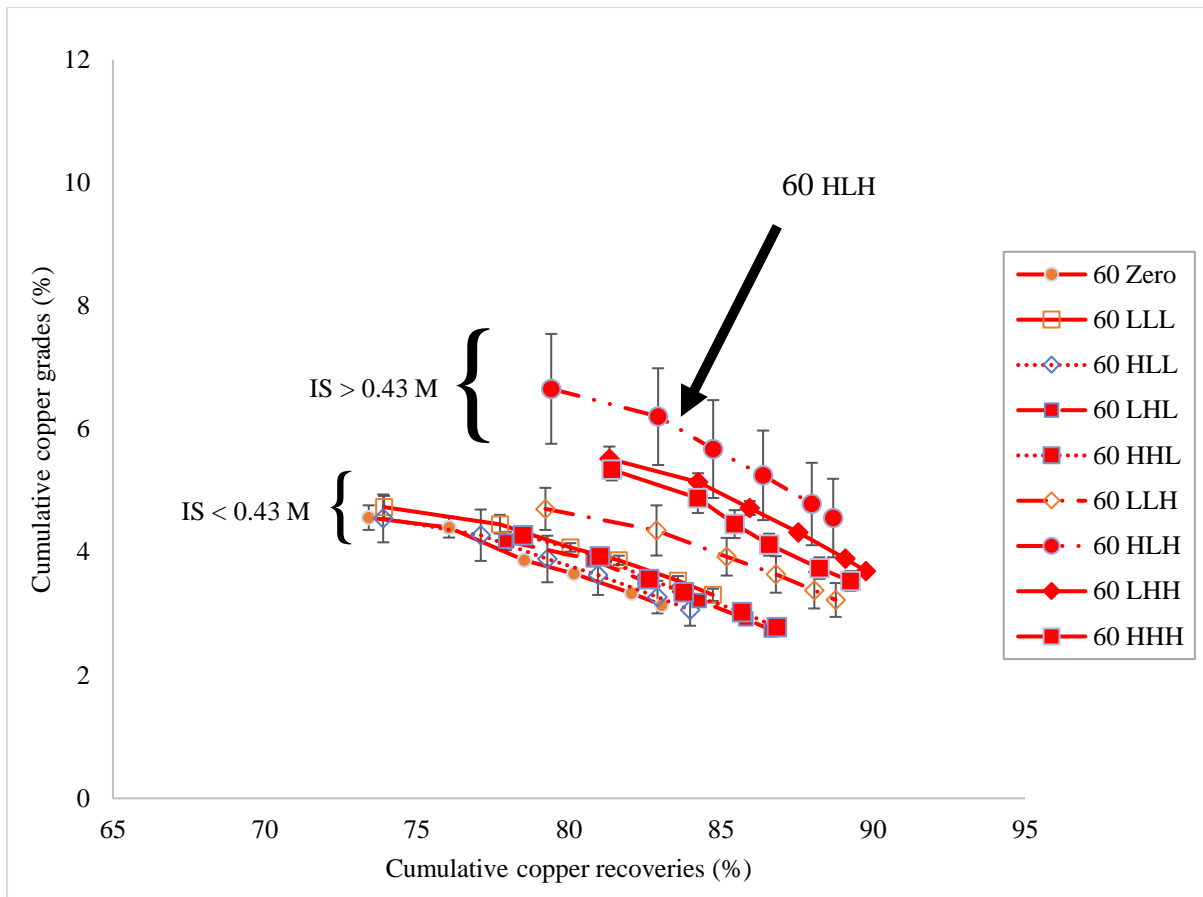


Figure 5-22: Graph showing the copper grade vs copper recovery at 60 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. X-axis has been shortened for clarity. A and B show grouped tests according to IS.

5.6 Nickel

5.6.1 Total Cumulative Nickel Recoveries and Final Cumulative Nickel Grades

Figure 5-23 shows total cumulative nickel recoveries and final cumulative nickel grades for the conditions tested. The dark green bars represent the total nickel recovered on the left axis. The lighter green bars represent the final nickel grades on the right axis. The average nickel recovery is shown by a yellow line. Figure 5-23 shows that there was little variation in the total nickel recoveries. Generally, at 25 °C it appears that the nickel grade decreases as the ionic strength increases. However, this is not the case at higher temperatures. Furthermore, the highest nickel grades were obtained at low concentrations of SO_4^{2-} .

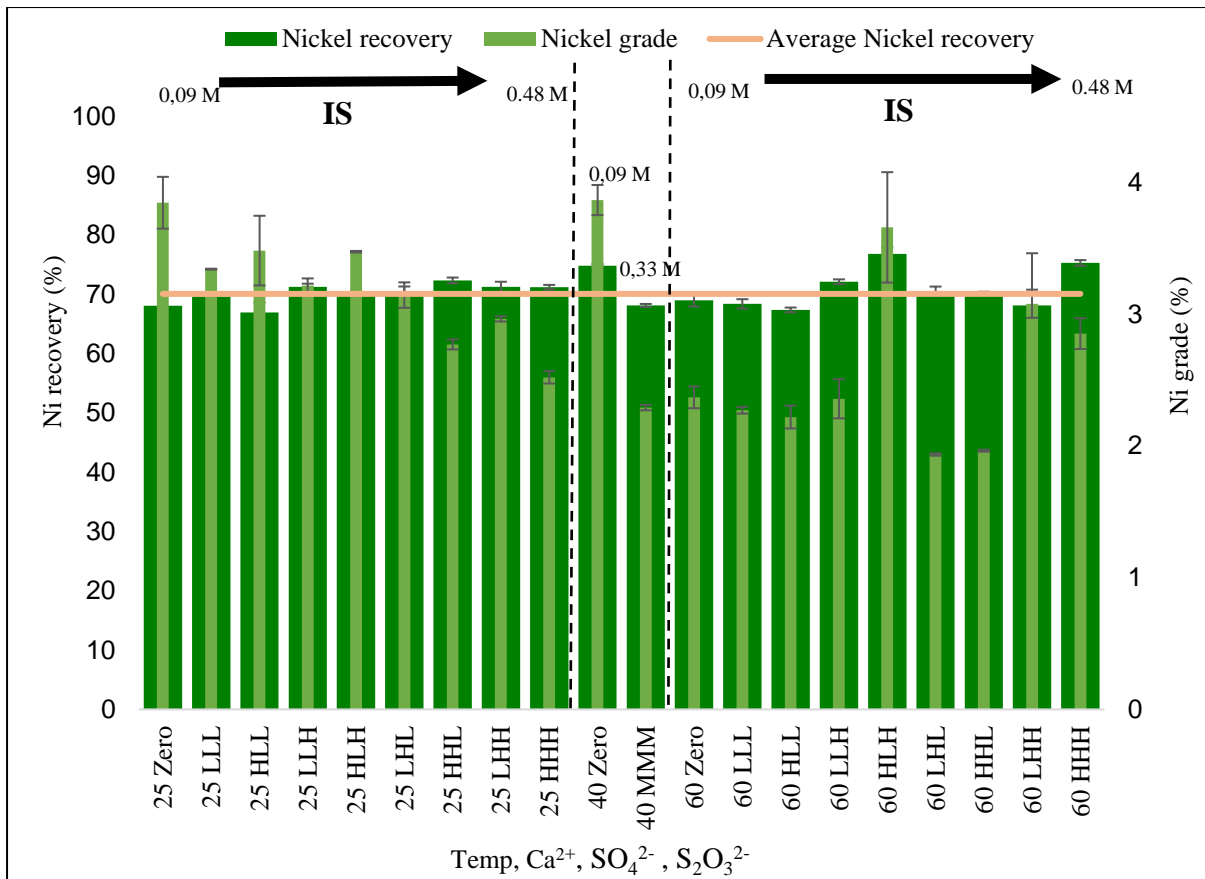


Figure 5-23: Graph showing the total nickel recoveries, final nickel grades and average nickel recovery for three temperatures and three levels of ionic concentrations of Ca²⁺, SO₄²⁻ and S₂O₃²⁻. Error bars represent standard error between duplicate runs.

As with the observations made from Figure 5-13 on copper grade, the nickel grade decreases as temperature increases as shown in Figure 5-24.

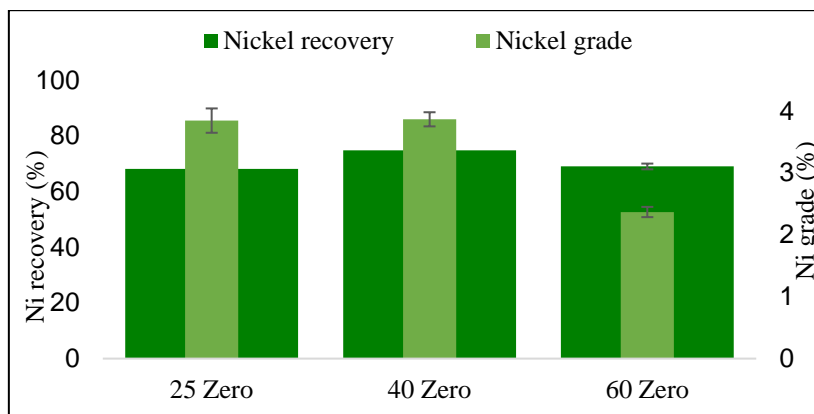


Figure 5-24: Graph showing the total nickel recoveries, final copper grades and average copper recovery for three temperatures and zero level ionic concentrations of Ca²⁺, SO₄²⁻ and S₂O₃²⁻. Error bars represent standard error between duplicate runs.

5.6.2 Cumulative Nickel Recoveries vs Time

Figure 5-25 shows the cumulative nickel recoveries vs. time for the conditions tested. The y-axis has been shortened for clarity. The final nickel recoveries vary between 65-77%. An increase in temperatures appears to increase the final nickel recovery.

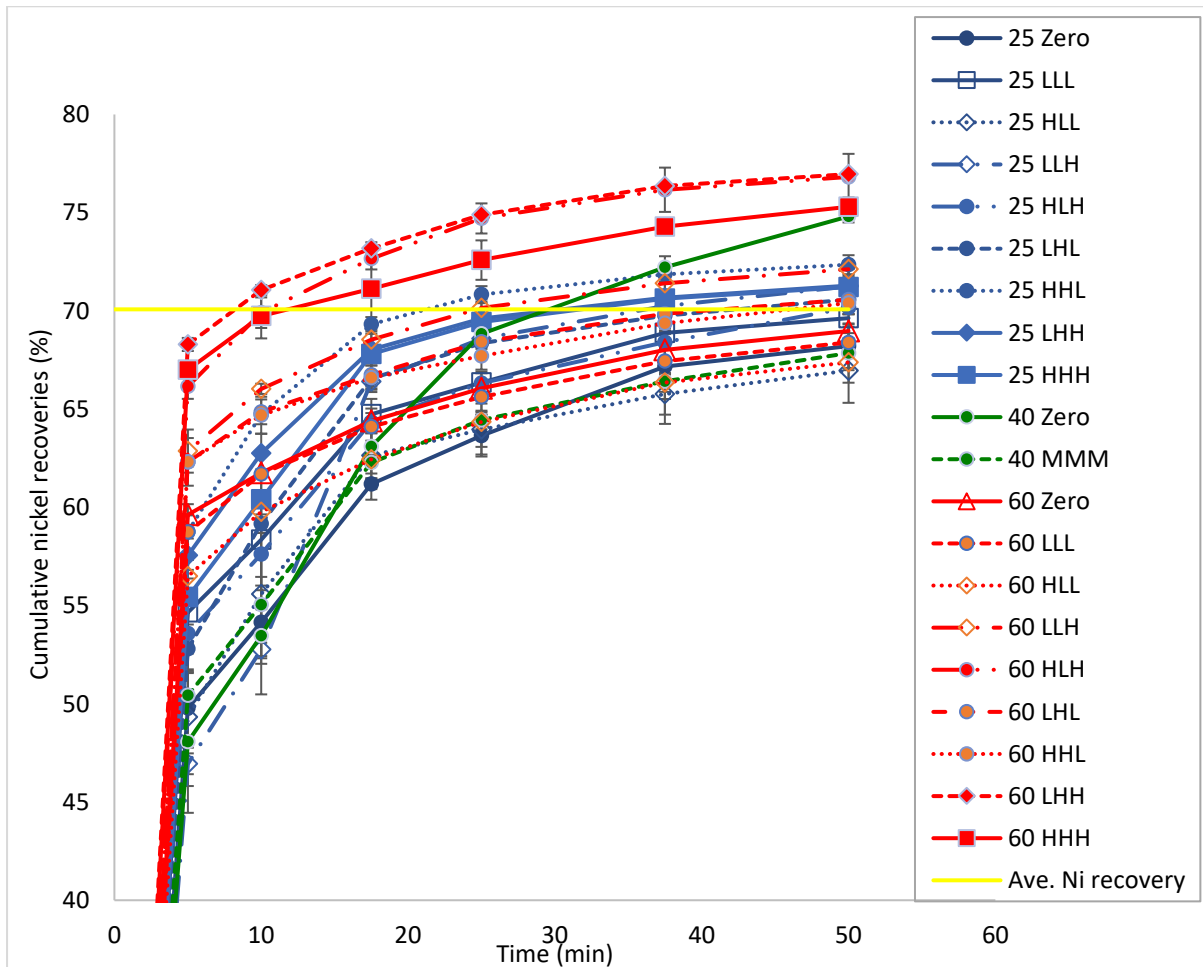


Figure 5-25: Graph showing the cumulative nickel recoveries vs time for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. Y-axis has been shortened for clarity.

Figure 5-26 shows the cumulative nickel recoveries vs. time at 25 °C. The three highest final nickel recoveries were observed with tests that have high SO_4^{2-} concentrations at 25 HHL, 25 LHH and 25 HHH. All three of these runs have $\text{IS} > 0.4 \text{ M}$.

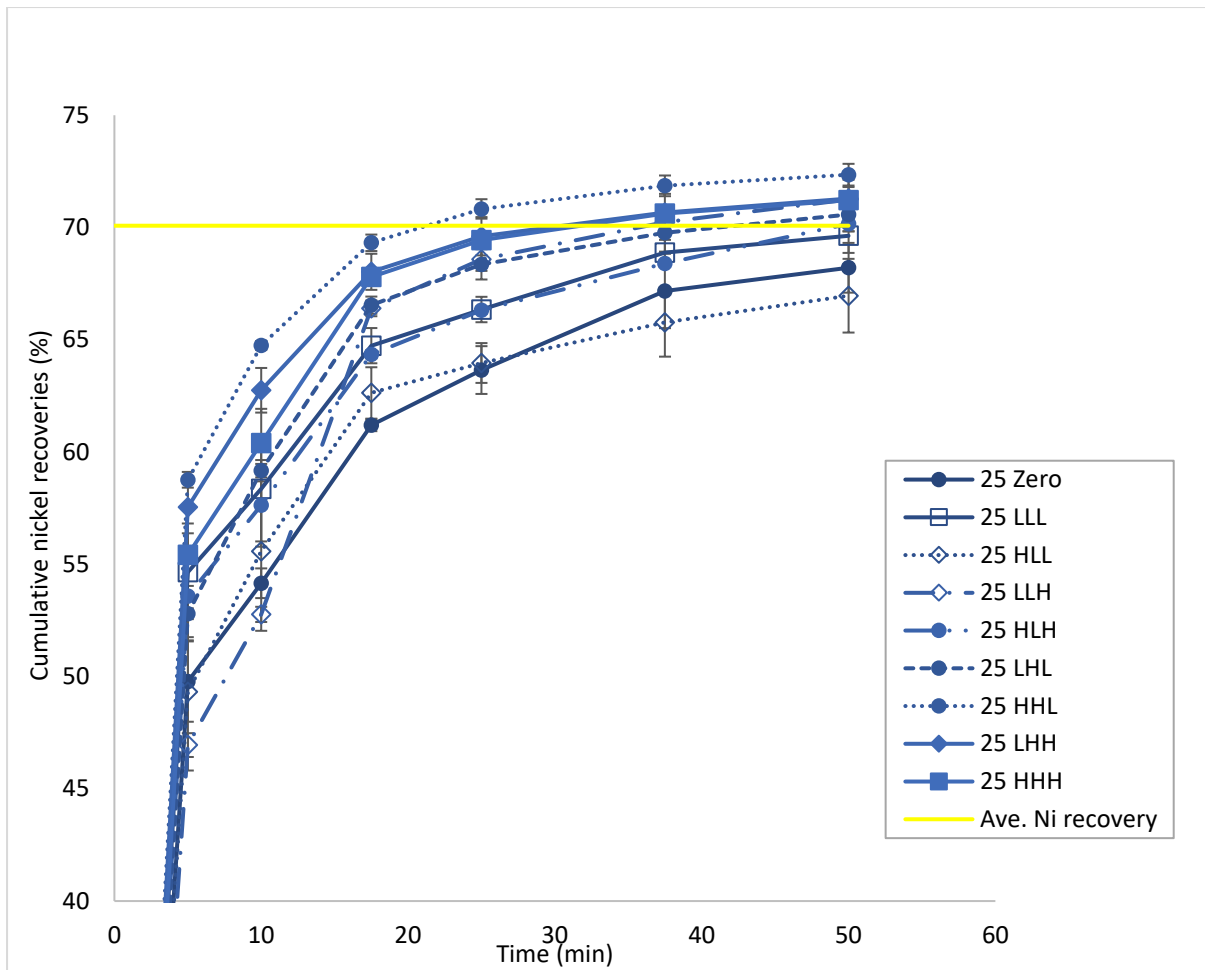


Figure 5-26: Graph showing the cumulative nickel recoveries vs time at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. Y-axis has been shortened for clarity.

Figure 5-27 shows that at 60 °C the two highest final nickel recoveries were observed with tests that have high $\text{S}_2\text{O}_3^{2-}$ concentrations, 60 HLH (0.281 M) and 60 LHH (0.437 M). The total cumulative nickel recoveries for all the tests with high $\text{S}_2\text{O}_3^{2-}$ concentration fell above the average nickel recovery for all tests.

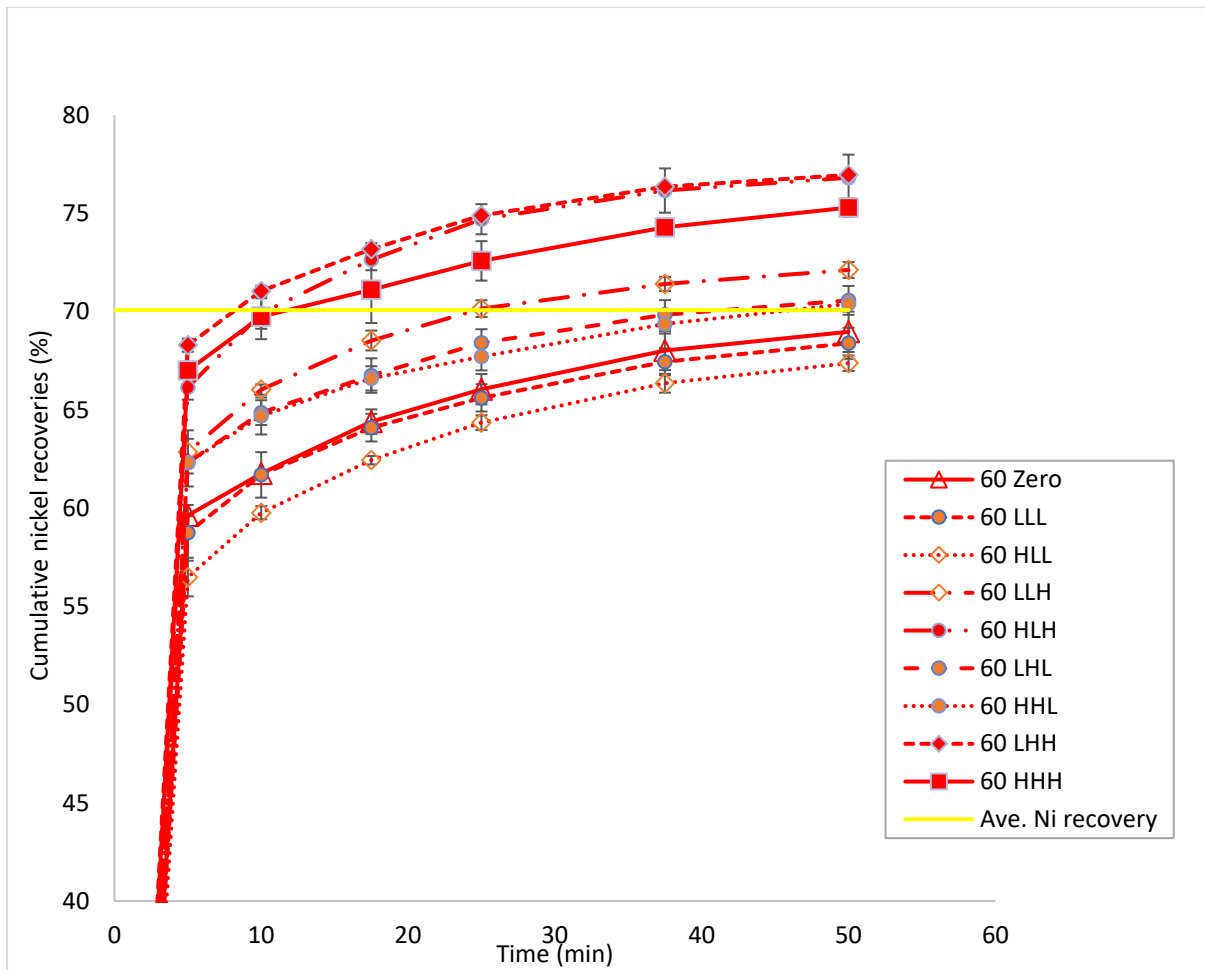


Figure 5-27: Graph showing the cumulative nickel recoveries vs time at 60 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. Y-axis has been shortened for clarity.

5.6.3 Cumulative Nickel Recoveries vs Cumulative Water Recoveries

Figure 5-28 shows the cumulative nickel recoveries vs. cumulative water recoveries for the conditions tested. Generally, it appears that the higher temperature (60 °C) recovers less water while recovering a similar amount of nickel as lower temperatures (25 °C and 40 °C).

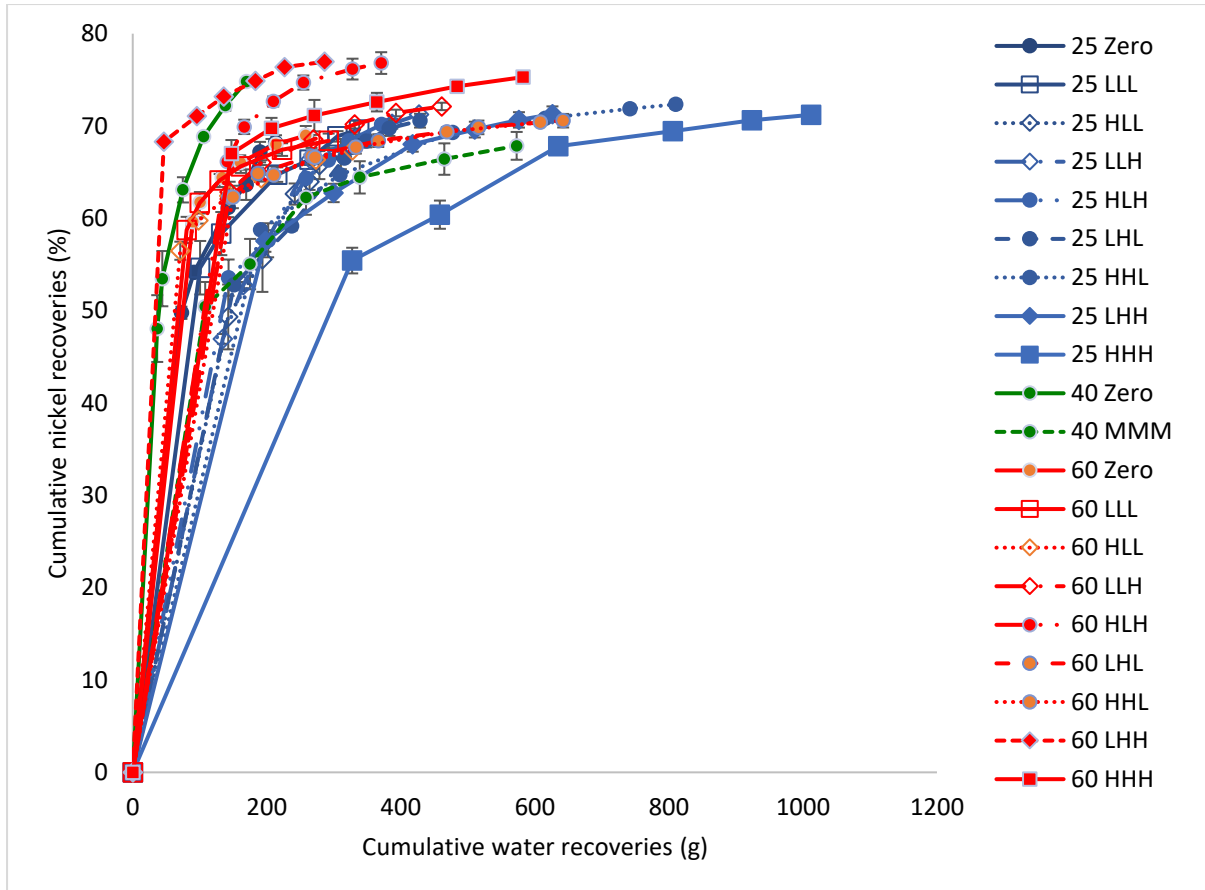


Figure 5-28: Graph showing the cumulative nickel recoveries vs cumulative water recoveries for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

Figure 5-29 shows the cumulative nickel recoveries vs. cumulative water recoveries for the tests conducted at 25 °C. The final nickel recoveries seem to fall within two regions with tests with $\text{IS} < 0.4 \text{ M}$ giving a higher nickel recovery to cumulative water ratio than tests with $\text{IS} > 0.4 \text{ M}$.

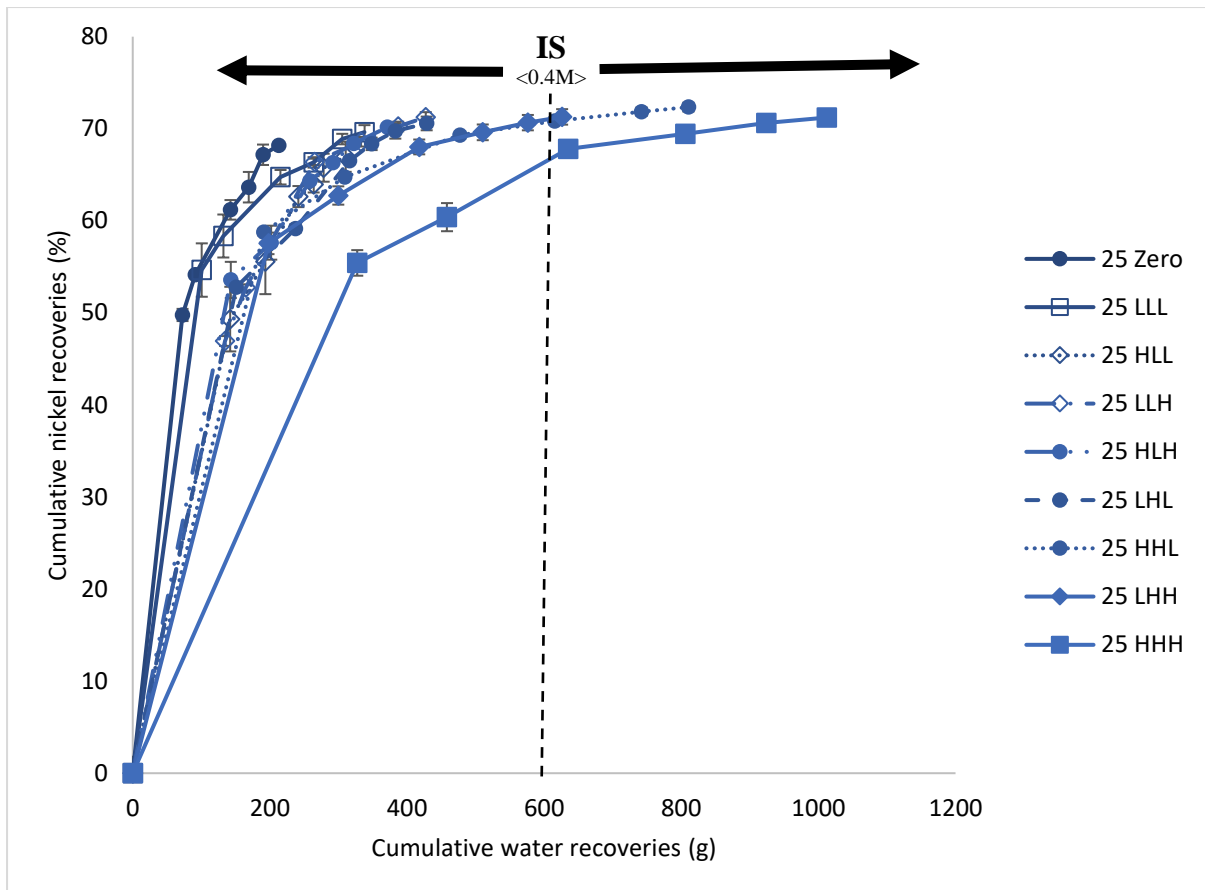


Figure 5-29: Graph showing the cumulative nickel recoveries vs cumulative water recoveries at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

Figure 5-30 shows cumulative nickel recoveries vs. cumulative water recoveries for the tests conducted at 60 °C. 60 Zero, 60 LLL and 60 HLL recovered similar amounts of nickel per gram of water. These runs had the lowest nickel recoveries per gram of water. The three highest nickel recoveries per gram of water can be summarized 60 LHH>60 HLH>60 HHH. It should be noted that these three tests all have high $\text{S}_2\text{O}_3^{2-}$ concentration.

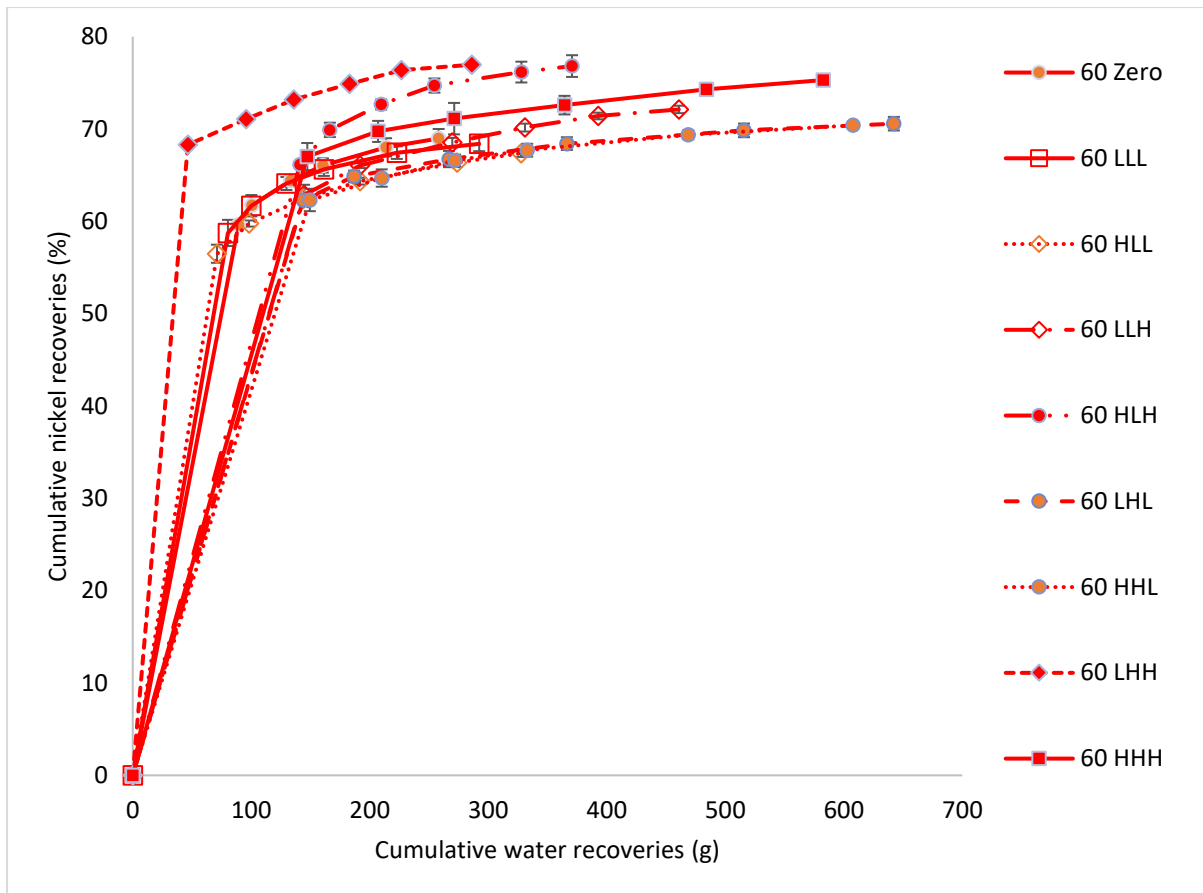


Figure 5-30: Graph showing the cumulative nickel recoveries vs cumulative water recoveries at 60 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs.

5.6.4 Cumulative Nickel Grades vs Cumulative Nickel Recoveries

The horizontal axes for all the graphs in 5.6.4 have been adjusted to start at 40 % for better visualisation. Figure 5-31 shows the cumulative nickel recoveries vs. cumulative nickel recoveries for the conditions tested. Nickel showed similar trends to those observed for copper shown in Figure 5-20. Within each temperature group, the copper grade decreases as the recovery increases. An increase in temperature appears to decrease the extent to which the grade decreases as the recovery increases.

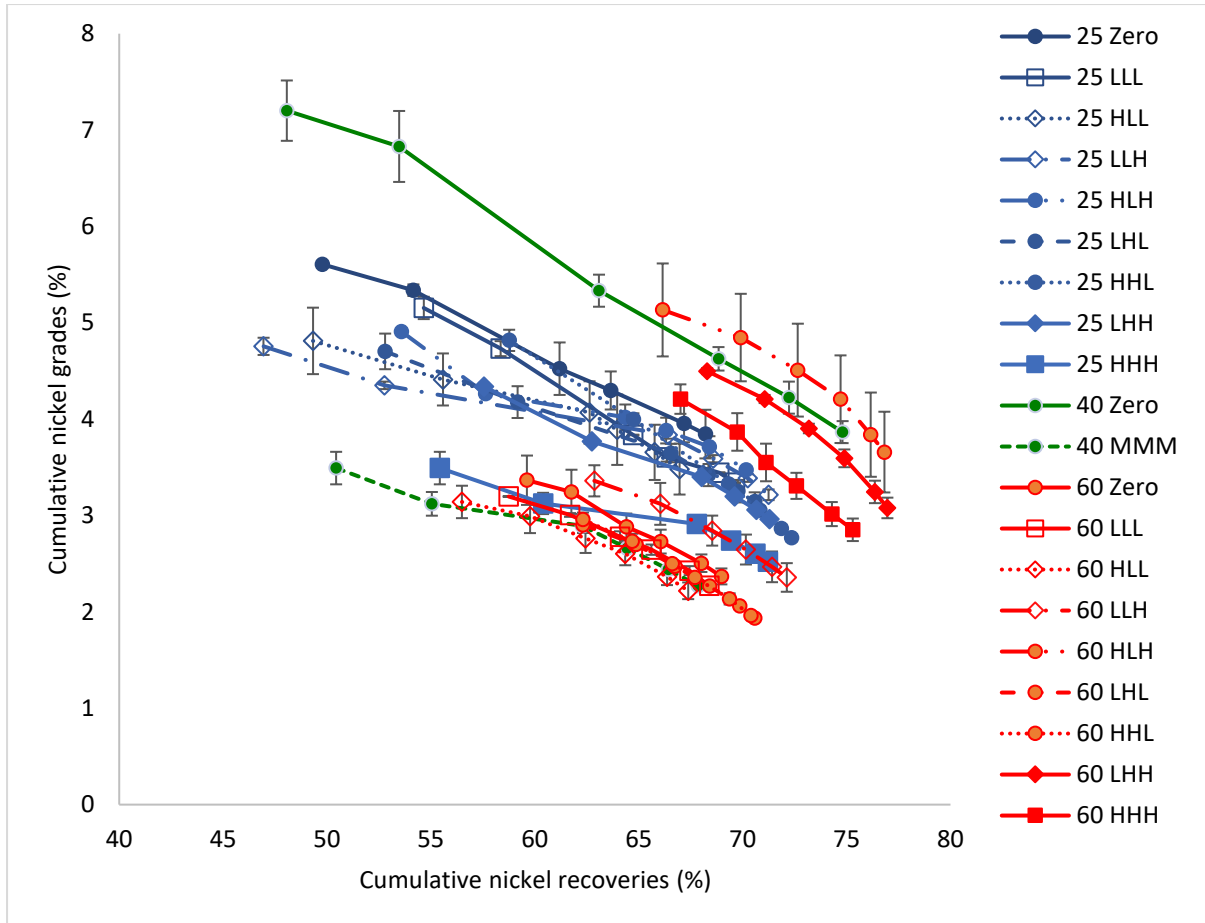


Figure 5-31: Graph showing the nickel grade vs nickel recovery for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. X-axis has been shortened for clarity.

Figure 5-32 shows tests at 25 °C whilst Figure 5-33 shows the tests at 60 °C. Although nickel showed similar trends as those observed for copper in 5.5.4, it should be noted that the 60 °C tests for nickel had a wider range than those for copper.

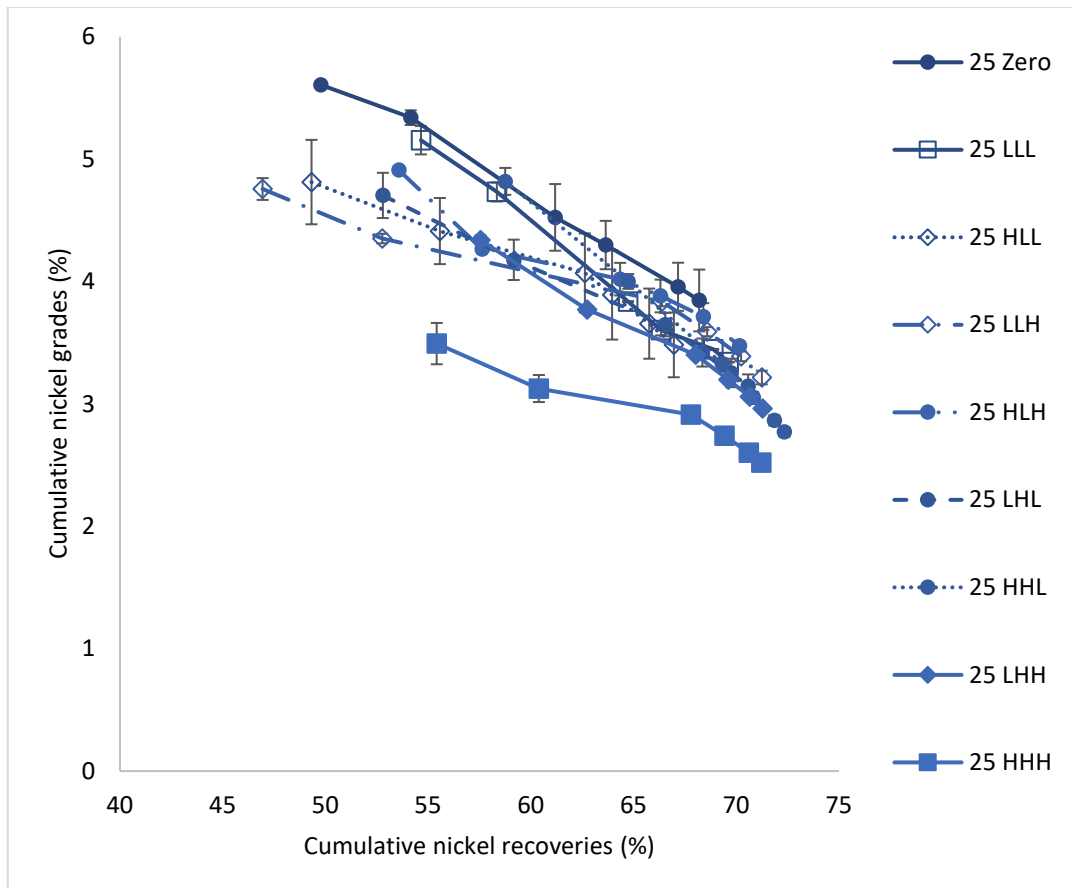


Figure 5-32: Graph showing the nickel grade vs nickel recovery at 25 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. X-axis has been shortened for clarity.

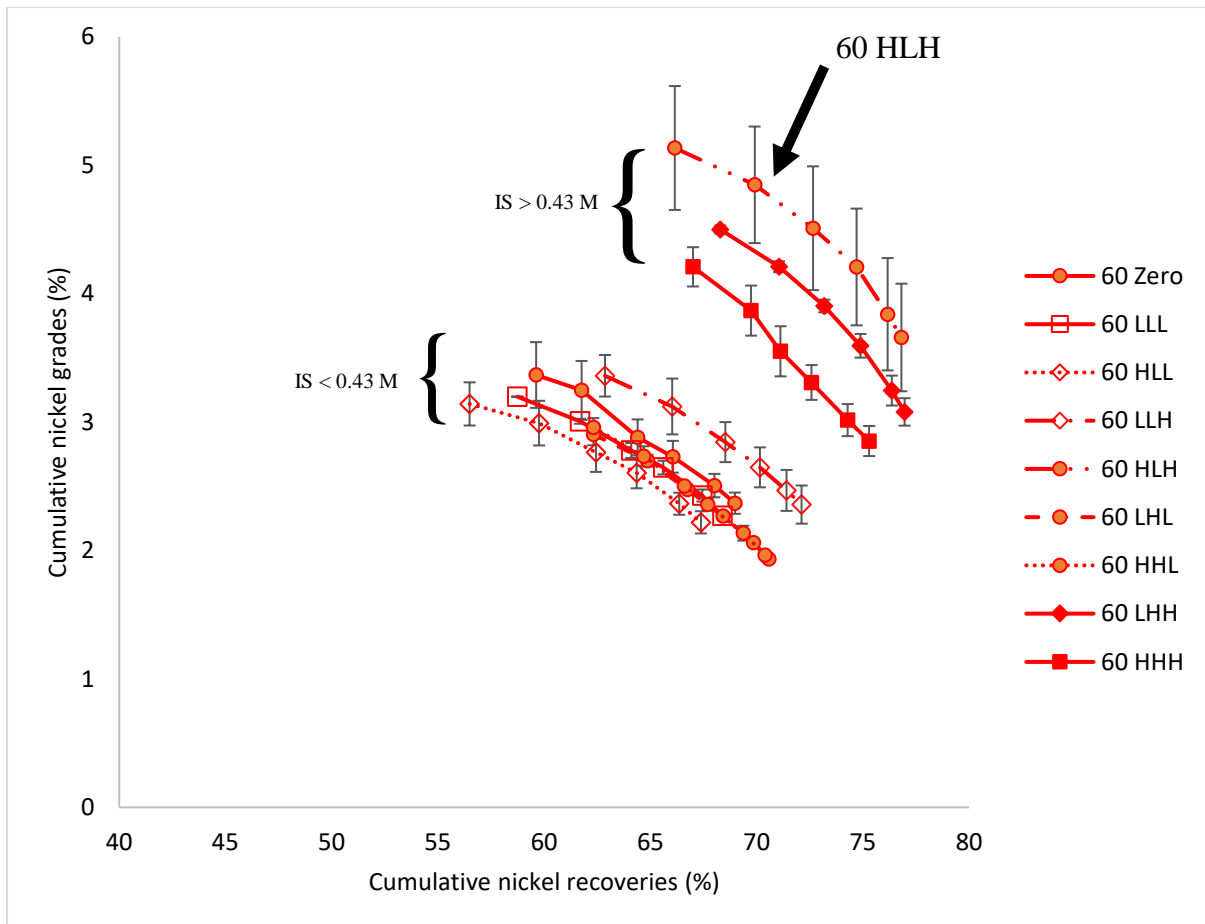


Figure 5-33: Graph showing the nickel grade vs nickel recovery at 60 °C and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. Error bars represent standard error between duplicate runs. X-axis has been shortened for clarity.

5.7 Determination of batch flotation kinetics using the classical model

This section presents the flotation kinetics parameters of the batch flotation tests, subject to varying the temperature, $[\text{Ca}^{2+}]$, $[\text{SO}_4^{2-}]$ and $[\text{S}_2\text{O}_3^{2-}]$. The classical first order kinetics model was used and is represented by the following equation:

$$R = R_{max} (1 - e^{-kt})$$

Where R is recovery of mineral, R_{max} is maximum possible recovery of mineral, k is the flotation rate constant (min^{-1}), and t is flotation time (mins).

Figure 5-34 show the rate constants for all the test conditions. Copper and nickel are used as the proxies for chalcopyrite and pentlandite, respectively. Overall, copper had higher flotation rates in comparison to nickel at both 25 °C and 60 °C. On comparing the flotation rates for copper, generally the flotation rates were higher at 25 °C than at 60 °C. The highest copper

flotation rate of 0.58 min^{-1} with $R_{max} = 86.27 \%$ was observed at test 25 HHL (IS=0.412 M). The flotation rates of copper at both 25 and 60 °C are within a small range of $0.46\text{-}0.55 \text{ min}^{-1}$.

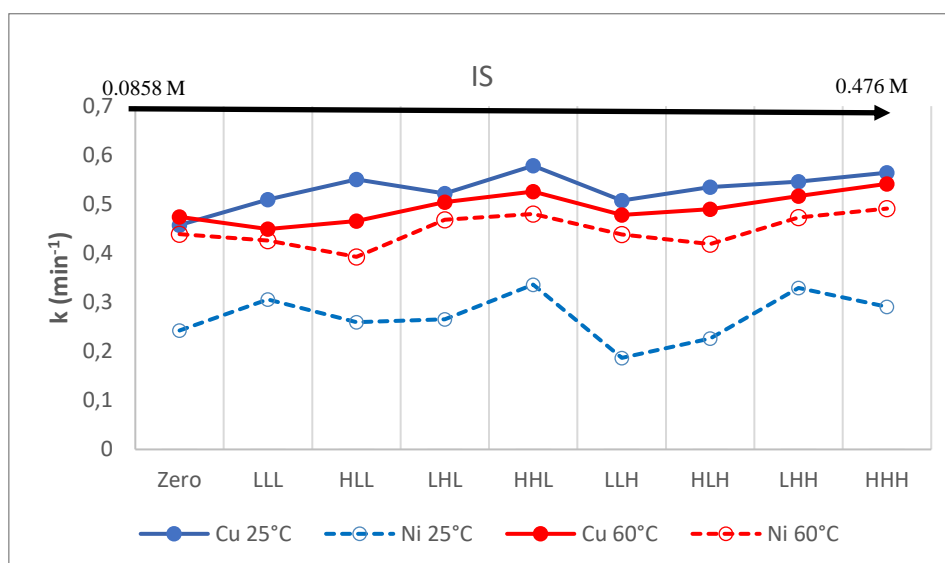


Figure 5-34: The rate constants for all the test conditions.

Whilst copper was faster floating at 25 °C than at 60 °C, the opposite was seen for nickel. Furthermore, the flotation rates of nickel were within a bigger range of 0.19 min^{-1} to 0.49 min^{-1} . The highest nickel flotation rate of 0.49 min^{-1} with $R_{max} = 72.80 \%$ was observed at test 60 HHH (IS=0.476 M). These variations in both copper and nickel attest to the differences in floatability of the sulphide minerals under different conditions. A summary of the flotation kinetics can be found in Table 5-2.

Table 5-2: Summary of the flotation kinetics rate constant (k) and maximum recovery (R_{max}) for copper and nickel for all tests.

Copper					Nickel						
Model no.	Test	IS (M)	R _{max} (%)	k (min ⁻¹)	Model no.	Test	IS (M)	R _{max} (%)	k (min ⁻¹)		
Model 1	25 Zero	0.0858	81.09	0.45	Model 4	25 Zero	0.0858	67.53	0.27		
	40 Zero	0.0858				40 Zero	0.0858				
	60 Zero	0.0858				25 LLL	0.178				
	60 LLL	0.178				25 HLL	0.217				
	60 HLL	0.217				25 LLH	0.241				
Model 2	25 LLL	0.178	85.18	0.51		25 HLH	0.281			69.41	0.45
	60 LLH	0.241				40 MMM	0.327				
	25 LLH	0.241				25 LHL	0.373				
	60 HLH	0.281				25 HHL	0.412				
	25 HLH	0.281				25 LHH	0.437				
	60 LHL	0.373				25 HHH	0.476				
	25 LHL	0.373				60 HLL	0.217				
	60 HHL	0.412				60 HLH	0.281				
	60 LHH	0.437				60 LLL	0.178				
Model 3	25 HLL	0.217	85.22	0.55		60 LLH	0.241			69.41	0.45
	40 MMM	0.327			60 Zero	0.086					
	25 HHL	0.412			60 LHL	0.373					
	25 LHH	0.437			60 LHH	0.437					
	60 HHH	0.476			60 HHL	0.412					
	25 HHH	0.476			60 HHH	0.476					

5.7.1 Classical model for copper

Figure 5-35 shows the kinetic models for cumulative copper recoveries vs. time for the conditions tested. Three models were obtained from the experimental data for copper. Detailed values showing the distribution of the test runs between the models are in

Table 5-2. Models 1, 2, and 3 have R_{\max} values of 81.09 %, 85.18 % and 85.22 % respectively. The corresponding rate constant values are 0.45 min^{-1} , 0.51 min^{-1} and 0.55 min^{-1} .

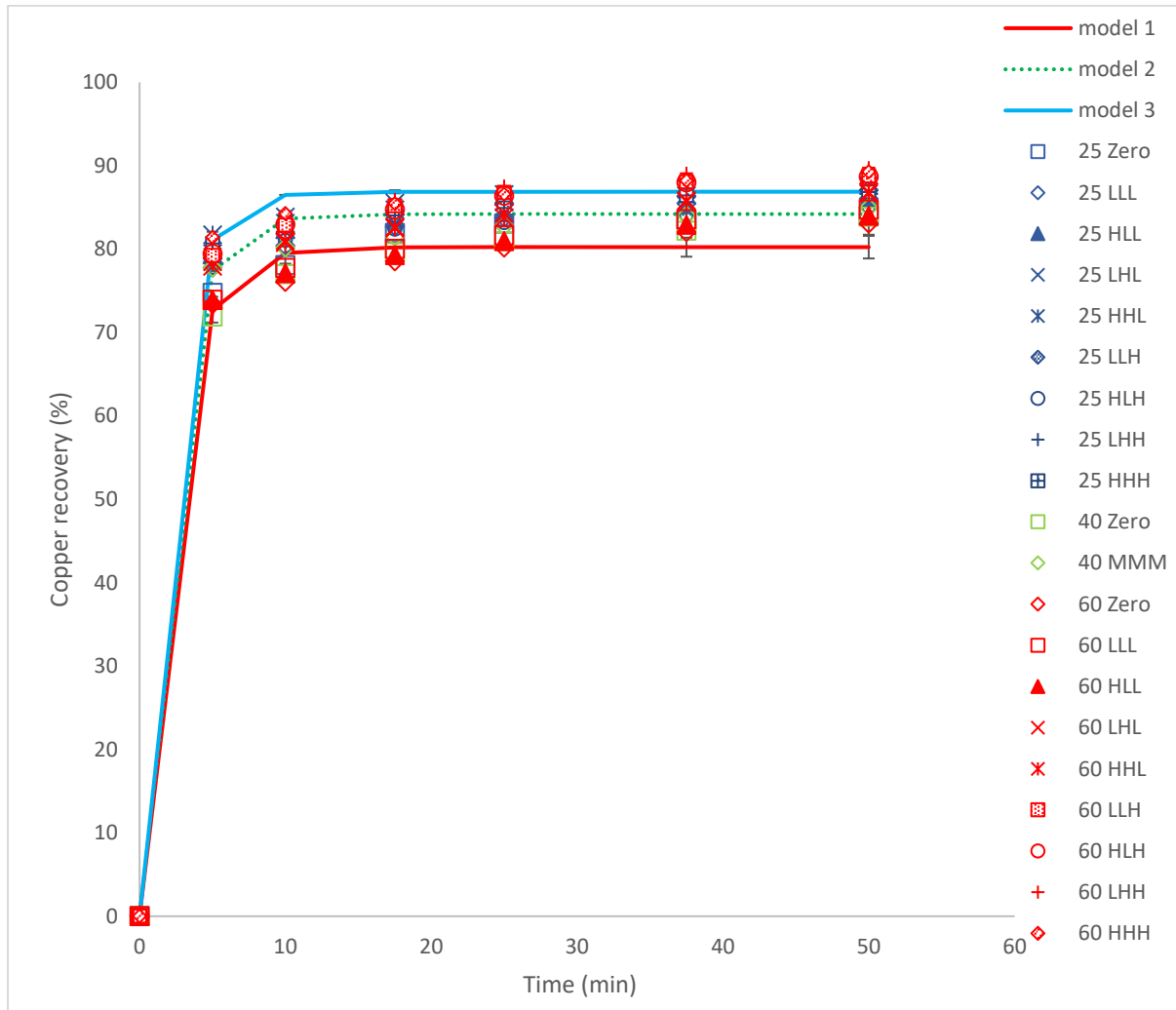


Figure 5-35: Graph showing the cumulative copper recoveries vs time for kinetics model for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. The markers represent experimental data with the standard error represented by error bars. The solid lines in the corresponding colours represent the modelled data.

5.7.2 Classical model for nickel

Figure 5-36 shows the kinetic models for cumulative nickel recoveries vs. time for the conditions tested. Two models were obtained from the experimental data for nickel. Detailed values showing the distribution of the test runs between the models are in

Table 5-2. There was a distinct temperature difference in the nickel recovery. Model 4 represents all the tests carried out at 25 °C and 40 °C whilst model 5 represents all the tests ran at 60 °C. Models 4, and 5 have R_{\max} values of 67.53 % and 69.41 % respectively. The corresponding rate constant values are 0.27 min^{-1} and 0.45 min^{-1} .

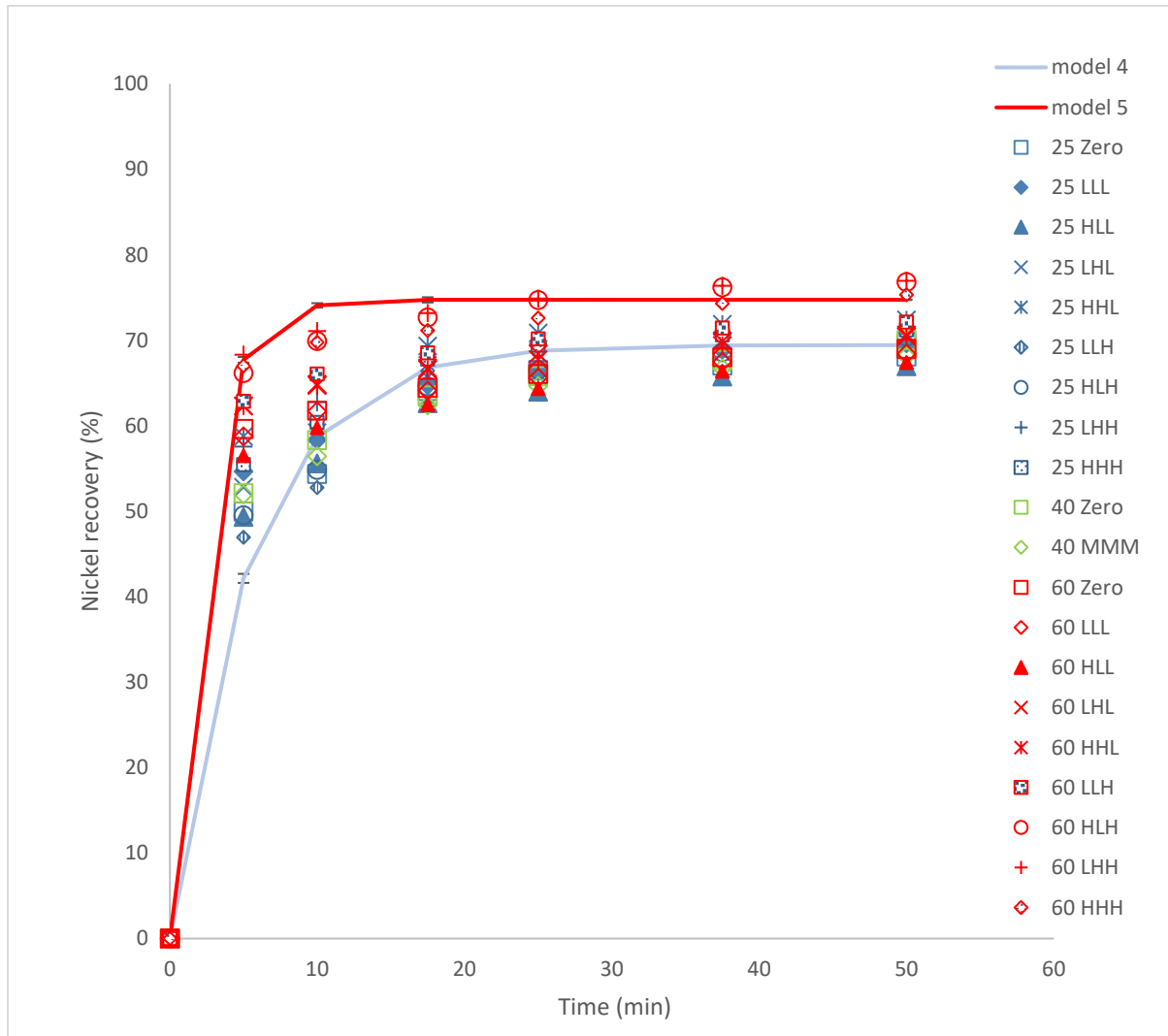


Figure 5-36: Graph showing the cumulative nickel recoveries vs time for kinetics model for three temperatures and three levels of ionic concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. The markers represent experimental data with the standard error represented by error bars. The solid lines in the corresponding colours represent the modelled data.

6. STATISTICAL MODELLING RESULTS

As stated earlier, all the terms were initially selected for the graphical modelling. A p-value was assigned to each term by ANOVA. For a 95 % confidence interval, a term was described as significant if the p-value was less than 0.05. More detail is given in Section 4.8. The non-significant terms and their corresponding hierarchical components were deselected for the graphical modelling. For each response, the significant factors and resulting models with the accompanying model graphs have been listed. The letters **A**, **B**, **C** and **D** represent temperature, Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$. To plot a 3D graph, a minimum of two nominal factors needs to be acceptable. Where two terms were both significant, 3D graphs were used to display the results. 2D graphs were used where only one term was significant.

6.1 Water Recovery

Significant factors: C and BC (SO_4^{2-} and interaction between Ca^{2+} and SO_4^{2-})

Terms used in the model: B, C and BC

Resulting model: $\text{Water recovery} = 498.67 + 55.73 * \mathbf{B} + 131.08 * \mathbf{C} + 73 * \mathbf{BC}$

Figure 6-1 shows the 3D surface graph giving the effects of Ca^{2+} and SO_4^{2-} on the water recovery. Figure 6-2 shows the interaction between Ca^{2+} and SO_4^{2-} . At low $[\text{SO}_4^{2-}]$, an increase in $[\text{Ca}^{2+}]$ causes a slight decrease in the amount of water recovered whilst at high $[\text{SO}_4^{2-}]$, an increase in $[\text{Ca}^{2+}]$ increases the amount of water recovered. The highest amount of water recovered is when both $[\text{Ca}^{2+}]$ and $[\text{SO}_4^{2-}]$ are high ($\text{IS} \geq 0.373 \text{ M}$) whilst the lowest is recovered when $[\text{Ca}^{2+}]$ is high and $[\text{SO}_4^{2-}]$ is low ($\text{IS} \leq 0.281 \text{ M}$).

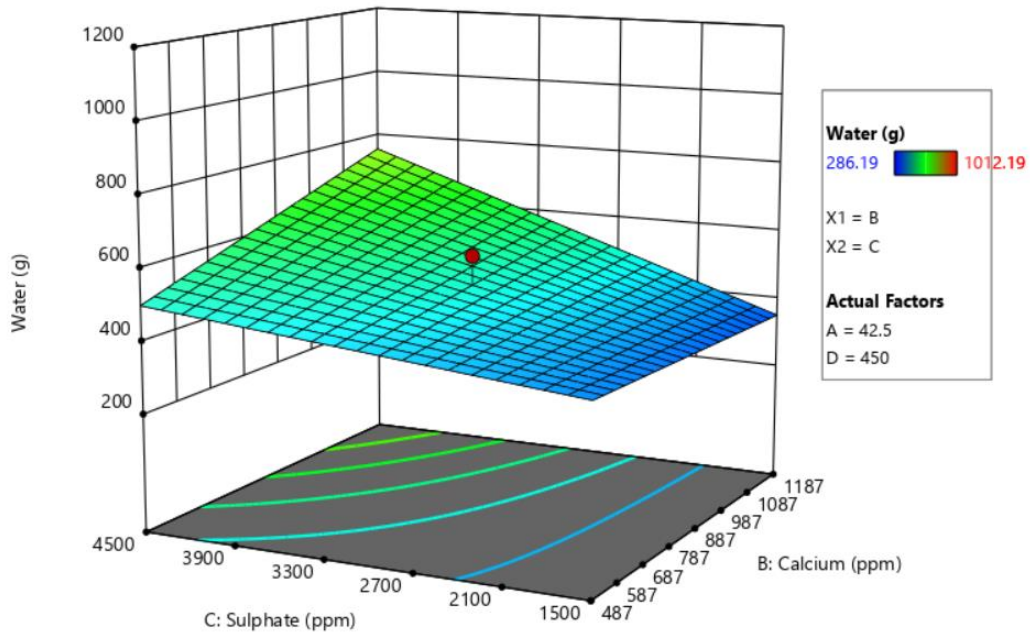


Figure 6-1: 3D surface graph showing the effects of Ca^{2+} and SO_4^{2-} on water recovery for all tests.

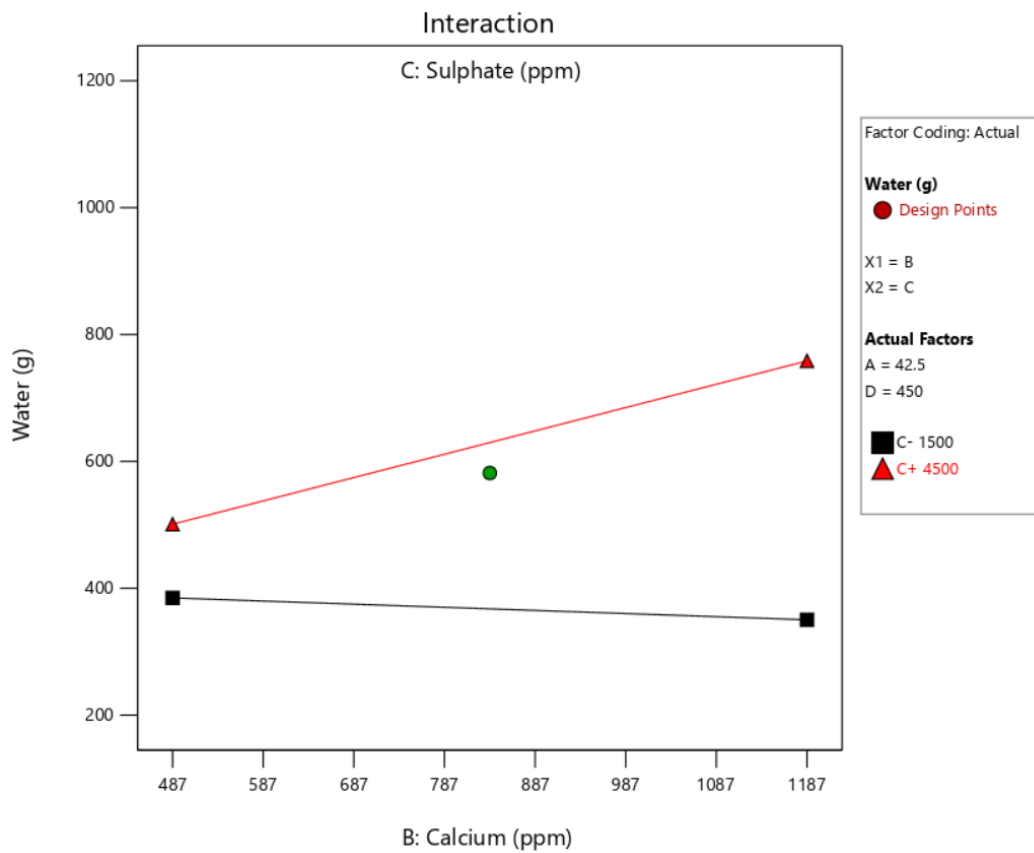


Figure 6-2: 2D linear graph showing the interaction effects of Ca^{2+} and SO_4^{2-} .

6.2 Solids Recovery

Significant factors: C and BC (SO_4^{2-} and interaction between Ca^{2+} and SO_4^{2-})

Terms used in the model: B, C and BC

Resulting model: $\text{Solids recovery} = 79.97 - 0.1473 * B + 6.14 * C + 3.18 * BC$

Figure 6-3 shows the 3D surface graph showing the effects of Ca^{2+} and SO_4^{2-} on the solids recovery. Figure 6-4 shows a 2D graph showing the interaction between Ca^{2+} and SO_4^{2-} . At low $[\text{SO}_4^{2-}]$, an increase in Ca^{2+} decreases the mass of solids recovered whilst at high $[\text{SO}_4^{2-}]$, an increase in Ca^{2+} increases the mass of solids recovered. The highest solids recovered is when both $[\text{Ca}^{2+}]$ and $[\text{SO}_4^{2-}]$ are high ($\text{IS} \geq 0.373 \text{ M}$) whilst the lowest is recovered when $[\text{Ca}^{2+}]$ is high and $[\text{SO}_4^{2-}]$ is low ($\text{IS} \leq 0.281 \text{ M}$).

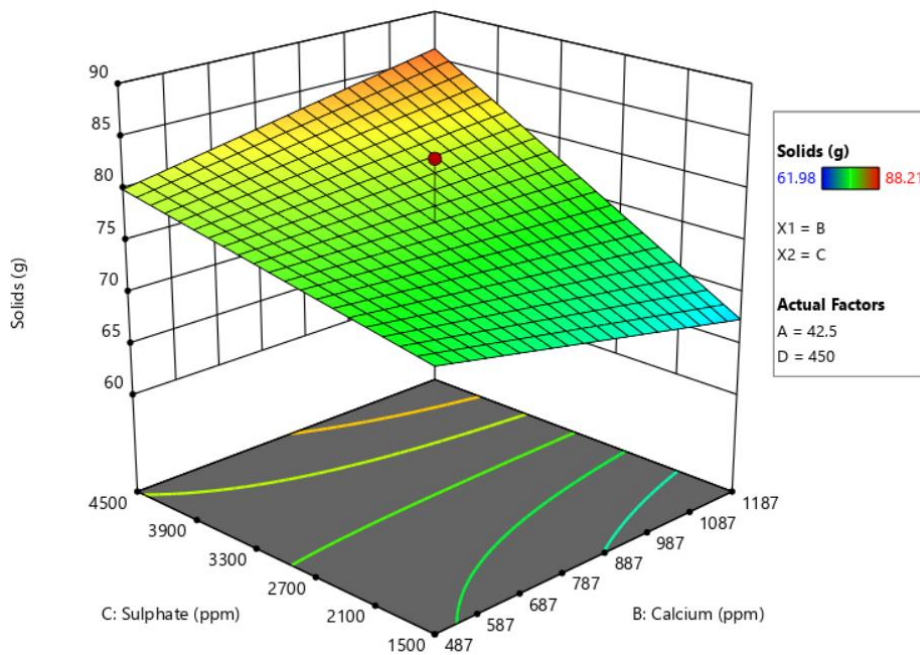


Figure 6-3: 3D surface graph showing the effects of Ca^{2+} and SO_4^{2-} on solids recovery for all tests.

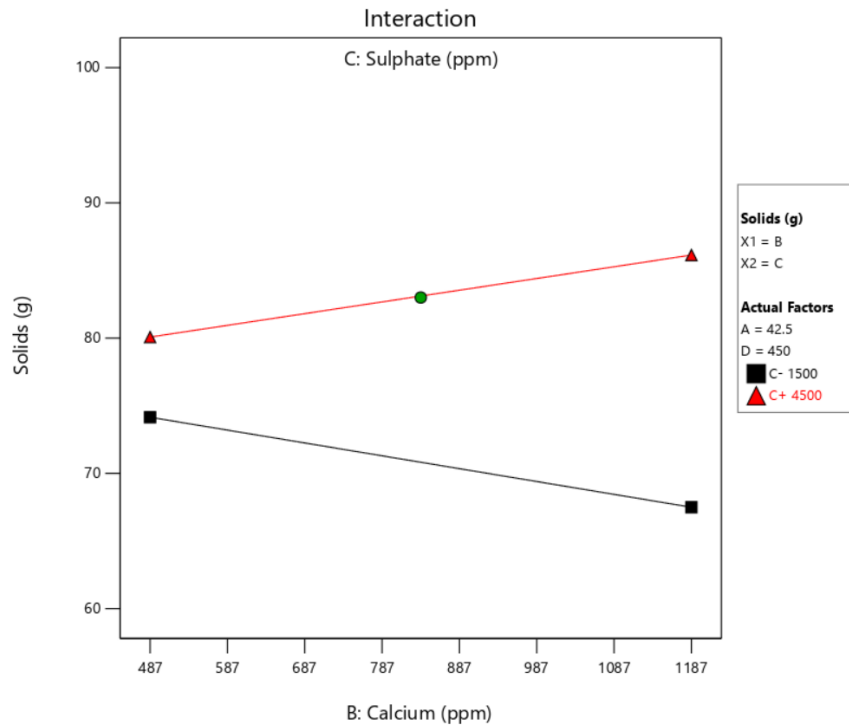


Figure 6-4: 2D graph showing the effects of Ca^{2+} and SO_4^{2-} on solids recovery for all tests.

6.3 Copper Recovery

Significant factors: C, D and AD
(SO_4^{2-} , $\text{S}_2\text{O}_3^{2-}$ and interaction between temperature and $\text{S}_2\text{O}_3^{2-}$)

Terms used in the model: A, C, D and AD

Resulting model:

$$\text{Copper recovery} = 86.81 + 0.4062 * A + 0.6294 * C + 0.8348 * D + 0.9495 * AD$$

Figure 6-5 shows a 2D graph showing the effect of SO_4^{2-} on copper recovery. An increase in SO_4^{2-} causes an increase in the copper recovery within a range of 1.26 %. The domain of SO_4^{2-} is 1 500 - 4 500 ppm.

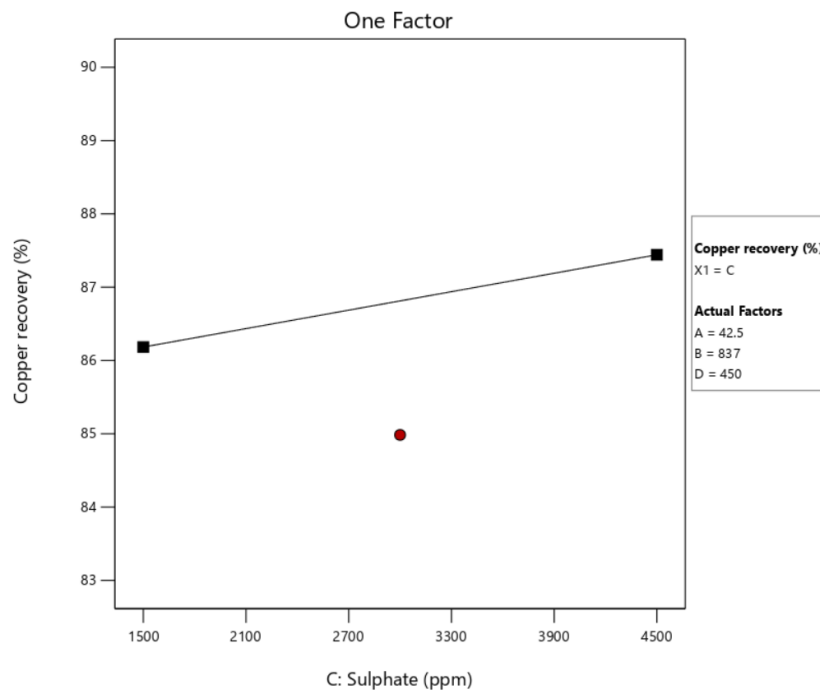


Figure 6-5: 2D linear graph showing the effects of SO_4^{2-} on copper recovery for all tests.

Figure 6-6 shows the 3D surface graph showing the effects of temperature and $\text{S}_2\text{O}_3^{2-}$ on copper recovery. Figure 6-7 shows a 2D graph showing the interaction between temperature and $\text{S}_2\text{O}_3^{2-}$. At low $[\text{S}_2\text{O}_3^{2-}]$, an increase in temperature decreases the copper recovery whilst at high $[\text{S}_2\text{O}_3^{2-}]$, an increase in temperature increases the copper recovery. As mentioned earlier in the copper section, the copper recovery range is very small.

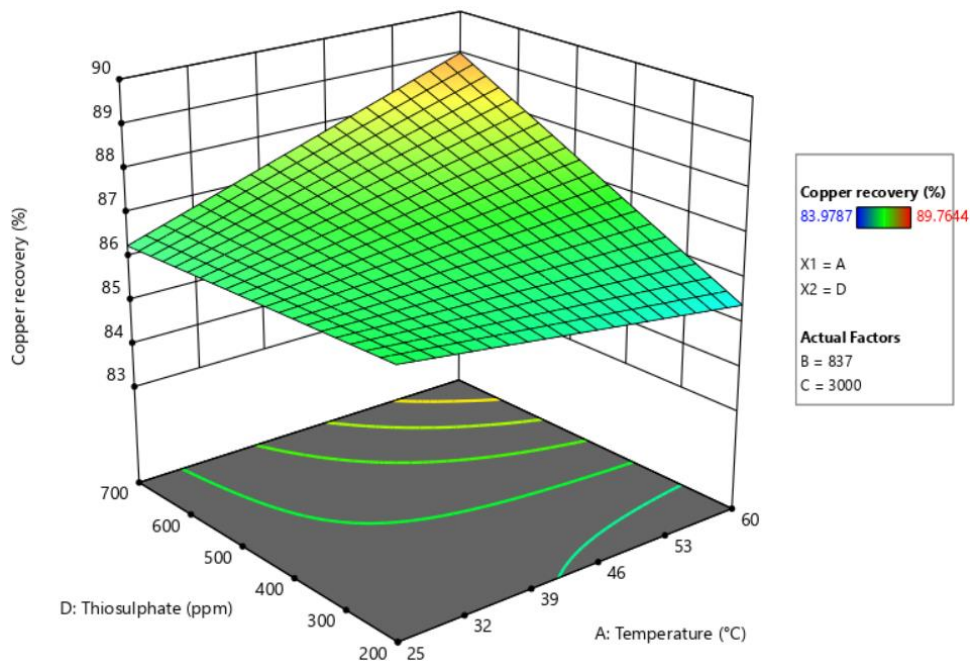


Figure 6-6: 3D surface graph showing the effects of temperature and $S_2O_3^{2-}$ on copper recovery for all tests.

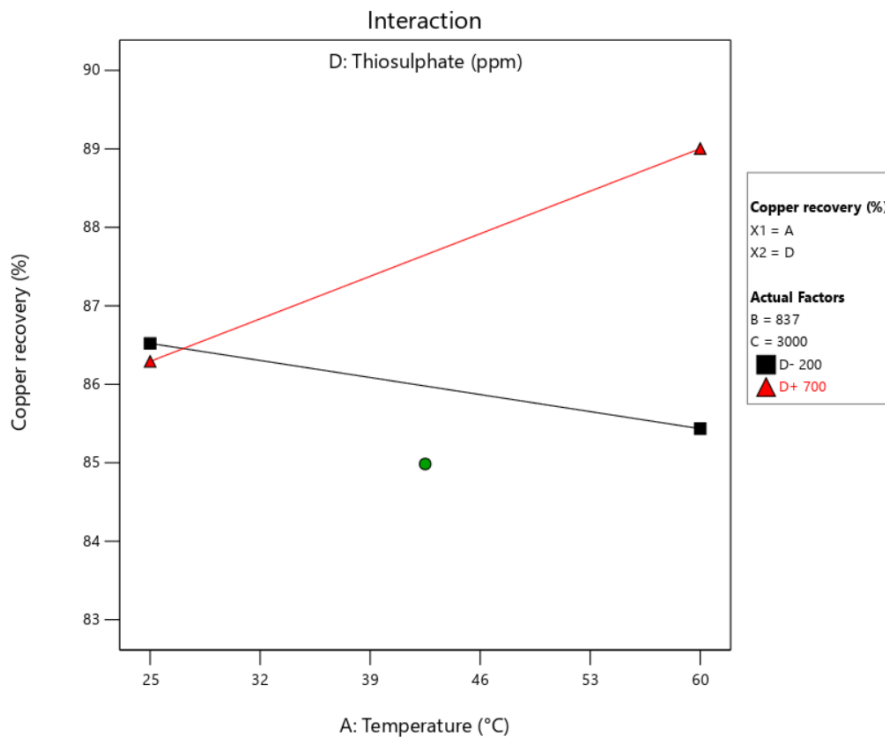


Figure 6-7: 2D linear graph showing the effects temperature and $S_2O_3^{2-}$ on copper recovery for all tests.

6.4 Copper Grade

Significant factors: A, C and AD
(Temperature, SO_4^{2-} and interaction between temperature and $\text{S}_2\text{O}_3^{2-}$)

Terms used in the model: A, C, D and AD

Resulting model:

$$\text{Copper grade} = 3.62 - 0.3033 * A - 0.2864 * C + 0.099 * D + 0.2899 * AD$$

Figure 6-8 shows a 2D graph showing the effect of SO_4^{2-} on copper grade. An increase in SO_4^{2-} causes a decrease in the copper grade. The domain of SO_4^{2-} is 1 500 - 4 500 ppm.

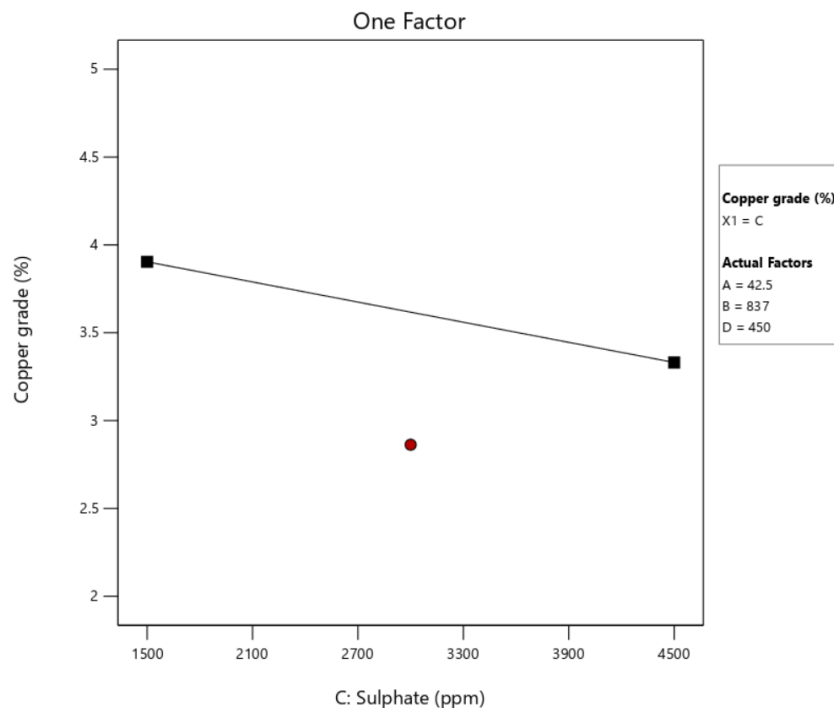


Figure 6-8: 2D linear graph showing the effects of SO_4^{2-} on copper grade for all tests

Figure 6-9 shows the 3D surface graph showing the effects of temperature and $\text{S}_2\text{O}_3^{2-}$ on copper grade. Figure 6-10 shows a 2D graph showing the interaction between temperature and $\text{S}_2\text{O}_3^{2-}$. At low $[\text{S}_2\text{O}_3^{2-}]$, an increase in temperature decreases the copper grade whilst at high $[\text{S}_2\text{O}_3^{2-}]$, an increase in temperature has no effect on the copper grade. The highest copper grade was achieved at low temperature and $[\text{S}_2\text{O}_3^{2-}]$.

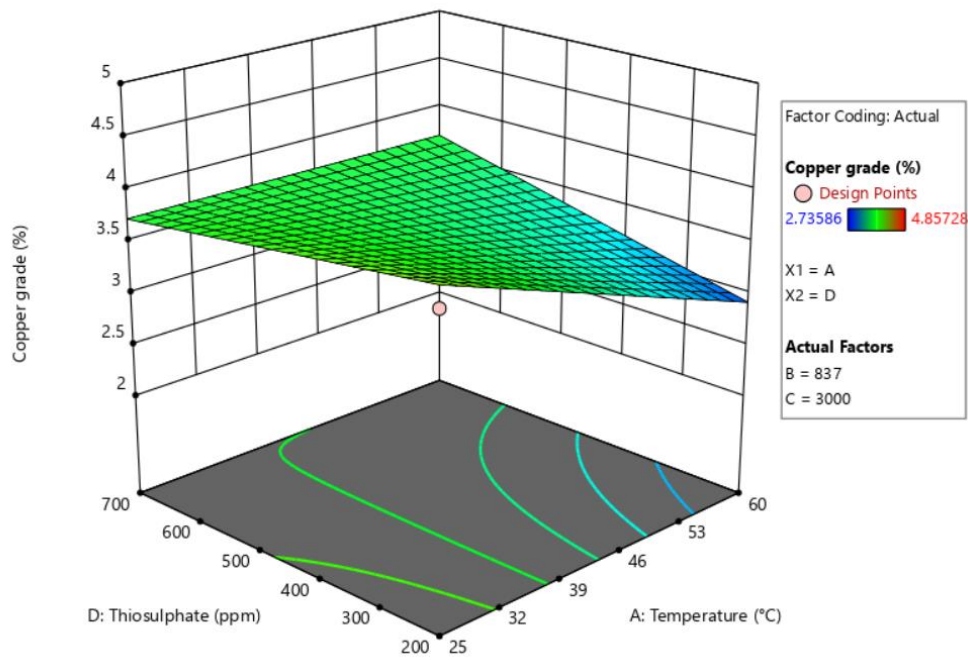


Figure 6-9: 3D surface graph showing the effect of temperature and $S_2O_3^{2-}$ on copper grade for all tests.

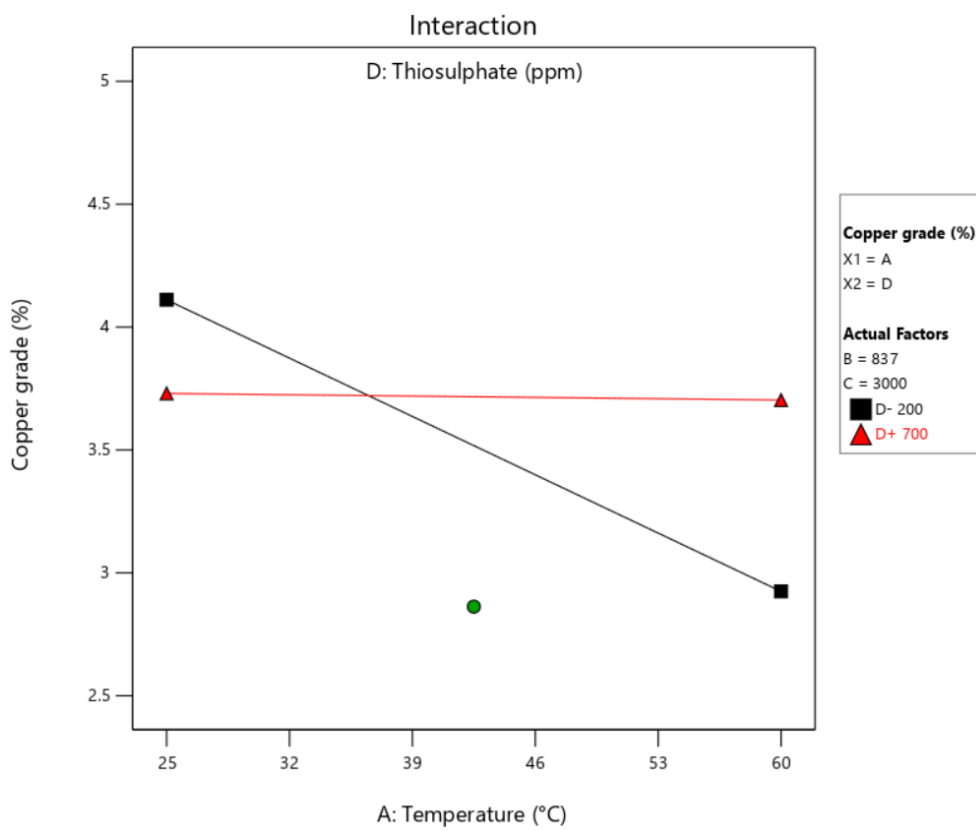


Figure 6-10: 2D linear figure of the effect of temperature and $S_2O_3^{2-}$ on copper grade for all tests

6.5 Nickel Recovery

Significant factors: D ($S_2O_3^{2-}$)

Terms used in the model: D

Resulting model: $Nickel\ recovery = 70.64 + 1.27 * D$

Figure 6-11 shows a 2D graph showing the effect of $S_2O_3^{2-}$ on nickel recovery. An increase in $S_2O_3^{2-}$ causes an increase in the nickel recovery. The domain of $S_2O_3^{2-}$ is 200 – 700 ppm.

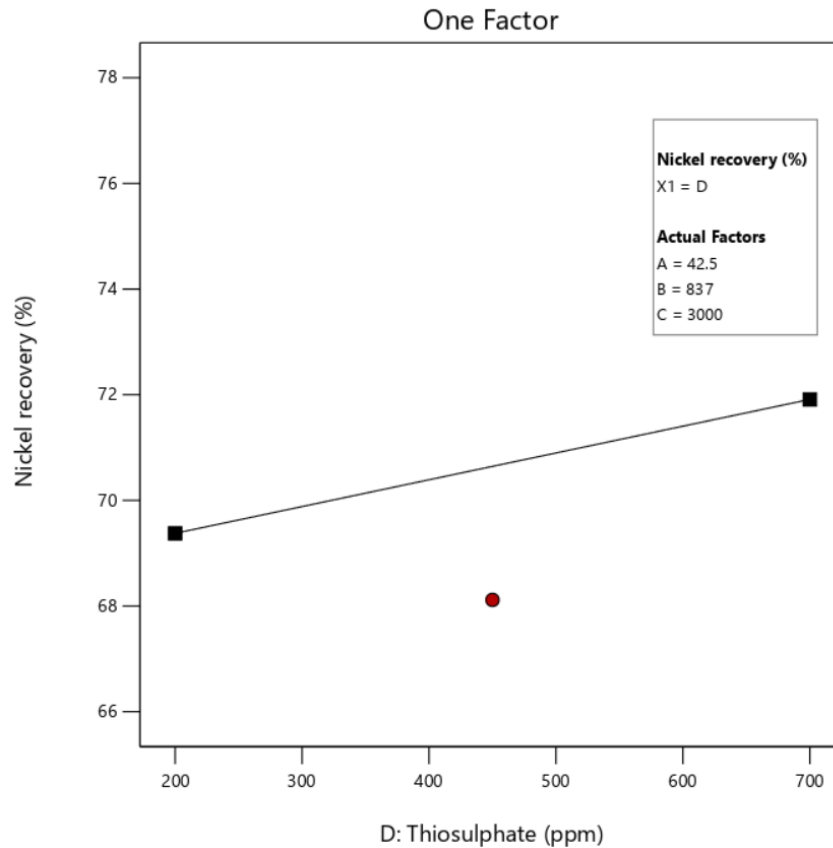


Figure 6-11: 2D linear graph showing the effect of $S_2O_3^{2-}$ on nickel recovery for all tests.

6.6 Nickel Grade

Significant factors: A and AD

(Temperature and interaction between temperature and $S_2O_3^{2-}$)

Terms used in the model: A, D and AD

Resulting model: $Nickel\ grade = 2.80 - 0.2859 * A + 0.1871 * D + 0.2578 * AD$

Figure 6-12 shows the 3D surface graph showing the effects of temperature and $S_2O_3^{2-}$ on nickel grade. Figure 6-13 shows a 2D graph showing the interaction between temperature and

$S_2O_3^{2-}$. At low $[S_2O_3^{2-}]$, an increase in temperature decreases the nickel grade whilst at high $[S_2O_3^{2-}]$, an increase in temperature has no effect on the nickel grade.

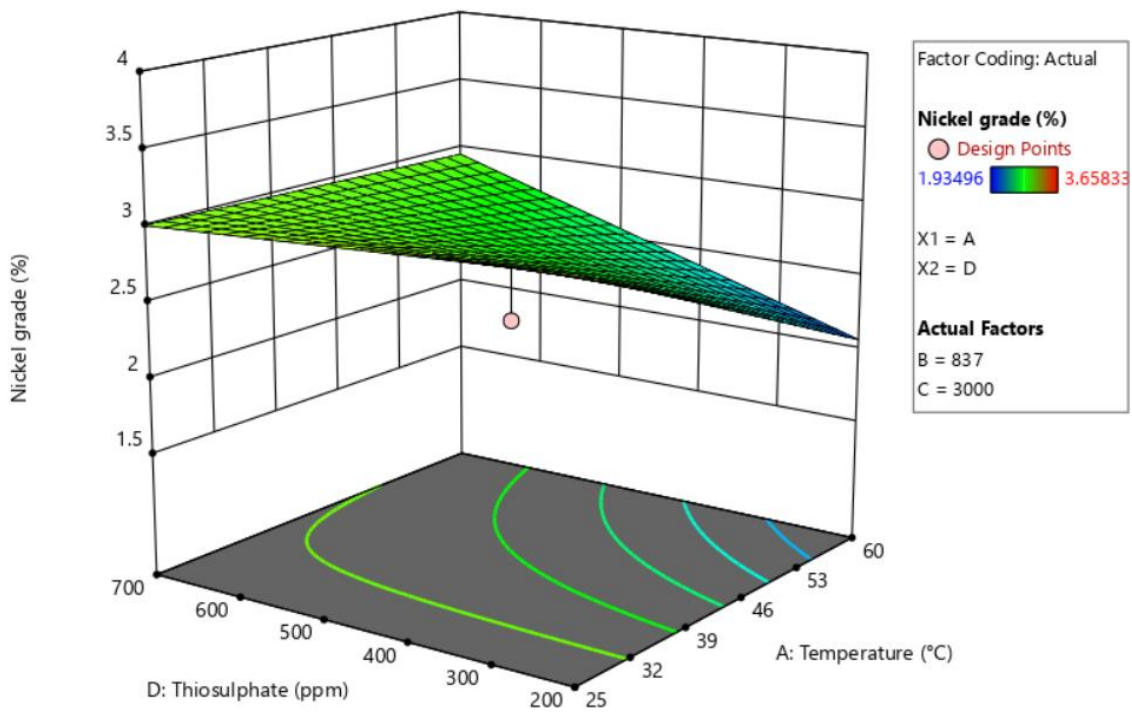


Figure 6-12: 3D surface graph showing the effect of temperature and $S_2O_3^{2-}$ on nickel grade for all tests.

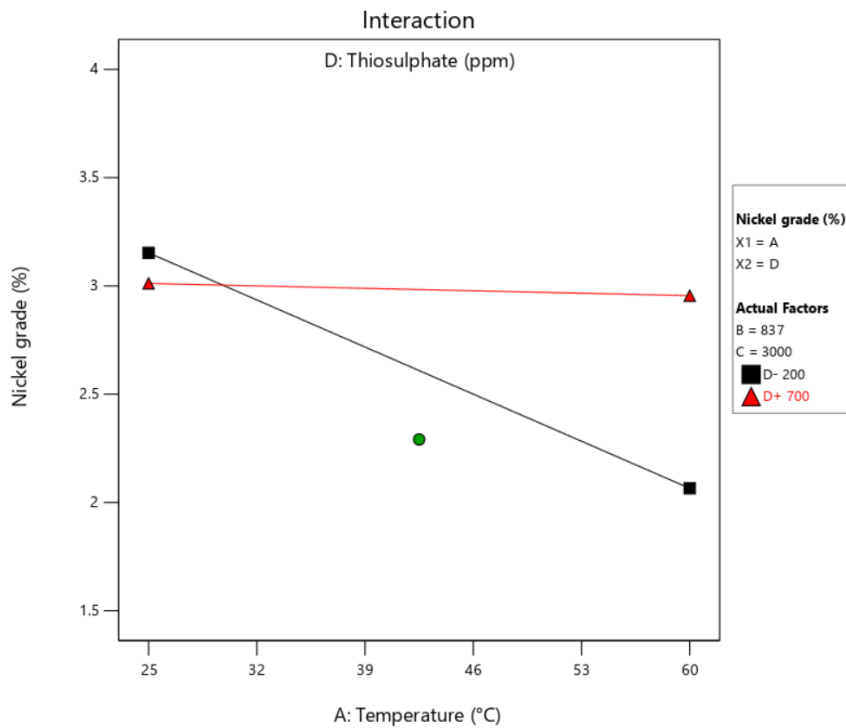


Figure 6-13: 2D surface graph showing the effect of temperature and $S_2O_3^{2-}$ on nickel grade for all tests

6.7 Key findings

This section contains a summary of the major findings as detailed in Chapters 5 and 6, highlighting the factors that influenced the flotation responses.

Table 6-1: Key findings from Chapters 5 and 6

Chapter 5 Key Findings	Chapter 6 Key Findings
Solids and Water Recoveries	
High or low $[\text{SO}_4^{2-}]$ separates the solids and water recovery into two groups.	The interaction between $[\text{Ca}^{2+}]$ and $[\text{SO}_4^{2-}]$ impacted the water and solids recoveries.
Higher water and solids recoveries were observed at high $[\text{SO}_4^{2-}]$.	Higher water and solids recoveries were observed at high $[\text{Ca}^{2+}]$ and high $[\text{SO}_4^{2-}]$.
Lower water and solids recoveries were observed at low $[\text{SO}_4^{2-}]$.	Lower water and solids recoveries were observed at high $[\text{Ca}^{2+}]$ and low $[\text{SO}_4^{2-}]$.
Generally, an increase in temperature and ionic strength shows higher recoveries of solids.	Statistically, temperature did not have a significant impact on the solids and water recoveries.
Copper Grade and Recoveries	
At 60 °C, there are three regions distinguished by high or low $[\text{SO}_4^{2-}]$ and $[\text{S}_2\text{O}_3^{2-}]$.	An increase in $[\text{SO}_4^{2-}]$ caused an increase in copper recovery whilst decreasing the copper grade.
Copper grade decreases with an increase in temperature	Copper grade and recovery decrease with an increase in temperature when $[\text{S}_2\text{O}_3^{2-}]$ is low. At high $[\text{S}_2\text{O}_3^{2-}]$, temperature has no effect on the copper grade.
Copper had faster flotation rates than nickel.	
Flotation rates within a small range (0.09 min^{-1}) in comparison to nickel.	Copper recovery increases when temperature increases at high $[\text{S}_2\text{O}_3^{2-}]$.
Flotation rates faster at 25 °C than at 60 °C.	
Nickel Grade and Recoveries	
Nickel grade decreases with an increase in temperature.	Nickel grade decreases with an increase in temperature at low $[\text{S}_2\text{O}_3^{2-}]$. At high $[\text{S}_2\text{O}_3^{2-}]$ temperature has no effect on the nickel grade.
Nickel had slower flotation rates than copper.	
Flotation rates within a larger range (0.30 min^{-1}) in comparison to copper.	An increase in $[\text{S}_2\text{O}_3^{2-}]$ caused an increase in nickel recovery.
Flotation rates faster at 60 °C than at 25 °C.	

7. DISCUSSION

The main aim of this project was to investigate the simultaneous effects of varying temperature and concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$ on the flotation response of a low-grade Cu-Ni-PGE ore. The key performance indicators used were (i) water recovery, (ii) solids recovery, (iii) valuable mineral recovery and (iv) mineral grade. Flotation responses can be complex to interpret due to interactive effects which may be present (Bradshaw et al., 2005). If there is an interaction between two or more independent variables, then the effect of one of the variables on a response will depend on the level of the other variable(s). Tests were conducted as outlined in Chapter 4. Table 6-1 shows a summary of results as presented in Chapters 5 and 6.

Ikumapayi et al.(2012) and Slatter et al. (2009) found that the presence of ions may increase or decrease the floatability of sulphide minerals. This, however, is dependent on the water chemistry as well as the type of mineral. Other research has revealed that at high concentrations, inorganic ions exhibit frothing properties (Corin & Wiese, 2014; Manono et al., 2012; Corin et al., 2011). Nickel recovery was found to increase slightly in increasing ionic strengths of synthetic plant water in a study by Corin & Weise (2014). Although copper and nickel grades generally decreased with an increase in ionic strength in the aforementioned study, nickel grade remained the same in a study by Manono et al. (2012). The slight increase in nickel recoveries (Corin & Wiese, 2014) and invariant nickel grade (Manono et al., 2012) might be a result of the presence of electrolytes increasing the floatability of nickel-gangue composites since some of the nickel is contained in unliberated pentlandite (Liu et al., 2013; Chandra & Gerson, 2009; Finkelstein, 1997).

For this study, the ionic strength values for the ions present in the plant water were calculated following the description in Section 2.5. The ranges for the ionic strength values of the ions that were being varied in this study are presented in Table 7-1.

Table 7-1: IS values for Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$

Ion	IS (M)	Difference (M)
Ca^{2+}	0.0081 - 0.0297	0.0216
SO_4^{2-}	0.0118 - 0.141	0.129
$\text{S}_2\text{O}_3^{2-}$	0.00700 - 0.0438	0.0368

7.1 The effect of Ca^{2+} and possible interactions with other parameters on flotation performance

Levay et. al (2001) and Ikumapayi and Makitalo (2012) stated that Ca^{2+} may precipitate as CaOH^+ which is considered a colloidal species which may attach to a mineral surface forming a hydrophilic coating. Metal hydroxides reduce the mineral hydrophobicity and make collector adsorption less selective (Clarke et al., 1995). In a sulphide flotation study by Gaudin & Charles (1953), the increase of Ca^{2+} in process water resulted in increased adsorption of Ca^{2+} onto valuable mineral surfaces thus hindering collector adsorption and resulting in the gangue floating by entrainment. Other studies however proposed that increased Ca^{2+} improves xanthate adsorption onto sulphide minerals (Boujounoui et al., 2015; Corin & Wiese, 2014; Wang, B. & Peng, 2014).

In this study, Ca^{2+} alone did not affect the flotation response. However, the interaction of Ca^{2+} and SO_4^{2-} impacted the water and solid recoveries only. Table 5-1 shows the overall pulp ionic strength for all the test conditions. Test conditions with high SO_4^{2-} concentration had $\text{IS} \geq 0.373$ M whilst those with low SO_4^{2-} concentration had $\text{IS} \leq 0.281$ M. At high SO_4^{2-} concentration, an increase in Ca^{2+} increased the mass of water and solids recovered. The opposite was seen for the solids and water recoveries at low $\text{IS} \leq 0.281$ M. That is, at low SO_4^{2-} concentration, an increase in Ca^{2+} decreased the mass of water and solids recovered. There is probable accumulation of Ca^{2+} and SO_4^{2-} ions at the bubble surface which might stabilise the froth and reduce froth drainage thus increasing entrainment as was the case in previous studies (Corin & Wiese, 2014; Manono et al., 2012; Corin et al., 2011). Additionally, higher ionic strength results in smaller bubble diameter in comparison to the bubble diameter at lower ionic strength. Smaller bubbles result in more stable froth and in turn recover more water than bigger bubbles which would explain why there was an increase in the water recovery at $\text{IS} \geq 0.373$ M whilst less water was recovered at $\text{IS} \leq 0.281$ M. Smaller bubbles also have larger surface area for solids recovery as was seen with the increase in solids recovery.

This suggests that at ionic strength 0.373 M or higher, Ca^{2+} and SO_4^{2-} are at high enough concentrations to modify the pulp and surface chemistry such that there is an increase in the probability of NFG entrainment as well as a more stable froth due to the smaller froth bubbles thus increasing the water and solid recoveries as already mentioned. In this study, the ranges for the concentrations of Ca^{2+} and SO_4^{2-} were 487–1187 mg/L and 1500–4500 mg/L, respectively.

7.2 The effect of SO_4^{2-} and possible interactions with other parameters on flotation performance

In addition to the interactive effects described in 7.1, SO_4^{2-} alone impacted the copper recovery and grade only. An increase in SO_4^{2-} caused an increase in copper recovery whilst decreasing the copper grade. This could have possibly been due to an increase in ionic strength as SO_4^{2-} increased, which is known to increase froth stability and therefore solids recovery as well as naturally floating gangue recovery which would decrease the concentrate grade. It should be noted that this increase in copper recovery was within a small range as shown in Figure 6-5 which is a probable reason there were no observable changes in the solids. Furthermore, copper only makes up a small fraction (1.14 %) of the total ore as highlighted in Table 4-1. Table 7-1 shows the ranges of the IS values for Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$.

7.3 The effect of $\text{S}_2\text{O}_3^{2-}$ and possible interactions with other parameters on flotation performance

Studies by Dzingai et al. (2021) suggested that an increase in $\text{S}_2\text{O}_3^{2-}$ was good for flotation. From electrical conductivity tests, they suggested that there might be possible improvement of xanthate attachment to the target sulphide mineral enhanced by the presence of $\text{S}_2\text{O}_3^{2-}$ in the pulp. Dzingai et al. (2021) considered a $\text{S}_2\text{O}_3^{2-}$ concentration range of 60-78 mg/L. For this study, the investigation considered a range of 200-700 mg/L for the $\text{S}_2\text{O}_3^{2-}$, which is clearly fair higher than that already considered by Dzingai et al. (2021).

Previous studies have shown that in the presence of sulphony compounds, xanthate decomposition can occur, while at high temperatures, the xanthate decomposition is more significant in comparison to lower temperatures. When dithionite ions are generated through oxidation of tetrathionates or when added as reagents to flotation waters, their intermediate oxidation products decompose xanthate (Mhonde et al., 2021). Furthermore, Mhonde et al. (2021) found that reducing the concentration of dithionites in solution resulted in a decline in the overall xanthate decomposition.

Chapter 6 showed that $\text{S}_2\text{O}_3^{2-}$ did not have any statistically significant impact on the solids and water recoveries. Copper and nickel sulphides make up a small fraction of the overall ore composition with 1.14 and 0.76 % respectively as shown in Table 4-1. Although Sections 7.3.1 and 7.3.2 show variation of the copper and nickel recoveries and grade with the change in $\text{S}_2\text{O}_3^{2-}$ and temperature, there were no observed changes in the solids recoveries at these

conditions. This may be attributed to the small mass fractions of the copper and nickel sulphides.

7.3.1 Copper response to $S_2O_3^{2-}$ and possible interactions with temperature

In this study, copper recovery was affected by the interaction of $S_2O_3^{2-}$ and temperature. Aerophine, a dithiophosphinate was the collector used to target copper. It has a similar structure to xanthates as shown in Section 2.2.1. Since xanthates have been seen to decompose in the presence of sulphoxy compounds (Mhonde et al., 2021), the same can be assumed for Aerophine. At high $S_2O_3^{2-}$ concentration an increase in temperature increased the copper recovery as shown in Figure 6-6 and Figure 6-7. It may be assumed that there are oxidation reactions of $S_2O_3^{2-}$ which give off intermediate products which decompose Aerophine. A possible explanation for this is that when $S_2O_3^{2-}$ is at a high concentration, then it may be in excess. On the basis that $S_2O_3^{2-}$ is in excess, then there is enough $S_2O_3^{2-}$ to decompose Aerophine while the excess $S_2O_3^{2-}$ may be acting as a collector since an increase in copper recoveries was seen with the increase in temperature at high $S_2O_3^{2-}$. The excess $S_2O_3^{2-}$ may attach to the mineral surface and promote copper flotation. Prior electrochemical studies by Hodgson & Agar (1989) showed that $S_2O_3^{2-}$ competes with xanthate for adsorption onto valuable mineral surfaces. The xanthate chemisorption occurs at the active mineral sites and thereafter the xanthate may undergo oxidation to form by-products which in turn enhance hydrophobicity (Hodgson & Agar, 1989). Perhaps there is chemisorption of the excess $S_2O_3^{2-}$ onto the active copper sites. The $S_2O_3^{2-}$ adsorbed on the mineral may undergo oxidation which may be supported by higher temperature. The oxidation by-products may have enhanced the mineral hydrophobicity and thus resulted in the observed increase in copper recovery. Additionally, $S_2O_3^{2-}$ was seen to improve sulphide floatability by decreasing the likelihood of hydrophilic compounds adsorbing onto the valuable mineral (Kirjavainen et al., 2002).

Figure 6-9 and Figure 6-10 show that at high $S_2O_3^{2-}$ concentration, an increase in temperature does not show any variation in the observed copper grade. This implies that the excess $S_2O_3^{2-}$ is above a concentration value for which there is no observable change in the copper grade. Figure 5-16 shows that the three highest cumulative copper recoveries were obtained at 60 °C and high $S_2O_3^{2-}$ concentration. The $S_2O_3^{2-}$ concentration showed a distinct trend at 60 °C unlike at 25 °C as shown in Figure 5-15.

At low $S_2O_3^{2-}$ concentration, an increase in temperature decreased the copper recovery. It may be assumed that there is enough $S_2O_3^{2-}$ to decompose Aerophine. The low $S_2O_3^{2-}$ concentration

however means that there are no excess $S_2O_3^{2-}$ ions to promote the flotation of copper with an increase in temperature as was seen with the decrease in copper recovery (see Figure 6-6 and Figure 6-7). Given that this study considered a range of 200-700 mg/L for the low and high $S_2O_3^{2-}$ concentration, it means that the $S_2O_3^{2-}$ concentration for which there is no observable change in the copper grade with an increase in temperature is above 200 mg/L but below 700 mg/L.

Chapter 6 shows that $S_2O_3^{2-}$ did not have any statistically significant impact on the solids and water recoveries. Another thing to note is that the overall cumulative copper recovery values for all test conditions were within a range of 6.72 % with lowest and highest recoveries at 83.04 and 89.76 % respectively. The final copper recoveries for all tests were within a fairly small range which is possibly why there was no observed change in the solids recoveries as $S_2O_3^{2-}$ concentration and temperature were being varied. This is in addition to the fact that copper-sulphides were making up only 1.14 % of the ore composition.

7.3.2 Nickel response to $S_2O_3^{2-}$ and possible interactions with temperature

In this study, $S_2O_3^{2-}$ alone affected the nickel recovery. An increase in $S_2O_3^{2-}$ caused an increase in nickel recovery as shown in Figure 6-11. Additionally, the two highest nickel recoveries at 60 °C were observed at high $S_2O_3^{2-}$ concentration as shown in Figure 5-27. The same figure also shows that the final nickel recoveries for all the tests with high $S_2O_3^{2-}$ concentration were above the average nickel recoveries of all the tests. This may be due to $S_2O_3^{2-}$ attaching onto the mineral surface and promoting nickel flotation thus allowing more nickel to report to the froth phase. Table 4-1 shows the ore composition with nickel only making up 0.76 % which may be a probable reason why there was no statistically significant impact on the solids response with the variation of $S_2O_3^{2-}$.

The nickel grade was not affected by $S_2O_3^{2-}$ alone but rather the interaction of $S_2O_3^{2-}$ and temperature. The observed nickel grade trends were the same as those observed for copper grade trends i.e., at high $S_2O_3^{2-}$ concentration there was no observable change in the nickel grade when temperature increased. At low $S_2O_3^{2-}$ concentration, an increase in temperature decreased the nickel grade. This was shown in Figure 6-12 and Figure 6-13 Figure 6-9 and Figure 6-10. SIPX was the collector used to target nickel and the structure is shown in Section 2.2.1. It may be assumed that SIPX decomposed following the same mechanism described for Aerophine decomposition in Section 7.3.1. For copper grade responses, at low $S_2O_3^{2-}$ concentration there was a decrease in the copper grade as temperature increased whilst at high

$S_2O_3^{2-}$ concentration, there was no observable change in the copper grade as temperature increased. Since the observed nickel grade trends were the same as the copper grade trends under the same conditions, the aforementioned possible explanation for observed copper trends apply to the observed nickel trends as well.

7.4 The effect of temperature and possible interactions with other parameters on flotation performance

Minerals respond differently to changes in temperature during flotation. A study by Strong et al., (2005), that investigated the properties of xanthates in sulphide flotation at elevated temperatures, found that at a higher temperature in comparison to room temperature, amyl xanthate concentration in the pulp was lower and the diamyl dioxanthogen and copper xanthate concentration on sulphides surfaces increased significantly. Consequently, higher temperatures at which hydrophobic species are at a high concentration improved the recovery of copper. Flotation studies by Ikumapayi et al. (2012) also showed that different ores can have different flotation responses depending on the water type and the temperature. The conclusions drawn from Ikumapayi et al. (2012) were based on flotation tests that were carried out at 4 °C, 11 °C and 22 °C using tap and process water on two complex sulphide ores from Boliden-Renstrom and Boliden-Kristeneberg. Pyrite flotation studies by O'Connor & Mills (1990) showed that a temperature increase from 3 to 44 °C resulted in an increase of both the recovery and grade of pyrite.

There was an interaction of temperature and $S_2O_3^{2-}$ as described in 7.3. There were no temperature interactions with Ca^{2+} and SO_4^{2-} . Additionally, Figure 5-13 and Figure 5-24 show that both the copper and nickel grades decrease with an increase in temperature given that $S_2O_3^{2-}$ was at a low concentration. Given that the increase in temperature did not have an observable change on the solids recoveries, then the decrease in the copper and nickel grades as temperature increased was most likely due to less copper and nickel reporting to the froth phase.

Kinetic studies were done, and the results are presented in Section 5.7. Overall, the copper flotation rates were higher than those of nickel. The flotation rates of copper at 25 and 60 °C were within a small range suggesting that the flotation rates were less temperature sensitive. Nickel however showed a larger difference in the flotation rates suggesting that nickel flotation rates were more temperature sensitive, with 60 °C favouring higher nickel flotation rates than

25 °C. It may be presumed that the higher temperature favors the faster formation of hydrophobic species which support nickel flotation.

8. CONCLUSIONS

The main aim of this study was to investigate the effect of specific ions and temperature, relevant to onsite process water recycling and temperature variations brought about by seasonal changes, on the separation of valuable minerals from gangue in batch flotation of a low-grade Cu-Ni-PGE ore. Five key questions were formulated as outlined in Chapter 3 in order to determine the relationship between the key performance indicators and the factors influencing them. In answering the key questions, the validity of the postulated hypothesis could be addressed.

1. What is the impact of spiking Ca^{2+} on the water, solids, mineral recoveries and mineral grade, whilst maintaining a complex process water background?

Ca^{2+} alone did not affect the flotation response but the interaction of Ca^{2+} and SO_4^{2-} affected the water and solids recoveries. The copper and nickel recoveries and grades were not impacted. At high SO_4^{2-} concentration ($\text{IS} \geq 0.373 \text{ M}$) an increase in Ca^{2+} increased the mass of water and solids recovered. At low SO_4^{2-} concentration ($\text{IS} \leq 0.281 \text{ M}$) an increase in Ca^{2+} decreased the mass of water and solids recovered. For this study, Ca^{2+} and SO_4^{2-} were key ions in contributing to the overall ionic strength of the pulp. The froth stability increases with an increase in ionic strength.

2. What is the impact of spiking SO_4^{2-} on the water, solids, mineral recoveries and mineral grade, whilst maintaining a complex process water background?

SO_4^{2-} alone impacted the copper recovery and grade only. An increase in SO_4^{2-} caused an increase in copper recovery whilst decreasing the copper grade. The gangue was activated by an increased ionic strength, which caused the grade to decrease. Additionally, there were interactive effects of Ca^{2+} and SO_4^{2-} as aforementioned.

3. What is the impact of spiking $\text{S}_2\text{O}_3^{2-}$ on the water, solids, mineral recoveries and mineral grade, whilst maintaining a complex process water background?

Copper: There was an interactive effect of $\text{S}_2\text{O}_3^{2-}$ and temperature on the copper recovery. At high $\text{S}_2\text{O}_3^{2-}$ concentration an increase in temperature increased the copper recovery whilst there was no observable change in the copper grade. At high $\text{S}_2\text{O}_3^{2-}$ concentration, higher temperatures supported the oxidation of excess $\text{S}_2\text{O}_3^{2-}$ which would have adsorbed onto mineral active sites thus enhanced mineral hydrophobicity as was shown by the increase in copper

recovery. At low $S_2O_3^{2-}$ concentration, an increase in temperature decreased the copper recovery whilst decreasing the copper grade. The low $S_2O_3^{2-}$ concentration was adequate to consume the collector resulting in less copper reporting to the concentrate as was seen in the decrease in copper grade and recovery.

Thus, increasing temperature at $S_2O_3^{2-}$ concentration less than 200 mg/L has adverse effects. Increasing the temperature with $S_2O_3^{2-}$ concentration above 200 mg/L but below 700 mg/L caused (i) no observable change in the copper grade and (ii) increased the copper recovery.

Nickel: $S_2O_3^{2-}$ alone affected the nickel recovery only. An increase in $S_2O_3^{2-}$ caused an increase in nickel recovery thus $S_2O_3^{2-}$ supports nickel flotation. The nickel grade was affected by interactive effect of $S_2O_3^{2-}$ and temperature. At high $S_2O_3^{2-}$ concentration there was no observable change in the nickel grade when temperature increased whilst at low $S_2O_3^{2-}$ concentration, an increase in temperature decreased the nickel grade.

Thus, an increase in $S_2O_3^{2-}$ concentration is good for nickel flotation. Increasing temperature at $S_2O_3^{2-}$ concentration less than 200 mg/L has adverse effects on the nickel grade. Increasing the temperature with $S_2O_3^{2-}$ concentration above 200 mg/L but below 700 mg/L caused no observable change in the nickel grade.

4. Is there a temperature effect on the water, solids, mineral recoveries and mineral grade, whilst maintaining a complex process water background?

There was an interactive effect of temperature and $S_2O_3^{2-}$ as previously described. Additionally, the kinetic studies showed a smaller range for copper flotation rates at 25 and 60 °C in comparison to the bigger range observed for nickel flotation rates at the same temperatures. Nickel flotation rates were therefore more temperature sensitive in comparison to copper flotation rates.

5. Are there any interactive effects between the varied factors on flotation performance?

There were interactive effects between the following:

- Ca^{2+} and SO_4^{2-} as discussed in Sections 7.1 and 7.2
- $S_2O_3^{2-}$ and temperature as discussed in Sections 7.3 and 7.4

The two hypotheses stated in Chapter 3 could be addressed as follows:

- 1: For select ions Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$, there exist optimal concentration ranges beyond which flotation performance is adversely affected. This is because some ions have been shown to be deleterious whilst others are beneficial to the flotation process.
- 2: Temperature variation with ion concentration variation affects the flotation response. This is because temperature affects the mineral flotation rates, and this may vary from mineral to mineral. Some ions have been seen to react with flotation reagents and some of these reactions may be affected by temperature thus affecting the flotation response.

This study has demonstrated that there are concentration ranges for specific ions beyond which flotation performance was adversely affected as well as ranges beyond which the ion concentration does not give an observable change in the flotation response. This understanding can enable the prediction of optimum operating conditions with regards to the number of recycles that plant water may undergo. Some responses were affected by single variables whilst others by the interaction of variables. The higher ionic concentrations and their corresponding ionic strengths resulted in more stable froth in comparison to lower ionic concentrations and consequently an improvement in the recoveries.

Water and solids recoveries were impacted by the interaction of Ca^{2+} and SO_4^{2-} (Sections 7.1 and 7.2). At high SO_4^{2-} concentration corresponding to ionic strength equal to or higher than 0.373 M, an increase in Ca^{2+} increased the mass of water and solids recovered. Less water was recovered at ionic strength less than or equal to 0.281 M. An increase in SO_4^{2-} alone within a range of 0.0118-0.141 M (Table 7-1), caused an increase in copper recovery whilst decreasing the copper grade (Section 7.2). $\text{S}_2\text{O}_3^{2-}$ alone affected the nickel recovery as outlined in Section 7.3.2; an increase in $\text{S}_2\text{O}_3^{2-}$ caused an increase in nickel recovery with $\text{S}_2\text{O}_3^{2-}$ ranging from 0.007-0.0438 M (Table 7-1), whilst the nickel grade was affected by the interaction of $\text{S}_2\text{O}_3^{2-}$ and temperature (Section 7.3.2). Furthermore, copper showed similar trends as those observed for nickel in the responses for mineral grade (Section 7.3.1). At high $\text{S}_2\text{O}_3^{2-}$ concentration there was no observable change in the nickel and copper grades when temperature increased. At low $\text{S}_2\text{O}_3^{2-}$ concentration, an increase in temperature decreased the nickel and copper grades.

Nickel was more temperature sensitive in comparison to copper (Section 7.4). There was an interactive effect of $S_2O_3^{2-}$ and temperature which affected the mineral grades.

It may thus be concluded that the postulated hypotheses are supported by this work.

9. RECOMMENDATIONS

As a result of the results and conclusions of the study, the following recommendations are made:

- Analysis of the collector through the system as conditions change would be valuable in order to understand the mineral-collector interactions as well as collector decomposition.
- As the range of $S_2O_3^{2-}$ concentration used in this study was large, 200-700 mg/L, narrowing this range, by investigating concentrations between these extremes, may elucidate the concentration threshold below/above which there are no adverse flotation responses.

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APPENDICES

Appendix A: Batch flotation data for tests conducted under 25 °C

25 Zero Run 1- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		38.94	13.27	22.7	12.23	16.53	13.45	28.07	27.41	28.06	1007.5
Paper		9.49	9.48	9.67	9.64	9.62	9.44	8.85	8.94	8.96	17.64
Solids (g)		29.45	3.79	13.03	2.59	6.91	4.01	19.22	18.47	19.1	989.86
Cumulative solids (g)	0	29.45	33.24	46.27	48.86	55.77	59.78				
Squirt bottle before		576.19	571.3	587.57	560.6	614.5	593.31				
Squirt bottle after		459.53	421.99	428.34	389.78	265.5	198.43				
wash water used		116.66	149.31	159.23	170.82	349	394.88				
Dish + conc + water		412.62	365.94	383.75	445.07	598.72	602.5				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		75.55	17.35	35.79	21.9	24.37	22.67				
cumulative water	0	75.55	92.9	128.69	150.59	174.96	197.63				
Ore (g)		1115.2									
Total solids collected		1106.43									
% solids collected		99.2									

25 Zero Run 2 - Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		39.09	13.94	19.39	15.58	16.71	10.31	28.61	30.99	28.08	1008.44
Paper		9.77	9.3	9.81	9.78	9.25	9.13	9.54	9.54	9.75	17.68
Solids (g)		29.32	4.64	9.58	5.8	7.46	1.18	19.07	21.45	18.33	990.76
Cumulative solids (g)	0	29.32	33.96	43.54	49.34	56.8	57.98				
Squirt bottle before		573.09	571.01	582.23	569.43	613.3	614				
Squirt bottle after		454.71	419.97	414.96	386.88	205.9	228.93				
wash water used		118.38	151.04	167.27	182.55	407.4	385.07				
Dish + conc + water		408.38	370.94	419.48	469.8	650.2	591.02				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		69.72	19.77	66.93	31.69	16.9	23.83				
cumulative water	0	69.72	89.49	156.42	188.11	205.01	228.84				
Ore (g)		1122.1									
Total solids collected		1107.59									
% solids collected		98.71									
25 Zero Run 1 – Recovery and Grade											
		Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2	
Copper Percentage (%)		0,28	8,17	2,47	0,88	0,96	1,01	0,79	0,05	0,05	
Copper Mass (g)		0,05	2,41	0,09	0,11	0,02	0,07	0,03	0,01	0,01	
Cumulative Copper Mass (g)			2,41	2,50	2,61	2,64	2,71	2,74			
Copper Grade (%)			8,17	7,52	5,65	5,40	4,86	4,58			
Copper Recovery (%)			73,40	76,25	79,75	80,51	82,65	83,62			
Nickel Percentage (%)		0,26	5,60	2,75	1,63	1,40	1,36	1,26	0,10	0,10	
Nickel Mass (g)		0,05	1,65	0,10	0,21	0,04	0,09	0,05	0,02	0,02	
Cumulative Nickel Mass (g)			1,65	1,75	1,97	2,00	2,10	2,15			
Nickel Grade (%)			5,60	5,28	4,25	4,10	3,76	3,59			
Nickel Recovery (%)			51,56	54,82	61,45	62,59	65,52	67,10			

25 Zero Run 2– Recovery and Grade											
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2		
Copper Percentage (%)	0,28	9,63	3,01	0,95	0,96	0,82	0,75	0,06	0,06		
Copper Mass (g)	0,05	2,82	0,14	0,09	0,06	0,06	0,01	0,01	0,01		
Cumulative Copper Mass (g)		2,82	2,96	3,06	3,11	3,17	3,18				
Copper Grade (%)		9,63	8,73	7,02	6,30	5,58	5,49				
Copper Recovery (%)		75,15	78,86	81,30	82,77	84,41	84,64				
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Nickel Percentage (%)	0,26	5,61	4,07	2,66	2,24	1,89	1,40	0,10	0,10		
Nickel Mass (g)	0,05	1,64	0,19	0,25	0,13	0,14	0,02	0,02	0,02		
Cumulative Nickel Mass (g)		1,64	1,83	2,09	2,22	2,36	2,38				
Nickel Grade (%)		5,61	5,40	4,80	4,50	4,15	4,10				
Nickel Recovery (%)		47,99	53,49	60,93	64,72	68,83	69,31				
<hr/>											
25 LLL Run 1 - Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		41.1	16.11	26.86	15.98	14.6	12.7	31.62	29.31	31.19	990.8
Paper		8.2	9.99	9.98	9.97	9.05	9.65	9.55	9.68	9.63	17.8
Solids (g)		32.9	6.12	16.88	6.01	5.55	3.05	22.07	19.63	21.56	973
Cumulative solids (g)	0	32.9	39.02	55.9	61.91	67.46	70.51				
Squirt bottle before		561.43	570.84	588.45	577.68	610.2	620.9				
Squirt bottle after		356.74	337.38	363.66	402.98	370.5	325.49				
wash water used		204.69	233.46	224.79	174.7	239.7	295.41				
Dish + conc + water		528.91	470.1	508.26	486.99	496.8	509.8				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		100.36	35.03	90.89	56.52	33.11	30.4				
cumulative water	0	100.36	135.39	226.28	282.8	315.91	346.31				
Ore (g)		1113.4									
Total solids collected		1106.77									
% solids collected		99.41									

25 LLL Run 2 - Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		46.6	13.95	22.16	13.9	15.07	11.59	26.79	28.3	30.56	992.6
Paper		8.89	8.61	8.87	9.64	10.13	9.01	9.06	8.84	9.02	17.56
Solids (g)		37.71	5.34	13.29	4.26	4.94	2.58	17.73	19.46	21.54	975.04
Cumulative solids (g)	0	37.71	43.05	56.34	60.6	65.54	68.12				
Squirt bottle before		571.95	567.93	588.42	573.96	606.2	614.8				
Squirt bottle after		425.55	390.24	438.46	461.96	386.67	316.64				
wash water used		146.4	177.69	149.96	112	219.53	298.16				
Dish + conc + water		476.07	406.39	414.9	405.8	493.51	516.08				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		101	27.87	75.95	39.78	50.6	34.4				
cumulative water	0	101	128.87	204.82	244.6	295.2	329.6				

Ore (g)	1115.8
Total solids collected	1101.89
% solids collected	98.75

25 LLL Run 1- Recovery and Grade										
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2	
Copper Percentage (%)	0,28	8,37	1,58	0,51	0,67	1,53	0,69	0,05	0,05	
Copper Mass (g)	0,06	2,75	0,10	0,09	0,04	0,08	0,02	0,01	0,01	
Cumulative Copper Mass (g)		2,75	2,85	2,94	2,98	3,06	3,08			
Copper Grade (%)		8,37	7,31	5,25	4,81	4,54	4,37			
Copper Recovery (%)		76,71	79,41	81,78	82,90	85,26	85,85			
Nickel Percentage (%)	0,26	5,27	2,33	1,57	1,02	2,22	1,04	0,10	0,10	
Nickel Mass (g)	0,06	1,73	0,14	0,27	0,06	0,12	0,03	0,02	0,02	
Cumulative Nickel Mass (g)		1,73	1,88	2,14	2,20	2,33	2,36			
Nickel Grade (%)		5,27	4,81	3,83	3,56	3,45	3,34			
Nickel Recovery (%)		51,75	56,02	63,95	65,78	69,45	70,39			

25 LLL Run 2– Recovery and Grade												
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2			
Copper Percentage (%)	0,27	7,00	1,60	0,57	0,80	0,72	0,60	0,05	0,05			
Copper Mass (g)	0,05	2,64	0,09	0,08	0,03	0,04	0,02	0,01	0,01			
Cumulative Copper Mass (g)		2,64	2,73	2,80	2,84	2,87	2,89					
Copper Grade (%)		7,00	6,33	4,97	4,68	4,38	4,24					
Copper Recovery (%)		78,83	81,39	83,63	84,65	85,71	86,17					
Nickel Percentage (%)	0,26	5,04	1,94	1,20	1,08	0,93	0,72	0,11	0,09			
Nickel Mass (g)	0,05	1,90	0,10	0,16	0,05	0,05	0,02	0,02	0,02			
Cumulative Nickel Mass (g)		1,90	2,00	2,16	2,21	2,26	2,27					
Nickel Grade (%)		5,04	4,65	3,84	3,65	3,44	3,34					
Nickel Recovery (%)		57,55	60,69	65,52	66,91	68,31	68,87					
25 HLL Run 1- Water and Solids												
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings	
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-	
Solids + paper		43.6	17.33	15.64	10.85	16.25	14.18	30.61	28.31	26.09	998.6	
Paper		9.39	9.38	9.32	8.44	10.14	10.03	8.32	9.36	9.46	17.79	
Solids (g)		34.21	7.95	6.32	2.41	6.11	4.15	22.29	18.95	16.63	980.81	
Cumulative solids (g)	0	34.21	42.16	48.48	50.89	57	61.15					
Squirt bottle before		570.38	567.47	590.21	569.93	601.7	585.44					
Squirt bottle after		471.31	455.61	431.83	399.84	238.7	197.74					
wash water used		99.07	111.86	158.38	170.09	363	387.7					
Dish + conc + water		468.07	374.74	377.78	439.87	601	606.6					
Dish		190.96	195.49	175.7	249.76	218.44	180.94					
Recovered water		143.83	59.44	37.38	17.61	13.45	33.81					
cumulative water	0	143.83	203.27	240.65	258.26	271.71	305.52					
Ore (g)		1116.5										
Total solids collected		1099.83										
% solids collected		98.5										

25 HLL Run 2 - Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		41.64	17.14	21.51	13.02	13.65	13.07	32.94	27.74	29.91	1011.04
Paper		9.91	10	9.6	8.44	10.01	9.26	9.89	9.41	10.04	18.09
Solids (g)		31.73	7.14	11.91	4.58	3.64	3.81	23.05	18.33	19.87	992.95
Cumulative solids (g)	0	31.73	38.87	50.78	55.36	59	62.81				
Squirt bottle before		577.77	575.69	563.18	575.79	611.1	610.5				
Squirt bottle after		449.01	437.46	407.93	444.44	319.43	170.85				
wash water used		128.76	138.23	155.25	131.35	291.67	439.65				
Dish + conc + water		492.18	383.73	401.91	412.47	529.55	654.7				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		140.73	42.87	59.05	26.78	15.8	30.3				
cumulative water	0	140.73	183.6	242.65	269.43	285.23	315.53				
Ore (g)		1122.1									
Total solids collected		1117.01									
% solids collected		99.55									
25 HLL Run 1- Recovery and Grade											
		Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2	
Copper Percentage (%)		0,28	8,48	1,59	0,51	0,66	0,72	0,59	0,05	0,05	
Copper Mass (g)		0,06	2,90	0,13	0,03	0,02	0,04	0,02	0,01	0,01	
Cumulative Copper Mass (g)			2,90	3,03	3,06	3,08	3,12	3,14			
Copper Grade (%)			8,48	7,18	6,31	6,04	5,47	5,14			
Copper Recovery (%)			79,77	83,24	84,14	84,57	85,78	86,45			
Nickel Percentage (%)		0,28	5,16	2,64	2,46	1,49	1,33	1,06	0,11	0,10	
Nickel Mass (g)		0,06	1,76	0,21	0,16	0,04	0,08	0,04	0,02	0,02	
Cumulative Nickel Mass (g)			1,76	1,97	2,13	2,17	2,25	2,29			
Nickel Grade (%)			5,16	4,68	4,39	4,26	3,94	3,75			
Nickel Recovery (%)			52,83	59,11	63,78	64,85	67,29	68,60			

25 HLL Run 2– Recovery and Grade									
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2
Copper Percentage (%)	0,28	8,34	1,23	0,50	0,70	0,67	0,59	0,05	0,05
Copper Mass (g)	0,06	2,65	0,09	0,06	0,03	0,02	0,02	0,01	0,01
Cumulative Copper Mass (g)		2,65	2,73	2,79	2,83	2,85	2,87		
Copper Grade (%)		8,34	7,03	5,50	5,10	4,83	4,57		
Copper Recovery (%)		78,91	81,52	83,29	84,24	84,97	85,64		
Nickel Percentage (%)	0,27	4,47	2,70	2,45	1,08	0,99	0,87	0,12	0,09
Nickel Mass (g)	0,06	1,42	0,19	0,29	0,05	0,04	0,03	0,02	0,02
Cumulative Nickel Mass (g)		1,42	1,61	1,90	1,95	1,99	2,02		
Nickel Grade (%)		4,47	4,14	3,75	3,53	3,37	3,22		
Nickel Recovery (%)		45,81	52,04	61,49	63,08	64,25	65,32		

25 LHL Run 1- Water and Solids												
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings	
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-	
Solids + paper		43.23	17.9	22.46	13.89	13.44	13.58	27.39	21.68	27.09		998.96
Paper		8.4	8.94	9	9.11	9.2	10.05	8.52	8.54	8.5		18
Solids (g)		34.83	8.96	13.46	4.78	4.24	3.53	18.87	13.14	18.59		980.96
Cumulative solids (g)	0	34.83	43.79	57.25	62.03	66.27	69.8					
Squirt bottle before		578.4	572.6	590.84	573.92	608.7	611.4					
Squirt bottle after		476	464.02	468.79	470.09	356.39	326.59					
wash water used		102.4	108.58	122.05	103.83	252.31	284.81					
Dish + conc + water		488.19	383.11	392.24	403.06	509.87	503.62					
Dish		190.96	195.49	175.7	249.76	218.44	180.94					
Recovered water		160	70.08	81.03	44.69	34.88	34.34					
cumulative water	0	160	230.08	311.11	355.8	390.68	425.02					
Ore (g)		1113.7										
Total solids collected		1101.36										
% solids collected		98.9										

25 LHL Run 2- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		45.38	18.1	21.82	15.71	14.54	12.07	29.2	29.33	31.31	982.01
Paper		8.55	8.29	9.35	9.29	9.44	9.28	10.07	8.34	10.1	17.82
Solids (g)		36.83	9.81	12.47	6.42	5.1	2.79	19.13	20.99	21.21	964.19
Cumulative solids (g)	0	36.83	46.64	59.11	65.53	70.63	73.42				
Squirt bottle before		578.1	576.6	589.27	574.01	610.3	616.3				
Squirt bottle after		462.52	457.87	474.72	461.16	278.37	310.47				
wash water used		115.58	118.73	114.55	112.85	331.93	305.83				
Dish + conc + water		485.7	426.07	379.21	389.19	589.7	546.64				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		142.33	102.04	76.49	20.16	34.23	57.08				
cumulative water	0	142.33	244.37	320.86	341.02	375.25	432.33				
Ore (g)		1110.5									
Total solids collected		1098.94									
% solids collected		98.96									

25 LHL Run 1– Recovery and Grade										
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2	
Copper Percentage (%)	0,2783	7,6683	1,299	0,4293	0,5596	0,527	0,4953	0,0468	0,0456	
Copper Mass (g)	0,05252	2,670869	0,11639	0,057784	0,026749	0,022345	0,017484	0,00615	0,008477	
Cumulative Copper Mass (g)		2,670869	2,787259	2,845043	2,871792	2,894137	2,911621			
Copper Grade (%)		7,67	6,37	4,97	4,63	4,37	4,17			
Copper Recovery (%)		79,03	82,48	84,19	84,98	85,64	86,16			
Nickel Percentage (%)	0,2793	4,8881	2,219	1,7964	1,0337	0,9488	0,8322	0,0964	0,0966	
Nickel Mass (g)	0,0527	1,702525	0,198822	0,241795	0,049411	0,040229	0,029377	0,012667	0,017958	
Cumulative Nickel Mass (g)		1,702525	1,901348	2,143143	2,192554	2,232783	2,26216			
Nickel Grade (%)		4,89	4,34	3,74	3,53	3,37	3,24			
Nickel Recovery (%)		52,56	58,69	66,16	67,68	68,93	69,83			

25 LHL Run 2– Recovery and Grade											
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2		
Copper Percentage (%)	0,2962	7,2099	1,2798	0,4065	0,5558	0,5401	0,4868	0,041	0,041		
Copper Mass (g)	0,0567	2,65541	0,12555	0,05069	0,03568	0,02755	0,01358	0,009	0,0087		
Cumulative Copper Mass (g)		2,65541	2,78095	2,83165	2,86733	2,89487	2,90845				
Copper Grade (%)		7,21	5,96	4,79	4,38	4,10	3,96				
Copper Recovery (%)		79,92	83,70	85,22	86,30	87,13	87,54				
Nickel Percentage (%)	0,2837	4,5182	2,1122	1,8322	1,0298	0,967	0,8101	0,089	0,09		
Nickel Mass (g)	0,0543	1,66405	0,20721	0,22848	0,06611	0,04932	0,0226	0,019	0,01909		
Cumulative Nickel Mass (g)		1,66405	1,87126	2,09974	2,16585	2,21517	2,23777				
Nickel Grade (%)		4,5182	4,01214	3,55225	3,30512	3,1363	3,0479				
Nickel Recovery (%)		53,0379	59,6421	66,9243	69,0315	70,6033	71,3237				
25 HHL Run 1- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		50.25	21.45	23.27	16.22	14.63	11.77	31.6	28.35	27.86	977.7
Paper		8.39	8.36	8.32	8.22	8.26	8.35	10	10.18	8.28	17.84
Solids (g)		41.86	13.09	14.95	8	6.37	3.42	21.6	18.17	19.58	959.86
Cumulative solids (g)	0	41.86	54.95	69.9	77.9	84.27	87.69				
Squirt bottle before		578.89	578.08	589.38	578.43	613.3	615.3				
Squirt bottle after		471.68	470.55	488.51	486.68	366.58	289.48				
wash water used		107.21	107.53	100.87	91.75	246.72	325.82				
Dish + conc + water		528.75	428.19	457.18	491.51	597.69	576.77				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		188.72	112.08	165.66	142	126.16	66.59				
cumulative water	0	188.72	300.8	466.46	608.46	734.62	801.21				
Ore (g)		1110.4									
Total solids collected		1106.9									
% solids collected		99.7									

25 HHL Run 2- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		49.04	23.07	25.61	17.6	16	13.26	32.35	29.07	30.61	980.1
Paper		9.7	9.66	9.74	9.84	9.8	9.75	10.02	9.84	9.71	17.42
Solids (g)		39.34	13.41	15.87	7.76	6.2	3.51	22.33	19.23	20.9	962.68
Cumulative solids (g)	0	39.34	52.75	68.62	76.38	82.58	86.09				
Squirt bottle before		576.73	572.22	582.21	567.3	610.4	604.1				
Squirt bottle after		471.55	474.63	478.62	443.44	359.76	349.99				
wash water used		105.18	97.59	103.59	123.86	250.64	254.11				
Dish + conc + water		528.51	431.27	465.73	515.65	602.2	508.6				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		193.03	124.78	170.57	134.27	126.92	70.04				
cumulative water	0	193.03	317.81	488.38	622.65	749.57	819.61				

Ore (g)	1117.7
Total solids collected	1111.23
% solids collected	99.42

25 HHL Run 1- Recovery and Grade									
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2
Copper Percentage (%)	0,29	6,40	1,00	0,39	0,42	0,40	0,36	0,04	0,04
Copper Mass (g)	0,06	2,68	0,13	0,06	0,03	0,03	0,01	0,01	0,01
Cumulative Copper Mass (g)		2,68	2,81	2,87	2,90	2,93	2,94		
Copper Grade (%)		6,40	5,11	4,10	3,72	3,47	3,35		
Copper Recovery (%)		79,78	83,66	85,40	86,41	87,17	87,54		
Nickel Percentage (%)	0,27	4,71	1,48	0,89	0,60	0,52	0,46	0,10	0,09
Nickel Mass (g)	0,06	1,97	0,19	0,13	0,05	0,03	0,02	0,02	0,02
Cumulative Nickel Mass (g)		1,97	2,16	2,30	2,35	2,38	2,40		
Nickel Grade (%)		4,71	3,94	3,29	3,01	2,82	2,73		
Nickel Recovery (%)		59,11	64,94	68,95	70,40	71,39	71,87		

25 HHL Run 2– Recovery and Grade												
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2			
Copper Percentage (%)	0,29	7,22	0,09	0,35	0,43	0,39	0,36	0,04	0,04			
Copper Mass (g)	0,07	2,84	0,01	0,06	0,03	0,02	0,01	0,01	0,01			
Cumulative Copper Mass (g)		2,84	2,85	2,91	2,94	2,97	2,98					
Copper Grade (%)		7,22	5,41	4,24	3,85	3,59	3,46					
Copper Recovery (%)		83,67	84,03	85,68	86,66	87,37	87,74					
Nickel Percentage (%)	0,27	4,93	1,52	1,08	0,67	0,57	0,49	0,09	0,09			
Nickel Mass (g)	0,06	1,94	0,20	0,17	0,05	0,04	0,02	0,02	0,02			
Cumulative Nickel Mass (g)		1,94	2,14	2,31	2,37	2,40	2,42					
Nickel Grade (%)		4,93	4,06	3,37	3,10	2,91	2,81					
Nickel Recovery (%)		58,41	64,54	69,69	71,26	72,32	72,84					
25 LLH Run 1- Water and Solids												
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings	
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-	
Solids + paper		34.33	12.91	20.29	9.64	9.27	9.33	30.68	30.57	30.11	957.07	
Paper		4.53	4.4	4.5	4.14	4.12	4.49	10.06	10	9.93	16.58	
Solids (g)		29.8	8.51	15.79	5.5	5.15	4.84	20.62	20.57	20.18	940.49	
Cumulative solids (g)	0	29.8	38.31	54.1	59.6	64.75	69.59					
Squirt bottle before		570.73	562.75	586.58	577.08	608.1	606.2					
Squirt bottle after		507.6	483.53	511.76	501.76	365.3	339.68					
wash water used		63.13	79.22	74.82	75.32	242.8	266.52					
Dish + conc + water		422.3	305.06	362.65	407.53	515.41	499.84					
Dish		190.96	195.49	175.7	249.76	218.44	180.94					
Recovered water		138.41	21.84	96.34	76.95	49.02	47.54					
cumulative water	0	138.41	160.25	256.59	333.54	382.56	430.1					
Ore (g)		1108.4										
Total solids collected		1071.45										
% solids collected		96.7										

25 LLH Run 2- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		36.77	9.95	26.87	15.84	15.11	13.91	26.6	24	23.17	987.93
Paper		4.27	4.3	9.96	10.04	10.03	9.73	4.42	4.48	4.53	16.9
Solids (g)		32.5	5.65	16.91	5.8	5.08	4.18	22.18	19.52	18.64	971.03
Cumulative solids (g)	0	32.5	38.15	55.06	60.86	65.94	70.12				
Squirt bottle before		507.51	483.42	584.28	563.75	608.2	595.33				
Squirt bottle after		402.8	339.42	443.57	447.48	374.49	328.28				
wash water used		104.71	144	140.71	116.27	233.71	267.05				
Dish + conc + water		458.92	384.06	437.87	430.54	516.07	485.05				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		130.75	38.92	104.55	58.71	58.84	32.88				
cumulative water	0	130.75	169.67	274.22	332.93	391.77	424.65				

Ore (g)	1109.8
Total solids collected	1101.49
% solids collected	99.25

25 LLH Run 1- Recovery and Grade									
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2
Copper Percentage (%)	0,2931	8,3572	1,2646	0,3778	0,7316	0,5939	0,5052	0,042	0,0399
Copper Mass (g)	0,06044	2,490446	0,107617	0,059655	0,040238	0,030586	0,024452	0,008639	0,008052
Cumulative Copper Mass (g)		2,490446	2,598063	2,657718	2,697956	2,728542	2,752993		
Copper Grade (%)		8,36	6,78	4,91	4,53	4,21	3,96		
Copper Recovery (%)		78,94	82,35	84,24	85,52	86,49	87,26		
Nickel Percentage (%)	0,2677	4,8448	2,4449	2,5496	1,1423	0,9952	0,6278	0,1014	0,0844
Nickel Mass (g)	0,0552	1,44375	0,208061	0,402582	0,062827	0,051253	0,030386	0,020858	0,017032
Cumulative Nickel Mass (g)		1,44375	1,651811	2,054393	2,11722	2,168473	2,198858		
Nickel Grade (%)		4,84	4,31	3,80	3,55	3,35	3,16		
Nickel Recovery (%)		46,42	53,11	66,05	68,07	69,72	70,69		

25 LLH Run 2– Recovery and Grade									
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2
Copper Percentage (%)	0,2821	8,1934	1,5614	0,5301	0,7099	0,6314	0,5394	0,045	0,0431
Copper Mass (g)	0,0626	2,66286	0,08822	0,08964	0,04117	0,03208	0,02255	0,009	0,00803
Cumulative Copper Mass (g)		2,66286	2,75107	2,84071	2,88189	2,91396	2,93651		
Copper Grade (%)		8,19	7,21	5,16	4,74	4,42	4,19		
Copper Recovery (%)		78,76	81,37	84,02	85,24	86,18	86,85		
Nickel Percentage (%)	0,2607	4,6663	2,7994	2,7051	1,2975	1,0473	0,7889	0,094	0,0841
Nickel Mass (g)	0,0578	1,51655	0,15817	0,45743	0,07526	0,0532	0,03298	0,018	0,01568
Cumulative Nickel Mass (g)		1,51655	1,67471	2,13215	2,2074	2,2606	2,29358		
Nickel Grade (%)		4,6663	4,38981	3,8724	3,62701	3,42827	3,27094		
Nickel Recovery (%)		47,4769	52,4285	66,7488	69,1048	70,7703	71,8027		

25 HLH Run 1- Water and Solids												
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings	
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-	
Solids + paper		40.67	13.04	10.23	7.72	9.17	11.77	24.09	23.96	24.68	995.7	
Paper		5.083	4.86	4.8	4.75	4.74	4.76	4.85	4.93	4.84	17.37	
Solids (g)		35.587	8.18	5.43	2.97	4.43	7.01	19.24	19.03	19.84	978.33	
Cumulative solids (g)	0	35.587	43.767	49.197	52.167	56.597	63.607					
Squirt bottle before		572.41	572.72	592.23	575.13	614.5	615.5					
Squirt bottle after		467.19	445.91	424.6	398.32	298.75	218.56					
wash water used		105.22	126.81	167.63	176.81	315.75	396.94					
Dish + conc + water		480.24	391.86	392.99	460.25	569.28	634.8					
Dish		190.96	195.49	175.7	249.76	218.44	180.94					
Recovered water		148.473	61.38	44.23	30.71	30.66	49.91					
cumulative water	0	148.473	209.853	254.083	284.793	315.453	365.363					
Ore (g)		1116.1										
Total solids collected		1100.047										
% solids collected		98.6										

25 HLH Run 2- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		39.37	12.79	16.07	9.3	9.37	9.05	25.86	24.67	25.84	986.3
Paper		5.64	4.46	5.47	5.41	5.35	4.87	4.71	4.73	4.76	17.24
Solids (g)		33.73	8.33	10.6	3.89	4.02	4.18	21.15	19.94	21.08	969.06
Cumulative solids (g)	0	33.73	42.06	52.66	56.55	60.57	64.75				
Squirt bottle before		579.46	571.39	587.19	565.54	596.81	612.1				
Squirt bottle after		459.81	445.1	456.03	419.26	274.53	254.5				
wash water used		119.65	126.29	131.16	146.28	322.28	357.6				
Dish + conc + water		481.85	386.81	385.83	436.72	574.78	590.88				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		137.51	56.7	68.37	36.79	30.04	48.16				
cumulative water	0	137.51	194.21	262.58	299.37	329.41	377.57				
Ore (g)		1117.5									
Total solids collected		1095.98									
% solids collected		98.07									
25 HLH Run 1- Recovery and Grade											
		Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2	
Copper Percentage (%)		0,30	6,67	1,13	0,60	0,74	0,75	0,54	0,05	0,04	
Copper Mass (g)		0,06	2,37	0,09	0,03	0,02	0,03	0,04	0,01	0,01	
Cumulative Copper Mass (g)			2,37	2,47	2,50	2,52	2,55	2,59			
Copper Grade (%)			6,67	5,64	5,08	4,83	4,51	4,08			
Copper Recovery (%)			77,90	80,93	82,00	82,73	83,81	85,07			
Nickel Percentage (%)		0,27	4,94	1,52	2,95	1,74	1,56	0,97	0,10	0,09	
Nickel Mass (g)		0,05	1,76	0,12	0,16	0,05	0,07	0,07	0,02	0,02	
Cumulative Nickel Mass (g)			1,76	1,88	2,04	2,09	2,16	2,23			
Nickel Grade (%)			4,94	4,30	4,15	4,02	3,82	3,51			
Nickel Recovery (%)			55,54	59,47	64,53	66,17	68,35	70,50			

25 HLH Run 2– Recovery and Grade									
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2
Copper Percentage (%)	0,29	7,66	1,36	0,51	0,71	0,69	0,58	0,05	0,05
Copper Mass (g)	0,06	2,58	0,11	0,05	0,03	0,03	0,02	0,01	0,01
Cumulative Copper Mass (g)		2,58	2,70	2,75	2,78	2,81	2,83		
Copper Grade (%)		7,66	6,41	5,23	4,92	4,64	4,37		
Copper Recovery (%)		77,71	81,11	82,75	83,58	84,42	85,15		
Nickel Percentage (%)	0,27	4,88	1,60	2,52	1,88	1,57	1,05	0,10	0,09
Nickel Mass (g)	0,06	1,65	0,13	0,27	0,07	0,06	0,04	0,02	0,02
Cumulative Nickel Mass (g)		1,65	1,78	2,05	2,12	2,18	2,23		
Nickel Grade (%)		4,88	4,23	3,89	3,75	3,60	3,44		
Nickel Recovery (%)		51,61	55,78	64,17	66,47	68,45	69,83		

25 LHH Run 1- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		49.17	15.71	14.9	10.42	9.01	7.77	29.39	27.19	25.21	978.9
Paper		4.61	4.66	4.63	4.65	4.76	4.73	4.74	4.66	4.64	17.16
Solids (g)		44.56	11.05	10.27	5.77	4.25	3.04	24.65	22.53	20.57	961.74
Cumulative solids (g)	0	44.56	55.61	65.88	71.65	75.9	78.94				
Squirt bottle before		580.11	577.45	588.31	574.64	606.5	615.6				
Squirt bottle after		472.04	479	466.56	449.49	320.09	290.96				
wash water used		108.07	98.45	121.75	125.15	286.41	324.64				
Dish + conc + water		547.63	408.78	416.52	471.18	570.18	558.34				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		204.04	103.79	108.8	90.5	61.08	49.72				
cumulative water	0	204.04	307.83	416.63	507.13	568.21	617.93				
Ore (g)		1120.3									
Total solids collected		1108.43									
% solids collected		98.9									

25 LHH Run 2- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		47.79	16.46	17.01	11.18	9.95	8.63	28.83	25.57	25.01	984
Paper		5.29	5.31	5.28	5.38	5.4	5.41	5.41	5.43	5.55	17.46
Solids (g)		42.5	11.15	11.73	5.8	4.55	3.22	23.42	20.14	19.46	966.54
Cumulative solids (g)	0	42.5	53.65	65.38	71.18	75.73	78.95				
Squirt bottle before		580.37	572.44	590.32	576.24	601.8	613.7				
Squirt bottle after		453.25	437.46	469.29	464.88	329.64	300.03				
wash water used		127.12	134.98	121.03	111.36	272.16	313.67				
Dish + conc + water		552.47	441.47	435.71	461.7	565.69	548.09				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		191.89	99.85	127.25	94.78	70.54	50.26				
cumulative water	0	191.89	291.74	418.99	513.77	584.31	634.57				

Ore (g)	1118
Total solids collected	1108.51
% solids collected	99.15

25 LHH Run 1- Recovery and Grade										
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2	
Copper Percentage (%)	0,28	5,89	0,90	0,49	0,53	0,50	0,43	0,05	0,04	
Copper Mass (g)	0,07	2,63	0,10	0,05	0,03	0,02	0,01	0,01	0,01	
Cumulative Copper Mass (g)		2,63	2,73	2,78	2,81	2,83	2,84			
Copper Grade (%)		5,89	4,90	4,21	3,92	3,73	3,60			
Copper Recovery (%)		79,57	82,59	84,10	85,04	85,67	86,07			
Nickel Percentage (%)	0,27	4,30	1,48	1,62	0,92	0,79	0,68	0,09	0,09	
Nickel Mass (g)	0,07	1,92	0,16	0,17	0,05	0,03	0,02	0,02	0,02	
Cumulative Nickel Mass (g)		1,92	2,08	2,25	2,30	2,33	2,35			
Nickel Grade (%)		4,30	3,74	3,41	3,21	3,08	2,98			
Nickel Recovery (%)		58,72	63,74	68,83	70,47	71,50	72,13			

25 LHH Run 2– Recovery and Grade											
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2		
Copper Percentage (%)	0,27	6,33	0,92	0,46	0,52	0,50	0,42	0,04	0,04		
Copper Mass (g)	0,06	2,69	0,10	0,05	0,03	0,02	0,01	0,01	0,01		
Cumulative Copper Mass (g)		2,69	2,79	2,85	2,88	2,90	2,91				
Copper Grade (%)		6,33	5,20	4,35	4,04	3,83	3,69				
Copper Recovery (%)		80,49	83,57	85,18	86,08	86,76	87,17				
Nickel Percentage (%)	0,26	4,38	1,59	1,54	0,87	0,78	0,63	0,10	0,09		
Nickel Mass (g)	0,06	1,86	0,18	0,18	0,05	0,04	0,02	0,02	0,02		
Cumulative Nickel Mass (g)		1,86	2,04	2,22	2,27	2,30	2,32				
Nickel Grade (%)		4,38	3,80	3,39	3,19	3,04	2,94				
Nickel Recovery (%)		56,38	61,76	67,22	68,76	69,83	70,45				
25 HHH Run 1- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		56.11	15.62	16.92	11.03	10.47	8.76	28.7	24.38	26.31	952.1
Paper		5.46	5.44	5.43	5.46	5.46	5.68	5.44	5.36	5.33	16.84
Solids (g)		50.65	10.18	11.49	5.57	5.01	3.08	23.26	19.02	20.98	935.26
Cumulative solids (g)	0	50.65	60.83	72.32	77.89	82.9	85.98				
Squirt bottle before		557.57	572.71	580.08	575.62	614.4	611.3				
Squirt bottle after		463.83	475.38	473.03	464.6	350.91	372.22				
wash water used		93.74	97.33	107.05	111.02	263.49	239.08				
Dish + conc + water		668.7	433.63	459.42	556.53	585.59	508.6				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		333.35	130.63	165.18	190.18	98.65	85.5				
cumulative water	0	333.35	463.98	629.16	819.34	917.99	1003.49				
Ore (g)		1096.8									
Total solids collected		1084.5									
% solids collected		98.9									

25 HHH Run 2- Water and Solids											
	C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings	
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		53.43	16.23	18.05	12.24	10.95	8.77	27.88	24.19	24.94	958.4
Paper		4.95	4.93	4.91	4.85	4.79	4.8	4.95	4.89	5.48	18.27
Solids (g)		48.48	11.3	13.14	7.39	6.16	3.97	22.93	19.3	19.46	940.13
Cumulative solids (g)	0	48.48	59.78	72.92	80.31	86.47	90.44				
Squirt bottle before		581.24	575.27	593.61	572.61	610.5	605.5				
Squirt bottle after		474.31	454.53	484.75	477.12	361.01	355.63				
wash water used		106.93	120.74	108.86	95.49	249.49	249.87				
Dish + conc + water		667.9	458.73	485.56	504.4	611.7	525.71				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		321.53	131.2	187.86	151.76	137.61	90.93				
cumulative water	0	321.53	452.73	640.59	792.35	929.96	1020.89				
Ore (g)		1102.7									
Total solids collected		1092.26									
% solids collected		99.05									

25 HHH Run 1– Recovery and Grade									
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2
Copper Percentage (%)	0,29	5,34	0,78	0,42	0,48	0,44	0,38	0,04	0,04
Copper Mass (g)	0,07	2,70	0,08	0,05	0,03	0,02	0,01	0,01	0,01
Cumulative Copper Mass (g)		2,70	2,78	2,83	2,86	2,88	2,89		
Copper Grade (%)		5,34	4,57	3,91	3,67	3,47	3,36		
Copper Recovery (%)		81,71	84,10	85,55	86,36	87,02	87,38		
Nickel Percentage (%)	0,27	3,32	1,48	2,34	0,88	0,74	0,59	0,10	0,09
Nickel Mass (g)	0,06	1,68	0,15	0,27	0,05	0,04	0,02	0,02	0,02
Cumulative Nickel Mass (g)		1,68	1,83	2,10	2,15	2,19	2,21		
Nickel Grade (%)		3,32	3,01	2,91	2,76	2,64	2,57		
Nickel Recovery (%)		54,04	58,87	67,48	69,07	70,26	70,84		

25 HHH Run 2– Recovery and Grade									
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2
Copper Percentage (%)	0,29	5,12	0,77	0,39	0,44	0,38	0,34	0,04	0,05
Copper Mass (g)	0,07	2,48	0,09	0,05	0,03	0,02	0,01	0,01	0,01
Cumulative Copper Mass (g)		2,48	2,57	2,62	2,65	2,68	2,69		
Copper Grade (%)		5,12	4,30	3,59	3,30	3,10	2,98		
Copper Recovery (%)		79,64	82,43	84,07	85,10	85,86	86,30		
Nickel Percentage (%)	0,26	3,66	1,41	1,47	0,72	0,60	0,48	0,09	0,09
Nickel Mass (g)	0,06	1,77	0,16	0,19	0,05	0,04	0,02	0,02	0,02
Cumulative Nickel Mass (g)		1,77	1,93	2,13	2,18	2,22	2,24		
Nickel Grade (%)		3,66	3,24	2,92	2,72	2,56	2,47		
Nickel Recovery (%)		56,82	61,92	68,12	69,81	70,99	71,59		

Appendix B: Batch flotation data for tests conducted under 60 °C

60 Zero Run 1- Water and Solids											
	C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings	
Time (min)	0	5	10	17,5	25	37,5	50	-	-	-	-
Solids + paper		47,2	9,96	15,44	10,99	14,1	11,26	29	29,26	26,66	978,67
Paper		6,9	6,62	6,34	6,36	6,37	6,39	6,9	6,4	6,52	15,55
Solids (g)		40,3	3,34	9,1	4,63	7,73	4,87	22,1	22,86	20,14	963,12
Cumulative solids (g)	0	40,3	43,64	52,74	57,37	65,1	69,97				
Squirt bottle before		570,09	573,49	577,27	572,18	614,62	609,83				
Squirt bottle after		444,58	421,29	479,74	440,76	304,94	268,94				
wash water used		125,51	152,2	97,53	131,42	309,68	340,89				
Dish + conc + water		436,2	362,97	318,99	413,8	598,42	574,2				
Dish		190,96	195,49	175,7	249,76	218,44	180,94				
Recovered water		79,43	11,94	36,66	27,99	62,57	47,5				
cumulative water	0	79,43	91,37	128,03	156,02	218,59	266,09				
Ore (g)		1116,88									
Total solids collected		1098,19									
% solids collected		98,3									

60 Zero Run 2 - Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17,5	25	37,5	50	-	-	-	-
Solids + paper		50,06	9,45	13,01	10,58	12,74	11,06	28,34	29,17	29,21	961,19
Paper		6,67	6,64	6,59	6,53	6,6	6,61	6,52	6,66	6,53	15,29
Solids (g)		43,39	2,81	6,42	4,05	6,14	4,45	21,82	22,51	22,68	945,9
Cumulative solids (g)	0	43,39	46,2	52,62	56,67	62,81	67,26				
Squirt bottle before		574,98	575,61	589,86	575,32	602,44	604,53				
Squirt bottle after		452,05	445,93	459,28	430,93	277,33	310,34				
wash water used		122,93	129,68	130,58	144,39	325,11	294,19				
Dish + conc + water		456,44	338,49	341,58	424,46	593,88	520,77				
Dish		190,96	195,49	175,7	249,76	218,44	180,94				
Recovered water		99,16	10,51	28,88	26,26	44,19	41,19				
cumulative water	0	99,16	109,67	138,55	164,81	209	250,19				
Ore (g)		1091,69									
Total solids collected		1080,17									
% solids collected		98,94									
60 Zero Run 1– Recovery and Grade											
		Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2	
Copper Percentage (%)		0,27	4,76	2,18	0,84	1,02	0,70	0,53	0,04	0,04	
Copper Mass (g)		0,06	1,92	0,07	0,08	0,05	0,05	0,03	0,01	0,01	
Cumulative Copper Mass (g)			1,92	1,99	2,07	2,11	2,17	2,19			
Copper Grade (%)			4,76	4,56	3,92	3,69	3,33	3,14			
Copper Recovery (%)			72,87	75,63	78,52	80,32	82,37	83,36			
Nickel Percentage (%)		0,25	3,62	1,70	0,84	0,95	0,69	0,50	0,07	0,07	
Nickel Mass (g)		0,06	1,46	0,06	0,08	0,04	0,05	0,02	0,02	0,01	
Cumulative Nickel Mass (g)			1,46	1,52	1,59	1,64	1,69	1,71			
Nickel Grade (%)			3,62	3,48	3,02	2,85	2,60	2,45			
Nickel Recovery (%)			59,59	61,91	65,03	66,83	69,00	70,00			

60 Zero Run 2– Recovery and Grade											
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2		
Copper Percentage (%)	0,27	4,36	2,31	0,82	0,92	0,72	0,57	0,04	0,04		
Copper Mass (g)	0,06	1,89	0,06	0,05	0,04	0,04	0,03	0,01	0,01		
Cumulative Copper Mass (g)		1,89	1,96	2,01	2,05	2,09	2,12				
Copper Grade (%)		4,36	4,24	3,82	3,61	3,33	3,15				
Copper Recovery (%)		73,94	76,48	78,54	79,99	81,73	82,73				
Nickel Percentage (%)	0,25	3,11	1,58	0,76	0,85	0,64	0,47	0,07	0,07		
Nickel Mass (g)	0,05	1,35	0,04	0,05	0,03	0,04	0,02	0,02	0,02		
Cumulative Nickel Mass (g)		1,35	1,39	1,44	1,48	1,52	1,54				
Nickel Grade (%)		3,11	3,02	2,74	2,61	2,41	2,29				
Nickel Recovery (%)		59,65	61,61	63,77	65,28	67,03	67,95				
60 LLL Run 1- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		47.31	12.12	13.2	10.45	13.32	11.26	31.12	25.43	26.97	976.59
Paper		6.81	6.83	6.34	6.52	6.56	6.57	6.8	6.48	6.48	18.56
Solids (g)		40.5	5.29	6.86	3.93	6.76	4.69	24.32	18.95	20.49	958.03
Cumulative solids (g)	0	40.5	45.79	52.65	56.58	63.34	68.03				
Squirt bottle before		568.26	570.72	582.28	573.41	598.98	611.76				
Squirt bottle after		480.03	444.31	477.41	446.31	374.89	386.13				
wash water used		88.23	126.41	104.87	127.1	224.09	225.63				
Dish + conc + water		393.3	347.07	317.05	411.78	510.41	478.89				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		73.61	19.88	29.62	30.99	61.12	67.63				
cumulative water	0	73.61	93.49	123.11	154.1	215.22	282.85				
Ore (g)		1100.89									
Total solids collected		1089.82									
% solids collected		99.0									

60 LLL Run 2- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		51.83	11.21	11.67	10.93	13.95	13.07	28.76	24.27	24.02	992.74
Paper		6.63	6.5	6.7	6.8	6.83	6.81	6.72	6.93	6.51	18.7
Solids (g)		45.2	4.71	4.97	4.13	7.12	6.26	22.04	17.34	17.51	974.04
Cumulative solids (g)	0	45.2	49.91	54.88	59.01	66.13	72.39				
Squirt bottle before		576.35	574.52	588.46	574.58	610.98	609.23				
Squirt bottle after		482.3	458.92	485.35	500.55	422.07	392.55				
wash water used		94.05	115.6	103.11	74.03	188.91	216.68				
Dish + conc + water		417.37	335.39	313.28	360.09	476.56	475.17				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		87.16	19.59	29.5	32.17	62.09	71.29				
cumulative water	0	87.16	106.75	136.25	168.42	230.51	301.8				

Ore (g)	1109.94
Total solids collected	1103.32
% solids collected	99.40

60 LLL Run 1- Recovery and Grade										
		Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2
Copper Percentage (%)		0,26	4,91	2,25	1,08	1,22	0,84	0,62	0,04	0,04
Copper Mass (g)		0,06	1,99	0,12	0,07	0,05	0,06	0,03	0,01	0,01
Cumulative Copper Mass (g)			1,99	2,11	2,18	2,23	2,29	2,32		
Copper Grade (%)			4,91	4,61	4,15	3,94	3,61	3,41		
Copper Recovery (%)			72,94	77,30	80,00	81,76	83,85	84,92		
Nickel Percentage (%)		0,24	3,20	1,37	0,94	0,88	0,62	0,40	0,07	0,07
Nickel Mass (g)		0,06	1,29	0,07	0,06	0,03	0,04	0,02	0,01	0,01
Cumulative Nickel Mass (g)			1,29	1,37	1,43	1,47	1,51	1,53		
Nickel Grade (%)			3,20	2,99	2,72	2,59	2,38	2,24		
Nickel Recovery (%)			57,32	60,53	63,40	64,92	66,76	67,60		

60 LLL Run 2– Recovery and Grade												
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2			
Copper Percentage (%)	0,26	4,55	1,91	1,06	0,95	0,70	0,53	0,04	0,04			
Copper Mass (g)	0,06	2,06	0,09	0,05	0,04	0,05	0,03	0,01	0,01			
Cumulative Copper Mass (g)		2,06	2,15	2,20	2,24	2,29	2,32					
Copper Grade (%)		4,55	4,30	4,01	3,79	3,46	3,21					
Copper Recovery (%)		74,89	78,16	80,08	81,51	83,32	84,54					
Nickel Percentage (%)	0,25	3,20	1,37	0,94	0,88	0,62	0,40	0,07	0,07			
Nickel Mass (g)	0,05	1,45	0,06	0,05	0,04	0,04	0,03	0,01	0,01			
Cumulative Nickel Mass (g)		1,45	1,51	1,56	1,59	1,64	1,66					
Nickel Grade (%)		3,20	3,03	2,84	2,70	2,47	2,30					
Nickel Recovery (%)		60,16	62,85	64,80	66,31	68,13	69,18					
60 HLL Run 1- Water and Solids												
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings	
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-	
Solids + paper		47.68	11.73	12.34	10.64	13.37	11.93	28.03	23.64	22.53	970.73	
Paper		6.32	6.37	6.29	6.36	6.37	6.41	6.29	6.37	6.33	14.55	
Solids (g)		41.36	5.36	6.05	4.28	7	5.52	21.74	17.27	16.2	956.18	
Cumulative solids (g)	0	41.36	46.72	52.77	57.05	64.05	69.57					
Squirt bottle before		575.11	576.15	574.26	575.82	609.15	612.21					
Squirt bottle after		473.64	470.54	446.75	493.35	406.74	411.37					
wash water used		101.47	105.61	127.51	82.47	202.41	200.84					
Dish + conc + water		397.84	347.48	357.95	380.23	512.16	439.31					
Dish		190.96	195.49	175.7	249.76	218.44	180.94					
Recovered water		64.05	41.02	48.69	43.72	84.31	52.01					
cumulative water	0	64.05	105.07	153.76	197.48	281.79	333.8					
Ore (g)		1101.67										
Total solids collected		1080.96										
% solids collected		98.1										

60 HLL Run 2- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		45.77	10	11.99	11.68	14.3	11.17	26.18	27.6	28.74	960.24
Paper		6.39	6.33	6.31	6.52	6.33	6.38	6.39	6.55	6.55	14.64
Solids (g)		39.38	3.67	5.68	5.16	7.97	4.79	19.79	21.05	22.19	945.6
Cumulative solids (g)	0	39.38	43.05	48.73	53.89	61.86	66.65				
Squirt bottle before		577.34	576.44	587.16	493.29	406.71	411.35				
Squirt bottle after		456.66	429.73	459.16	384.46	182.31	190.18				
wash water used		120.68	146.71	128	108.83	224.4	221.17				
Dish + conc + water		428.97	359.28	352.22	415.69	530.03	463.35				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		77.95	13.41	42.84	51.94	79.22	56.45				
cumulative water	0	77.95	91.36	134.2	186.14	265.36	321.81				
Ore (g)		1101.13									
Total solids collected		1075.28									
% solids collected		97.65									
60 HLL Run 1- Recovery and Grade											
		Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2	
Copper Percentage (%)		0,265	4,159	1,532	0,828	0,773	0,566	0,467	0,038	0,043	
Copper Mass (g)		0,058	1,720	0,082	0,050	0,033	0,040	0,026	0,007	0,007	
Cumulative Copper Mass (g)			1,720	1,802	1,853	1,886	1,925	1,951			
Copper Grade (%)			4,159	3,858	3,511	3,305	3,006	2,804			
Copper Recovery (%)			73,208	76,702	78,833	80,241	81,928	83,026			
Nickel Percentage (%)		0,249	2,973	1,621	1,022	0,908	0,601	0,443	0,073	0,075	
Nickel Mass (g)		0,054	1,230	0,087	0,062	0,039	0,042	0,024	0,013	0,012	
Cumulative Nickel Mass (g)			1,230	1,316	1,378	1,417	1,459	1,484			
Nickel Grade (%)			2,973	2,818	2,612	2,484	2,278	2,133			
Nickel Recovery (%)			55,511	59,433	62,225	63,979	65,879	66,983			

60 HLL Run 2 – Recovery and Grade												
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2			
Copper Percentage (%)	0,27	4,94	2,07	1,04	0,97	0,72	0,57	0,04	0,04			
Copper Mass (g)	0,05	1,94	0,08	0,06	0,05	0,06	0,03	0,01	0,01			
Cumulative Copper Mass (g)		1,94	2,02	2,08	2,13	2,19	2,21					
Copper Grade (%)		4,94	4,69	4,27	3,95	3,54	3,32					
Copper Recovery (%)		74,57	77,49	79,74	81,67	83,89	84,93					
Nickel Percentage (%)	0,26	3,31	1,62	1,02	0,91	0,60	0,44	0,07	0,07			
Nickel Mass (g)	0,05	1,30	0,06	0,06	0,05	0,05	0,02	0,02	0,02			
Cumulative Nickel Mass (g)		1,30	1,36	1,42	1,47	1,52	1,54					
Nickel Grade (%)		3,31	3,17	2,92	2,72	2,45	2,31					
Nickel Recovery (%)		57,47	60,10	62,66	64,72	66,84	67,77					
60 LHL Run 1- Water and Solids												
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings	
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-	
Solids + paper		57.75	14.1	14.87	14.29	16.46	13.48	29.65	27.8	29.89	961.05	
Paper		7.14	7.04	7.07	7.07	6.98	6.98	7.1	7.13	7.11	18.22	
Solids (g)		50.61	7.06	7.8	7.22	9.48	6.5	22.55	20.67	22.78	942.83	
Cumulative solids (g)	0	50.61	57.67	65.47	72.69	82.17	88.67					
Squirt bottle before		577.4	574.75	590.79	576.29	606.6	612.88					
Squirt bottle after		475.11	460.59	487.94	476.31	378.15	412.63					
wash water used		102.29	114.16	102.85	99.98	228.45	200.25					
Dish + conc + water		487.64	366.97	364.67	459.8	606.42	511.42					
Dish		190.96	195.49	175.7	249.76	218.44	180.94					
Recovered water		143.78	50.26	78.32	102.84	150.05	123.73					
cumulative water	0	143.78	194.04	272.36	375.2	525.25	648.98					
Ore (g)		1103.63										
Total solids collected		1097.5										
% solids collected		99.4										

60 LHL Run 2- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		57.76	11.99	13.04	15.05	15.28	13.11	30.02	22.47	24.27	977.86
Paper		6.93	6.94	6.94	7.09	7.25	7.37	7.28	7.35	7.35	17.95
Solids (g)		50.83	5.05	6.1	7.96	8.03	5.74	22.74	15.12	16.92	959.91
Cumulative solids (g)	0	50.83	55.88	61.98	69.94	77.97	83.71				
Squirt bottle before		578.27	575.14	590.98	577.08	609.53	603.39				
Squirt bottle after		487.71	489.44	512.44	505.95	413.33	434.12				
wash water used		90.56	85.7	78.54	71.13	196.2	169.27				
Dish + conc + water		475.88	322.19	342.18	425.01	571.52	485.14				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		143.53	35.95	81.84	96.16	148.85	129.19				
cumulative water	0	143.53	179.48	261.32	357.48	506.33	635.52				

Ore (g)	1109.14
Total solids collected	1098.4
% solids collected	99.03

60 LHL Run 1- Recovery and Grade										
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2	
Copper Percentage (%)	0,28	4,33	1,33	0,69	0,61	0,45	0,33	0,04	0,04	
Copper Mass (g)	0,06	2,19	0,09	0,05	0,04	0,04	0,02	0,01	0,01	
Cumulative Copper Mass (g)		2,19	2,29	2,34	2,38	2,43	2,45			
Copper Grade (%)		4,33	3,96	3,57	3,28	2,95	2,76			
Copper Recovery (%)		78,15	81,49	83,43	85,00	86,52	87,28			
Nickel Percentage (%)	0,26	2,99	1,01	0,66	0,50	0,38	0,27	0,07	0,07	
Nickel Mass (g)	0,06	1,51	0,07	0,05	0,04	0,04	0,02	0,01	0,02	
Cumulative Nickel Mass (g)		1,51	1,58	1,63	1,67	1,71	1,72			
Nickel Grade (%)		2,99	2,75	2,50	2,30	2,08	1,94			
Nickel Recovery (%)		62,55	65,49	67,63	69,11	70,59	71,31			

60 LHL Run 2– Recovery and Grade												
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2			
Copper Percentage (%)	0,28	4,03	1,25	0,64	0,66	0,51	0,41	0,03	0,04			
Copper Mass (g)	0,06	2,05	0,06	0,04	0,05	0,04	0,02	0,01	0,01			
Cumulative Copper Mass (g)		2,05	2,11	2,15	2,20	2,25	2,27					
Copper Grade (%)		4,03	3,78	3,47	3,15	2,88	2,71					
Copper Recovery (%)		77,70	80,09	81,57	83,55	85,12	86,02					
Nickel Percentage (%)	0,25	2,82	0,98	0,62	0,54	0,40	0,29	0,07	0,07			
Nickel Mass (g)	0,06	1,43	0,05	0,04	0,04	0,03	0,02	0,01	0,01			
Cumulative Nickel Mass (g)		1,43	1,48	1,52	1,56	1,60	1,61					
Nickel Grade (%)		2,82	2,65	2,45	2,24	2,05	1,93					
Nickel Recovery (%)		62,08	64,23	65,87	67,73	69,11	69,84					
60 HHL Run 1- Water and Solids												
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings	
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-	
Solids + paper		58.98	13.46	12.94	12.84	16.38	11.88	29.68	28.04	24.04	958.36	
Paper		7.3	7.21	7.14	7.08	6.95	6.94	6.93	7.19	6.58	18.33	
Solids (g)		51.68	6.25	5.8	5.76	9.43	4.94	22.75	20.85	17.46	940.03	
Cumulative solids (g)	0	51.68	57.93	63.73	69.49	78.92	83.86					
Squirt bottle before		577.93	564.05	591.03	576.22	615.42	617.25					
Squirt bottle after		468.26	462.62	493.53	500.62	378.65	341.29					
wash water used		109.67	101.43	97.5	75.6	236.77	275.96					
Dish + conc + water		536.18	349.13	328.25	402.82	571.89	604.17					
Dish		218.44	180.94	175.7	249.76	190.96	195.49					
Recovered water		156.39	60.51	49.25	71.7	134.73	127.78					
cumulative water	0	156.39	216.9	266.15	337.85	472.58	600.36					
Ore (g)		1091.42										
Total solids collected		1084.95										
% solids collected		99.41										

60 HHL Run 2- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		54.54	12.63	14.86	10.82	15.17	17.6	32.89	27.13	24.5	975.58
Paper		6.57	6.64	6.7	6.68	6.68	6.78	6.78	6.84	6.8	18.34
Solids (g)		47.97	5.99	8.16	4.14	8.49	10.82	26.11	20.29	17.7	957.24
Cumulative solids (g)	0	47.97	53.96	62.12	66.26	74.75	85.57				
Squirt bottle before		575.91	576.76	587.34	578.27	607.47	614.31				
Squirt bottle after		471.36	469	489.99	488.29	371.45	375.62				
wash water used		104.55	107.76	97.35	89.98	236.02	238.69				
Dish + conc + water		485.95	370.09	355.53	394.14	599.95	581.09				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		142.47	60.85	74.32	50.26	137	150.64				
cumulative water	0	142.47	203.32	277.64	327.9	464.9	615.54				

Ore (g)	1113.87
Total solids collected	1106.91
% solids collected	99.38

60 HHL Run 1- Recovery and Grade										
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2	
Copper Percentage (%)	0,28	4,24	0,99	0,56	0,57	0,45	0,35	0,04	0,04	
Copper Mass (g)	0,06	2,19	0,06	0,03	0,03	0,04	0,02	0,01	0,01	
Cumulative Copper Mass (g)		2,19	2,25	2,28	2,32	2,36	2,38			
Copper Grade (%)		4,24	3,89	3,58	3,33	2,99	2,83			
Copper Recovery (%)		80,05	82,31	83,48	84,67	86,22	86,86			
Nickel Percentage (%)	0,25	2,88	0,79	0,64	0,48	0,36	0,28	0,07	0,07	
Nickel Mass (g)	0,06	1,49	0,05	0,04	0,03	0,03	0,01	0,01	0,01	
Cumulative Nickel Mass (g)		1,49	1,54	1,58	1,60	1,64	1,65			
Nickel Grade (%)		2,88	2,66	2,47	2,31	2,08	1,97			
Nickel Recovery (%)		63,53	65,63	67,22	68,40	69,86	70,44			

60 HHL Run 2- Recovery and Grade												
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2			
Copper Percentage (%)	0,27	4,31	1,26	0,68	0,70	0,72	0,42	0,03	0,04			
Copper Mass (g)	0,07	2,07	0,08	0,06	0,03	0,06	0,05	0,01	0,01			
Cumulative Copper Mass (g)		2,07	2,14	2,20	2,23	2,29	2,33					
Copper Grade (%)		4,31	3,97	3,54	3,36	3,06	2,73					
Copper Recovery (%)		76,92	79,73	81,78	82,86	85,15	86,82					
Nickel Percentage (%)	0,23	3,03	1,05	0,65	0,59	0,53	0,32	0,07	0,07			
Nickel Mass (g)	0,06	1,45	0,06	0,05	0,02	0,04	0,03	0,01	0,01			
Cumulative Nickel Mass (g)		1,45	1,52	1,57	1,59	1,64	1,67					
Nickel Grade (%)		3,03	2,81	2,53	2,41	2,19	1,96					
Nickel Recovery (%)		61,10	63,75	65,99	67,01	68,89	70,36					
60 LLH Run 1- Water and Solids												
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings	
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-	
Solids + paper		58.7	15.35	13.58	13.64	13.92	10.94	31.2	23.66	23.42		973.1
Paper		6.42	6.31	6.38	6.4	6.34	6.38	6.56	6.48	6.42		14.6
Solids (g)		52.28	9.04	7.2	7.24	7.58	4.56	24.64	17.18	17		958.5
Cumulative solids (g)	0	52.28	61.32	68.52	75.76	83.34	87.9					
Squirt bottle before		575.02	558.54	590.48	573.34	609.96	615.14					
Squirt bottle after		469.49	451.7	488.06	476.34	364.87	463.54					
wash water used		105.53	106.84	102.42	97	245.09	151.6					
Dish + conc + water		502.32	353.42	368.15	415	531.84	405.49					
Dish		190.96	195.49	175.7	249.76	218.44	180.94					
Recovered water		153.55	42.05	82.83	61	60.73	68.39					
cumulative water	0	153.55	195.6	278.43	339.43	400.16	468.55					
Ore (g)		1123.46										
Total solids collected		1105.22										
% solids collected		98.4										

60 LLH Run 2- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		58.84	11.36	15.5	12.72	12.48	11.11	26.57	36.11	26.82	965.69
Paper		6.42	6.46	6.38	6.46	6.32	6.43	6.87	6.78	6.75	14.79
Solids (g)		52.42	4.9	9.12	6.26	6.16	4.68	19.7	29.33	20.07	950.9
Cumulative solids (g)	0	52.42	57.32	66.44	72.7	78.86	83.54				
Squirt bottle before		576.38	572.43	588.09	576.78	612.31	611.82				
Squirt bottle after		461.18	449.08	484.7	472.6	366.81	367.36				
wash water used		115.2	123.35	103.39	104.18	245.5	244.46				
Dish + conc + water		494.18	376.48	360.83	421.81	532.95	498.15				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		135.6	52.74	72.62	61.61	62.85	68.07				
cumulative water	0	135.6	188.34	260.96	322.57	385.42	453.49				
Ore (g)		1116.6									
Total solids collected		1103.54									
% solids collected		98.83									
60 LLH Run 1- Recovery and Grade											
		Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2	
Copper Percentage (%)		0,28	4,36	1,54	0,85	0,71	0,52	0,45	0,04	0,03	
Copper Mass (g)		0,07	2,28	0,14	0,06	0,05	0,04	0,02	0,01	0,01	
Cumulative Copper Mass (g)			2,28	2,42	2,48	2,53	2,57	2,59			
Copper Grade (%)			4,36	3,94	3,62	3,34	3,09	2,95			
Copper Recovery (%)			77,63	82,36	84,45	86,20	87,55	88,24			
Nickel Percentage (%)		0,25	3,20	1,20	0,85	0,64	0,47	0,40	0,07	0,08	
Nickel Mass (g)		0,06	1,67	0,11	0,06	0,05	0,04	0,02	0,01	0,01	
Cumulative Nickel Mass (g)			1,67	1,78	1,84	1,89	1,92	1,94			
Nickel Grade (%)			3,20	2,90	2,69	2,49	2,31	2,21			
Nickel Recovery (%)			61,77	65,77	68,03	69,73	71,05	71,72			

60 LLH Run 2– Recovery and Grade												
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2			
Copper Percentage (%)	0,28	5,04	1,72	0,91	0,78	0,63	0,50	0,04	0,03			
Copper Mass (g)	0,05	2,64	0,08	0,08	0,05	0,04	0,02	0,01	0,01			
Cumulative Copper Mass (g)		2,64	2,73	2,81	2,86	2,90	2,92					
Copper Grade (%)		5,04	4,76	4,23	3,93	3,68	3,50					
Copper Recovery (%)		80,81	83,39	85,92	87,40	88,58	89,30					
Nickel Percentage (%)	0,24	3,52	1,37	0,87	0,71	0,56	0,46	0,07	0,09			
Nickel Mass (g)	0,05	1,85	0,07	0,08	0,04	0,03	0,02	0,02	0,02			
Cumulative Nickel Mass (g)		1,85	1,91	1,99	2,04	2,07	2,09					
Nickel Grade (%)		3,52	3,34	3,00	2,80	2,63	2,51					
Nickel Recovery (%)		63,96	66,30	69,04	70,58	71,77	72,53					
60 HLH Run 1- Water and Solids												
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings	
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-	
Solids + paper		51.43	10.3	13.34	12.1	13.94	10.47	25.95	29.15	26.44		984.08
Paper		5.2	5.27	6.27	6.25	6.27	6.26	5.22	6.31	6.43		17.82
Solids (g)		46.23	5.03	7.07	5.85	7.67	4.21	20.73	22.84	20.01		966.26
Cumulative solids (g)	0	46.23	51.26	58.33	64.18	71.85	76.06					
Squirt bottle before		575.11	579.2	594.01	572.12	610.91	613.64					
Squirt bottle after		528.89	451.25	457.13	463.13	383.59	421.1					
wash water used		46.22	127.95	136.88	108.99	227.32	192.54					
Dish + conc + water		432.41	352.44	360.87	410.93	529.36	420.5					
Dish		190.96	195.49	175.7	249.76	218.44	180.94					
Recovered water		149	23.97	41.22	46.33	75.93	42.81					
cumulative water	0	149	172.97	214.19	260.52	336.45	379.26					
Ore (g)		1121.3										
Total solids collected		1105.9										
% solids collected		98.6										

60 HLH Run 2- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		51.19	11.67	11.12	11.78	13.64	10.42	23.36	24.24	25.86	1003.63
Paper		6.53	5.88	6.08	6.02	6.51	6.43	5.64	6.45	6.54	17.86
Solids (g)		44.66	5.79	5.04	5.76	7.13	3.99	17.72	17.79	19.32	985.77
Cumulative solids (g)	0	44.66	50.45	55.49	61.25	68.38	72.37				
Squirt bottle before		545.17	565.82	571.87	556.71	607.73	591.32				
Squirt bottle after		457.15	443.12	465.6	444.27	386.96	389.21				
wash water used		88.02	122.7	106.27	112.44	220.77	202.11				
Dish + conc + water		456.91	350.4	332.36	411.55	517.1	429.84				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		133.27	26.42	45.35	43.59	70.76	42.8				
cumulative water	0	133.27	159.69	205.04	248.63	319.39	362.19				

Ore (g)	1110.04
Total solids collected	1112.97
% solids collected	100.26

60 HLH Run 1– Recovery and Grade										
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2	
Copper Percentage (%)	0,27	5,76	2,24	1,00	0,94	0,70	0,56	0,04	0,04	
Copper Mass (g)	0,06	2,66	0,11	0,07	0,05	0,05	0,02	0,01	0,01	
Cumulative Copper Mass (g)		2,66	2,78	2,85	2,90	2,95	2,98			
Copper Grade (%)		5,76	5,42	4,88	4,52	4,11	3,92			
Copper Recovery (%)		78,69	82,03	84,11	85,72	87,31	88,01			
Nickel Percentage (%)	0,26	4,65	2,02	1,37	1,02	0,47	0,47	0,08	0,08	
Nickel Mass (g)	0,05	2,15	0,10	0,10	0,06	0,04	0,02	0,02	0,02	
Cumulative Nickel Mass (g)		2,15	2,25	2,35	2,41	2,44	2,46			
Nickel Grade (%)		4,65	4,39	4,03	3,75	3,40	3,24			
Nickel Recovery (%)		66,01	69,13	72,11	73,94	75,04	75,64			

60 HLH Run 2– Recovery and Grade												
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2			
Copper Percentage (%)	0,28	7,55	2,68	1,29	1,21	0,95	0,74	0,05	0,04			
Copper Mass (g)	0,05	3,37	0,16	0,06	0,07	0,07	0,03	0,01	0,01			
Cumulative Copper Mass (g)		3,37	3,53	3,59	3,66	3,73	3,76					
Copper Grade (%)		7,55	6,99	6,47	5,98	5,45	5,19					
Copper Recovery (%)		80,14	83,83	85,38	87,04	88,65	89,36					
Nickel Percentage (%)	0,27	5,62	2,87	1,89	1,49	0,97	0,66	0,08	0,08			
Nickel Mass (g)	0,05	2,51	0,17	0,10	0,09	0,07	0,03	0,01	0,02			
Cumulative Nickel Mass (g)		2,51	2,67	2,77	2,86	2,92	2,95					
Nickel Grade (%)		5,62	5,30	4,99	4,66	4,28	4,08					
Nickel Recovery (%)		66,29	70,69	73,20	75,47	77,29	77,99					
60 LHH Run 1- Water and Solids												
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings	
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-	
Solids + paper		59.41	14.09	14.75	15.25	14.62	10.28	25.29	27.66	23.61	983.23	
Paper		8.48	8.62	8.64	9.44	6.61	5.42	6.6	9.63	8.82	20.44	
Solids (g)		50.93	5.47	6.11	5.81	8.01	4.86	18.69	18.03	14.79	962.79	
Cumulative solids (g)	0	50.93	56.4	62.51	68.32	76.33	81.19					
Squirt bottle before		575.05	572.39	589.59	575.96	615.89	614.56					
Squirt bottle after		370.25	486.52	463.69	494.72	369.24	431.13					
wash water used		204.8	85.87	125.9	81.24	246.65	183.43					
Dish + conc + water		490.93	341.18	343.91	381.1	518.58	426.03					
Dish		190.96	195.49	175.7	249.76	218.44	180.94					
Recovered water		44.24	54.35	36.2	44.29	45.48	56.8					
cumulative water	0	44.24	98.59	134.79	179.08	224.56	281.36					
Ore (g)		1100.9										
Total solids collected		1095.49										
% solids collected		99.5										

60 LHH Run 2- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		55.25	12.23	12.68	14.47	16.15	11.33	26.69	23.68	23.2	975.44
Paper		6.55	6.54	6.53	6.54	6.43	6.58	6.49	6.61	6.31	16.16
Solids (g)		48.7	5.69	6.15	7.93	9.72	4.75	20.2	17.07	16.89	959.28
Cumulative solids (g)	0	48.7	54.39	60.54	68.47	78.19	82.94				
Squirt bottle before		545.17	450.69	472.43	486.34	617.39	616.74				
Squirt bottle after		340.25	346.52	363.69	394.72	409.24	431.13				
wash water used		204.92	104.17	108.74	91.62	208.15	185.61				
Dish + conc + water		493.7	349.06	334.88	399.28	477.85	433.69				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		49.12	43.71	44.29	49.97	41.54	62.39				
cumulative water	0	49.12	92.83	137.12	187.09	228.63	291.02				

Ore (g)	1105.12
Total solids collected	1096.38
% solids collected	99.21

60 LHH Run 1- Recovery and Grade										
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2	
Copper Percentage (%)	0,28	5,32	1,97	1,02	0,81	0,63	0,51	0,04	0,04	
Copper Mass (g)	0,05	2,71	0,11	0,06	0,05	0,05	0,02	0,01	0,01	
Cumulative Copper Mass (g)		2,71	2,82	2,88	2,92	2,98	3,00			
Copper Grade (%)		5,32	4,99	4,60	4,28	3,90	3,70			
Copper Recovery (%)		80,74	83,94	85,80	87,20	88,72	89,46			
Nickel Percentage (%)	0,27	4,53	1,65	1,20	0,81	0,60	0,42	0,08	0,08	
Nickel Mass (g)	0,05	2,31	0,09	0,07	0,05	0,05	0,02	0,01	0,01	
Cumulative Nickel Mass (g)		2,31	2,40	2,47	2,52	2,57	2,59			
Nickel Grade (%)		4,53	4,25	3,95	3,69	3,36	3,19			
Nickel Recovery (%)		68,63	71,32	73,49	74,90	76,32	76,93			

60 LHH Run 2– Recovery and Grade												
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2			
Copper Percentage (%)	0,28	5,72	1,57	0,85	0,77	0,55	0,44	0,03	0,03			
Copper Mass (g)	0,06	2,78	0,09	0,05	0,06	0,05	0,02	0,01	0,01			
Cumulative Copper Mass (g)		2,78	2,87	2,93	2,99	3,04	3,06					
Copper Grade (%)		5,72	5,28	4,83	4,36	3,89	3,69					
Copper Recovery (%)		81,91	84,54	86,09	87,88	89,46	90,07					
Nickel Percentage (%)	0,26	4,47	1,60	1,08	0,81	0,50	0,39	0,07	0,08			
Nickel Mass (g)	0,05	2,18	0,09	0,07	0,06	0,05	0,02	0,01	0,01			
Cumulative Nickel Mass (g)		2,18	2,27	2,33	2,40	2,45	2,46					
Nickel Grade (%)		4,47	4,17	3,85	3,50	3,13	2,97					
Nickel Recovery (%)		67,96	70,80	72,88	74,88	76,41	77,00					
60 HHH Run 1- Water and Solids												
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings	
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-	
Solids + paper		58.72	12.3	12.96	12.93	14.5	12.27	29.2	23.24	22.57	973.44	
Paper		7.53	6.61	6.46	6.64	6.66	6.59	7.54	7.42	6.24	18.03	
Solids (g)		51.19	5.69	6.5	6.29	7.84	5.68	21.66	15.82	16.33	955.41	
Cumulative solids (g)	0	51.19	56.88	63.38	69.67	77.51	83.19					
Squirt bottle before		571.3	578.12	586.81	577.06	609.03	612.25					
Squirt bottle after		452.43	459.06	479.9	479.15	330.41	371.21					
wash water used		118.87	119.06	106.91	97.91	278.62	241.04					
Dish + conc + water		514.29	374.12	360.26	444.37	623.53	530.17					
Dish		190.96	195.49	175.7	249.76	218.44	180.94					
Recovered water		153.27	53.88	71.15	90.41	118.63	102.51					
cumulative water	0	153.27	207.15	278.3	368.71	487.34	589.85					
Ore (g)		1097.82										
Total solids collected		1092.41										
% solids collected		99.5										

60 HHH Run 2- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		54.33	14.21	12.68	12.24	15.6	11.33	27.32	24.39	24.33	986.75
Paper		5.12	6.53	6.56	6.53	6.42	5.91	6.81	7.78	6.07	20.11
Solids (g)		49.21	7.68	6.12	5.71	9.18	5.42	20.51	16.61	18.26	966.64
Cumulative solids (g)	0	49.21	56.89	63.01	68.72	77.9	83.32				
Squirt bottle before		452.43	459.06	479.9	479.15	615.27	611.79				
Squirt bottle after		345.45	350.35	370.46	418.24	376.97	358.24				
wash water used		106.98	108.71	109.44	60.91	238.3	253.55				
Dish + conc + water		488.36	377.62	348.3	412.35	586.75	534.49				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		141.21	65.74	57.04	95.97	120.83	94.58				
cumulative water	0	141.21	206.95	263.99	359.96	480.79	575.37				

Ore (g)	1112.82
Total solids collected	1105.34
% solids collected	99.33

60 HHH Run 1- Recovery and Grade										
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2	
Copper Percentage (%)	0,27	5,52	1,58	0,84	0,44	0,50	0,65	0,04	0,04	
Copper Mass (g)	0,06	2,82	0,09	0,05	0,03	0,04	0,04	0,01	0,01	
Cumulative Copper Mass (g)		2,82	2,91	2,97	3,00	3,03	3,07			
Copper Grade (%)		5,52	5,12	4,68	4,30	3,92	3,69			
Copper Recovery (%)		82,30	84,93	86,52	87,32	88,47	89,56			
Nickel Percentage (%)	0,26	4,36	1,37	0,98	0,40	0,44	0,64	0,08	0,08	
Nickel Mass (g)	0,06	2,23	0,08	0,06	0,02	0,03	0,04	0,01	0,01	
Cumulative Nickel Mass (g)		2,23	2,31	2,37	2,40	2,43	2,47			
Nickel Grade (%)		4,36	4,06	3,75	3,44	3,14	2,97			
Nickel Recovery (%)		68,48	70,88	72,83	73,59	74,66	75,77			

60 HHH Run 2– Recovery and Grade									
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2
Copper Percentage (%)	0,28	5,17	1,25	0,43	0,81	0,74	0,56	0,04	0,03
Copper Mass (g)	0,06	2,54	0,10	0,03	0,05	0,07	0,03	0,01	0,01
Cumulative Copper Mass (g)		2,54	2,64	2,66	2,71	2,78	2,81		
Copper Grade (%)		5,17	4,64	4,23	3,94	3,57	3,37		
Copper Recovery (%)		80,50	83,54	84,38	85,83	88,00	88,95		
Nickel Percentage (%)	0,26	4,06	1,22	0,41	1,15	0,78	0,51	0,08	0,07
Nickel Mass (g)	0,05	2,00	0,09	0,03	0,07	0,07	0,03	0,01	0,01
Cumulative Nickel Mass (g)		2,00	2,09	2,11	2,18	2,25	2,28		
Nickel Grade (%)		4,06	3,67	3,36	3,17	2,89	2,74		
Nickel Recovery (%)		65,52	68,60	69,42	71,58	73,92	74,83		

Appendix C: Batch flotation data for tests conducted under 40 °C

K zero 40 Run 1- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		30.18	10.25	18.28	15.56	14.56	12.63	25.62	21.56	23.73	977.19
Paper		6.37	6.33	6.42	6.37	6.41	6.53	8.67	6.39	6.26	16.08
Solids (g)		23.81	3.92	11.86	9.19	8.15	6.1	16.95	15.17	17.47	961.11
Cumulative solids (g)	0	23.81	27.73	39.59	48.78	56.93	63.03				
Squirt bottle before		579.21	572.95	590.97	575.07	596.95	607.31				
Squirt bottle after		468.77	436.76	443.26	429.37	290.05	361.39				
wash water used		110.44	136.19	147.71	145.7	306.9	245.92				
Dish + conc + water		367.64	341.74	364.85	437.3	564.62	465.49				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		42.43	6.14	29.58	32.65	31.13	32.53				
cumulative water	0	42.43	48.57	78.15	110.8	141.93	174.46				
Ore (g)		1094.19									
Total solids collected		1073.73									
% solids collected		98.1									

K Zero 40 Run 2- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17.5	25	37.5	50	-	-	-	-
Solids + paper		28.05	12.29	22.23	18.9	14.86	16.91	27.47	26.86	28.65	985.17
Paper		8.76	8.71	8.5	8.49	8.63	8.6	8.7	8.67	8.66	19.83
Solids (g)		19.29	3.58	13.73	10.41	6.23	8.31	18.77	18.19	19.99	965.34
Cumulative solids (g)	0	19.29	22.87	36.6	47.01	53.24	61.55				
Squirt bottle before		468.77	436.76	443.26	429.37	592.12	605				
Squirt bottle after		316.8	353.63	282.97	279.78	231.87	152.69				
wash water used		151.97	83.13	160.29	149.59	360.25	452.31				
Dish + conc + water		392.83	291.3	381.61	439.06	618.3	671.96				
Dish		190.96	195.49	175.7	249.76	218.44	180.94				
Recovered water		30.61	9.1	31.89	29.3	33.38	30.4				
cumulative water	0	30.61	39.71	71.6	100.9	134.28	164.68				

Ore (g)	1128.2
Total solids collected	1083.84
% solids collected	96.07

K Zero 40 Run 1– Recovery and Grade										
		Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2
Copper Percentage (%)		0,29	10,77	3,25	1,02	0,98	1,01	0,85	0,04	0,05
Copper Mass (g)		0,05	2,56	0,13	0,12	0,09	0,08	0,05	0,01	0,01
Cumulative Copper Mass (g)			2,56	2,69	2,81	2,90	2,98	3,04		
Copper Grade (%)			10,77	9,70	7,10	5,95	5,24	4,82		
Copper Recovery (%)			73,52	77,16	80,64	83,23	85,59	87,07		
Nickel Percentage (%)		0,27	6,89	3,87	2,14	1,65	1,38	0,89	0,08	0,08
Nickel Mass (g)		0,05	1,64	0,15	0,25	0,15	0,11	0,05	0,01	0,01
Cumulative Nickel Mass (g)			1,64	1,79	2,05	2,20	2,31	2,36		
Nickel Grade (%)			6,89	6,46	5,17	4,50	4,06	3,75		
Nickel Recovery (%)			51,68	56,46	64,45	69,23	72,78	74,50		

K Zero 40 Run 2– Recovery and Grade											
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2		
Copper Percentage (%)	0,28	12,55	4,92	1,51	1,32	1,24	1,05	0,05	0,05		
Copper Mass (g)	0,05	2,42	0,18	0,21	0,14	0,08	0,09	0,01	0,01		
Cumulative Copper Mass (g)		2,42	2,60	2,80	2,94	3,02	3,11				
Copper Grade (%)		12,55	11,36	7,66	6,26	5,67	5,05				
Copper Recovery (%)		67,08	71,96	77,70	81,50	83,63	86,05				
Nickel Percentage (%)	0,27	7,51	5,49	2,67	2,11	1,69	1,35	0,08	0,08		
Nickel Mass (g)	0,05	1,45	0,20	0,37	0,22	0,11	0,11	0,01	0,02		
Cumulative Nickel Mass (g)		1,45	1,65	2,01	2,23	2,34	2,45				
Nickel Grade (%)		7,51	7,20	5,50	4,75	4,39	3,98				
Nickel Recovery (%)		44,45	50,48	61,72	68,44	71,67	75,11				
40 MMM Run 1- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17,5	25	37,5	50	-	-	-	-
Solids + paper		55,61	18,14	16,75	18,78	19,7	17,68	27,4	29,9	10,28	960,15
Paper		10,3	10,32	10,34	10,29	10,21	10,15	10,37	10,25	28,74	16,28
Solids (g)		45,31	7,82	6,41	8,49	9,49	7,53	17,03	19,65	-18,46	943,87
Cumulative solids (g)	0	45,31	53,13	59,54	68,03	77,52	85,05				
Squirt bottle before		579,51	578,57	593,86	578,88	613,13	614,99				
Squirt bottle after		454,65	446,36	449,79	456,17	319,46	282,89				
wash water used		124,86	132,21	144,07	122,71	293,67	332,1				
Dish + conc + water		480,18	386,72	390,01	485,93	621,55	663,03				
Dish		190,96	195,49	175,7	249,76	218,44	180,94				
Recovered water		119,05	51,2	63,83	104,97	99,95	142,46				
cumulative water	0	119,05	170,25	234,08	339,05	439	581,46				
Ore (g)		1102,19									
Total solids collected		1047,14									
% solids collected		95,0									

40 MMM Run 2- Water and Solids											
		C1	C2	C3	C4	C5	C6	Feed	Tails 1	Tails 2	Tailings
Time (min)	0	5	10	17,5	25	37,5	50	-	-	-	-
Solids + paper		51,15	18,85	17,88	18,22	19,2	17,31	32,46	29,51	30,21	970,64
Paper		9,95	9,94	9,99	10,34	10,36	10,36	9,85	9,75	9,89	16,42
Solids (g)		41,2	8,91	7,89	7,88	8,84	6,95	22,61	19,76	20,32	954,22
Cumulative solids (g)	0	41,2	50,11	58	65,88	74,72	81,67				
Squirt bottle before		568,16	575,11	590,46	578,82	608,3	618,41				
Squirt bottle after		439,06	430,72	448,49	454,73	314,91	305,31				
wash water used		129,1	144,39	141,97	124,09	293,39	313,1				
Dish + conc + water		483,5	406,68	391,52	473,81	657,72	625,42				
Dish		190,96	195,49	175,7	249,76	218,44	180,94				
Recovered water		122,24	57,89	65,96	92,08	137,05	124,43				
cumulative water	0	122,24	180,13	246,09	338,17	475,22	599,65				
Ore (g)		1106,11									
Total solids collected		1098,58									
% solids collected		99,32									
40 MMM Run 1- Recovery and Grade											
		Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2	
Copper Percentage (%)		0,29	5,34	0,78	0,42	0,48	0,44	0,38	0,04	0,04	
Copper Mass (g)		0,05	2,42	0,06	0,03	0,04	0,04	0,03	0,01	-0,01	
Cumulative Copper Mass (g)			2,42	2,48	2,51	2,55	2,59	2,62			
Copper Grade (%)			5,34	4,66	4,21	3,74	3,34	3,08			
Copper Recovery (%)			80,03	82,04	82,93	84,27	85,65	86,61			
Nickel Percentage (%)		0,27	3,32	1,48	2,34	0,88	0,74	0,59	0,10	0,09	
Nickel Mass (g)		0,05	1,51	0,12	0,15	0,08	0,07	0,04	0,02	-0,02	
Cumulative Nickel Mass (g)			1,51	1,62	1,77	1,85	1,92	1,96			
Nickel Grade (%)			3,32	3,05	2,97	2,71	2,47	2,31			
Nickel Recovery (%)			53,00	57,07	62,34	64,98	67,46	69,02			

40 MMM Run 2– Recovery and Grade									
	Feed	C1	C2	C3	C4	C5	C6	Tails 1	Tails 2
Copper Percentage (%)	0,29	5,12	0,77	0,39	0,44	0,38	0,34	0,04	0,05
Copper Mass (g)	0,07	2,11	0,07	0,03	0,03	0,03	0,02	0,01	0,01
Cumulative Copper Mass (g)		2,11	2,18	2,21	2,24	2,28	2,30		
Copper Grade (%)		5,12	4,35	3,81	3,41	3,05	2,82		
Copper Recovery (%)		77,14	79,65	80,77	82,02	83,26	84,14		
Nickel Percentage (%)	0,26	3,66	1,41	1,47	0,72	0,60	0,48	0,09	0,09
Nickel Mass (g)	0,06	1,51	0,13	0,12	0,06	0,05	0,03	0,02	0,02
Cumulative Nickel Mass (g)		1,51	1,63	1,75	1,81	1,86	1,89		
Nickel Grade (%)		3,66	3,26	3,02	2,74	2,49	2,32		
Nickel Recovery (%)		53,98	58,49	62,64	64,66	66,55	67,74		