

https://dspace.org/

Investigating the opportunity to increase yield by means of froth washing on mechanical coal flotation cells

Du Plessis, Cherryl

2018

https://hdl.handle.net/10539/26587

Du Plessis, Cherryl (2018) Investigating the opportunity to increase yield by means of froth washing on mechanical coal flotation cells, University of the Witwatersrand, Johannesburg, <http://hdl.handle.net/10539/26587>

Downloaded from a DSpace repository. https://dspace.org/

Investigating the opportunity to increase yield by means of froth washing on mechanical coal flotation cells

MSc (50/50)

Prepared by

Cherryl du Plessis

1145394

Submitted to

School of Chemical and Metallurgical Engineering, Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, South Africa

Supervisors: Prof Vusumuzi Sibanda & Prof Marek Dworzanowski

July, 2018

DECLARATION

I Cherryl du Plessis (Student number: 1145394) am a student registered for MSc(chemical engineering) in the year 2017. I hereby declare that this master's research submitted for assessment in this report is my own work except where I have explicitly indicated otherwise. In this case I have followed the required conventions in referencing the thoughts and ideas of others. The work has not been submitted anywhere else for academic credit by myself or another person. I am aware that plagiarism (the use of someone else's work without their permission and/or without acknowledging the original source) is wrong. I understand that the University of the Witwatersrand may take disciplinary action against me if there is a belief that this is not my own unaided work or that I have failed to acknowledge the source of the ideas or words in my writing.

Signature: _____ Date: _____

ABSTRACT

Froth washing is a process where water is injected or sprayed onto or into the froth to remove or flash-down gangue particles present in the froth because of hydraulic entrainment. This process was recently tested at Anglo American's Goedehoop South (GHS) Flotation plant to evaluate its effects on the yield and product quality during coal fines flotation. The research aimed to design a suitable and effective froth wash system, and to use this design to test froth washing. The most suitable froth wash design was found to be a lip wash design. The performance of flotation cells with lip washing were compared to flotation without lip washing. The primary goal of the study was to determine whether lip washing on flotation cells can improve yield while maintaining the required product quality. The flotation plant produces an A grade thermal coal product with a target product calorific value (CV) of 27.30 MJ/kg (air dry basis), known within Anglo thermal coal as an AAC product.

The test work compared different scenarios of lip wash against the current plant performance. This was done by sampling two identical flotation lines feeding from the same head box. One flotation line was run at the current optimum plant operating parameters to represent the current plant performance. On the other line a lip wash design was installed and different scenarios were applied to the lip wash line. The flotation reagent dosage on the flotation cells line without lip washing was kept constant at 1.3 kg/t which corresponds to the optimized plant operating dosage. The flotation reagent dosage on the flotation line with lip washing was varied between 1.3 kg/t and 1.75 kg/t to determine the optimum dosage rate that could be used when applying lip wash. Various configurations of froth washing was also tested, washing was either done on the primary flotation cell, i.e. primary wash only (PWO) or on the secondary flotation cell which is fed from the underflow of the primary cell, i.e. secondary wash only (SWO) or on both primary and secondary cells. Some experimental runs were done at specific settings to evaluate the effects of lip wash when different feed types are used. All the lip washing tests were compared with a baseline test where no lip washing was done (and therefore to current plant performance).

The results of the test work showed that lip washing can increase product yields on the flotation cells by 8% - 40%, depending on the type and quality of the feed fed to the cells. Lip wash can increase yields without compromising product quality for reagent dosages of 1.3kg/ton-

1.45kg/ton. An interesting observation was that lip wash increased yields while achieving similar product qualities at the current plant's optimum reagent dosage of 1.3kg/ton, contrary to froth wash studies in literature where froth wash leads to a decrease in yield and increase in product quality. Primary wash only (PWO) was found to achieve higher product yield than secondary wash only (SWO), however the resultant product quality was found to be poorer than that achievable by SWO and baseline flotation cells. SWO produced higher yields than baseline cells while achieving a better product quality as well.

The advantages of applying lip wash were found to be significantly higher when washing poorer feed material that results in low yields in the conventional flotation plant without lip wash (yields between 10%-40%). Yield increases between 30-40% were observed when lip wash is introduced to flotation cells floating low yielding coals.

The mechanisms that are potentially responsible for the increased yield and high product qualities when lip washing is applied are a combination of the following:

i. The increased froth mobility due to lip wash
ii. Lip wash water washing hydraulically entrained material out of the froth phase and back to the pulp phase
iii. The reduced residence time on the secondary cleaning stage resulting in a reduction in coalescence of bubbles in the froth phase.

DEDICATION

This research report is dedicated to my husband, parents and God. To my husband who always stands by me, always lifts me up, supports me in living out my dreams, and allows me to be myself while loving and accepting every part of who I am. To my parents who have raised me to be an independent, strong and confident person. And arming me with valuable skills to conquer all challenges put to me. Most importantly this thesis is dedicated to my Lord and Savior, I am truly blessed beyond measure and thankful from the deepest place in my heart for my countless blessings.

ACKNOWLEDGEMENTS

I would like to thank and acknowledge the following people for their contributions to this work.

Professor V. Sibanda of Chemical Engineering (Wits)

I am incredibly grateful for all the energy and time that Prof Sibanda has put into my work. Especially with writing up and formalizing the findings of my research. Without him the research report would probably not make sense to many people and people would probably struggle to get through the report. I thank him for guiding me by pointing out information that was missing from the work and identifying the information that was excessive.

Professor M. Dworzanowski

I thank my co-supervisor for all his inputs to my work, especially with writing up the research proposal for the work.

R Nthangeni

I thank my plant superintendent and line manager for allowing me all the freedom and authority to complete the project in the best way I saw fit. I thank him for the time he allowed me to dedicate to the work and all the motivation and support from him

E Ntsendwana

I thank Elvis, my lab assistant, for his assistance in the laboratory with sample preparation and analysis. With a total of 65 samples that had to be filtered, dried and prepared for analysis, and over 800 analysis done, there was hours and hours of work. Thanks for putting in the overtime whenever it was required to get all the analysis done, long before we knew what story the results would tell.

Table of Contents

CHAPTER 1 - INTRODUCTION ..... - 1 -

1.1 PROBLEM STATEMENT: ..... - 3 -

1.2 RESEARCH OBJECTIVES: ..... - 3 -

Project Scope ..... - 4 -

CHAPTER 2 - LITERATURE REVIEW ..... - 5 -

2. 1 Flotation principles ..... - 5 -

2. 2 Flotation dynamics ..... - 7 -

2.2.1 Coal flotation dynamics in South Africa ..... - 9 -

2.3 Flotation Reagents ..... - 10 -

2.4 Functions of the froth phase ..... - 12 -

2.5 Froth washing principles ..... - 13 -

2.6 Goedehoop South Plant background ..... - 16 -

2.7 Flotation at Goedehoop South Plant ..... - 17 -

2.7.1 Flotation Reagents at GHS ..... - 19 -

2.7.2 Cell design at GHS flotation ..... - 20 -

Chapter summary ..... - 23 -

CHAPTER 3 – DESIGN AND TEST METHODOLOGY ..... - 24 -

3 .1 Stage 1: Froth wash system design ..... - 24 -

3.1.1 Froth wash tray design ..... - 24 -

3.1.2 Lip wash design ..... - 25 -

3.2 Stage 2: Experimental design ..... - 26 -

3.3 Stage 3: Experimental runs ..... - 28 -

3.3.1 Experimental runs 1-4: Combined lip wash on primary and secondary cells vs baseline cells ..... - 28 -

3.3.2 Experimental Runs 5-7: Repeat Runs on different feed material ..... - 29 -
3.3.3 Experimental Runs 8-11: PWO and SWO vs baseline flotation cells ..... - 30 -
3.3.4 Experimental Runs 12 and 13: plant performance of lip wash cells against baseline cells when running the plant in AUTO. ..... - 30 -
3.4 Stage 4: Sampling & Analysis ..... - 31 -
3.4.1 Sampling Procedures for manual sampling of Slurries ..... - 31 -
3.4.2 Test work sampling ..... - 32 -
3.4.3 Sample preparation and analysis ..... - 33 -
3.4.3.1 Sample analysis ..... - 33 -
CHAPTER 4 - RESULTS AND DISCUSSION ..... - 35 -
4.1 CV-ASH correlation ..... - 35 -
4.2 Combined primary wash (PW) and secondary wash (SW) vs baseline flotation: Experimental runs 1 -4 ..... - 36 -
4.2.1 Effect of varying reagent dosage on yield ..... - 36 -
4.2.2 Effect of varying reagent dosage on product quality ..... - 38 -
4.2.3 Yield and quality as a function of particle size ..... - 42 -
4.3 Combined primary and secondary wash vs baseline flotation: Experimental runs 5 -7 . - 43 -
4.3.1 Effect of varying reagent dosage on yield on a different coal feed material ..... - 43 -
4.4 Comparison of the Effect of Primary Wash Only (PWO) & Secondary Wash Only (SWO) vs Baseline Flotation: Experimental Runs 8-11 ..... - 45 -
4.5 Experimental runs 12 and 13: Plant performance lip wash cells against baseline cells when running the plant in AUTO ..... - 47 -
4.6 Possible mechanisms: froth washing at GHS ..... - 48 -
CHAPTER 5 – CONCLUSIONS AND RECOMMENDATIONS ..... - 50 -
5.1 Froth wash design ..... - 50 -
5.2 Lip wash test work ..... - 50 -

5.3 Recommendations ..... - 52 -
REFERENCES ..... - 53 -
APPENDICES 58
Appendix A: Composite analysis results for experimental runs 58
Appendix B: Analysis by size ..... - 61 -

LIST OF FIGURES

Figure 1: Typical operation of a mechanical flotation cell (Wills and Napier-Munn, 2006) ..... - 6 -
Figure 2: Schematic diagram of factors influencing flotation. Adapted (Klimpel, 1995) ..... - 7 -
Figure 3: Woollaccott and Eric (1994) illustration of hydrophobicity with contact angle between air and mineral ..... - 8 -
Figure 4: Schematic diagram to illustrate hydraulic entrainment in the froth layer. Adapted from Wills and Napier-Munn (2006) ..... - 12 -
Figure 5: Process flow diagram of a flotation module at GHS ..... - 17 -
Figure 6: Schematic diagram of the Dual cell patented by Enprotec ..... - 21 -
Figure 7: Dual cell process flow and control diagram ..... - 22 -
Figure 8: Lip wash design and installation onto a Dual cell (cut-away view of the flotation cell) ..... - 25 -
Figure 9: Schematic diagram showing sampling points for test work ..... - 27 -
Figure 10: CV vs Ash for all product samples analysed for runs 1-13 ..... - 36 -
Figure 11: Baseline flotation yield and increased lip wash yield for run 1-4 ..... - 37 -
Figure 12: Effect of flotation reagent dosage on % product ash and yield ..... - 39 -
Figure 13: Product quality comparison between Baseline and Lip wash flotation cells for runs 1-4 ..... - 40 -
Figure 14: Yield and quality as a function of particle size for run 1 ..... - 42 -
Figure 15: Comparison of lip wash on different coal feed qualities ..... - 43 -
Figure 16: Comparison of Primary Wash Only (PWO) and Secondary Wash Only (SWO) ... - 45 -
Figure 17: Lip wash results when running the plant in AUTO ..... - 47 -

LIST OF TABLES

Table 1: Common reagents, frothers and modifiers used in coal flotation (Laskowski, 1996)- 10 -
Table 2: Flotation plant operating parameters .....- 18 -
Table 3: Standard constant flotation operating parameters.....- 27 -
Table 4: Settings for the first experimental run: Combined (PW and SW) with varying reagent dosages on lip wash line A2.....- 28 -
Table 5: PWO and SWO reagent dosage rates .....- 30 -
Table 6: Minimum mass of solids in a lot sample for general analysis (South African Coal Processing Society, 2002).....- 32 -

CHAPTER 1 - INTRODUCTION

Flotation has offered a viable solution to recover ultra-fine coal product in the coal processing industry. The treatment of ultra-fine coal remains a concern in South Africa. Contrary to the fine coal behavior in the rest of the world South African coals are very difficult to float and they require significantly higher amounts of flotation reagents to be floated successfully. This inevitably results in high reagent costs per ton of coal washed. The economic imperative is therefore that flotation devices need to have high efficiencies to ensure that the process remains viable (Peatfield, 2002). The flotation process has been used for just over a century and the understanding of how it works has improved over time. Early improvements to the flotation process focused on the understanding of the chemistry involved in the flotation process. More recently the physics or the mechanisms of the process have received more attention and have become better understood leading to improvements in the performance and efficiency of flotation plants.

Froth washing is the process whereby water is injected or sprayed onto or into the froth layer to increase the grade of the concentrate by removing gangue particles which accumulate in the froth by hydraulic entrainment (Finch and Dobby, 1990). Froth washing in the coal flotation industry has been commonly applied in column flotation cells, but little application of froth washing has been reported on conventional mechanical cells. The basic concept behind froth washing however suggests that efficiencies in flotation on mechanical coal flotation cells might also be improved by application of this technology. In this research the effect of froth washing on mechanical coal flotation cells will be investigated. Although froth washing has generally been used to improve the grade of the flotation product (both in column flotation and the limited trials on mechanical flotation cells), it is a hypothesis in the present work that this technology could potentially be adapted and used to increase yields on mechanical coal flotation cells considering that the required product quality specification is normally achieved in the current plant practice. In this research the possibility of increasing yield during flotation of ultrafine coal in mechanical coal flotation cells will be investigated. The strategy to increase yield will be pursued by increasing the reagent dosage rate with the intention to float more lower-quality coal particles, and then simultaneously applying wash water to remove impurities and entrained gangue from the froth. The ultimate effect of

increasing the removal of entrained ash from the froth (by means of lip wash) while floating more coal (by increasing reagent dosage rates to float lower quality coal particles) could result in increased yields in mechanical coal flotation cells while maintaining the product quality required. The hypothesis of the current research is that an increase in product yield could be achieved while maintaining product quality by applying lip wash while increasing flotation reagent dosage that increases the flotation rate. The research aims to explore this hypothesis.

Wash water is the water that is sprayed onto the froth in froth and lip washing. The understanding of how wash water behaves in the froth is limited, and existing wash water systems are largely based on trial and error (Ireland et al, 2006). In South Africa, limited trials have been conducted to assess the effects of washing the froth during fine coal flotation. Published work on thermal coal flotation froth washing in literature is almost non-existant and plant trials are discussed amoungst professionals in industry by word of mouth. It is anticipated that the research results from such a study will have a positive effect on the operation of coal flotation cells in the South African industry.

In 2007, a flotation plant was commissioned at Goedehoop South (GHS) Plant for the treatment of particles below 212 µm in size in response to the economic environment where all opportunities including the treatment of ultra-fines in coal need to be evaluated to increase revenue and profits and ensure a sustainable business model. Without a flotation plant all particles below 212 µm were discarded on the slimes dam. Therefore, flotation offers an opportunity to recover coal product from material that would usually be discarded, while also reducing discard handling costs and slurry storage space requirements. Considering that coal fields are becoming depleted and that coal grades are reducing as the coal fields are depleted, all opportunities to increase product tons economically need to be exploited.

An opportunity was identified at GHS plant to increase yields by applying froth wash on mechanical coal flotation cells. As a part of this study a simple, effective and low cost froth wash system was designed and installed on a flotation line in the plant to evaluate the effects of froth wash at GHS flotation plant, and to explore the opportunity to increase yields. The capital costs of installing a froth washing system are relatively low, while the possible increase in saleable tons

(and therefore revenue) through froth washing is expected to significantly outweigh the cost of installing a froth wash system.

The research aims to improve the understanding and knowledge of applying wash water to mechanical coal flotation cells treating South African coal seams using Anglo American's GHS Flotation Plant as a case study and to use this technique to effectively remove the entrained ash from the product froth to increase recovery while maintaining the required product quality.

1.1 PROBLEM STATEMENT:

a. Wash water applications for froth washing have not been tested sufficiently in the coal flotation industry in South Africa.
b. Fine coal froth washing test work has never been conducted at GHS flotation plant, and very little test work has been conducted on mechanical coal flotation cells.
c. GHS flotation plant easily achieves the target product quality required, but an increase in yield could be possible if lip wash is applied with higher flotation reagent dosage rates.
d. The aim is to increase yield while not compromising product quality.
e. The hypothesis is that yield can be increased while maintaining the target product quality in the flotation plant by applying wash water to the current flotation cells while increasing the reagent dosage.

1.2 RESEARCH OBJECTIVES:

a. To design a practical and functioning froth wash system for GHS flotation cells associated with low capital and installation cost. This design will be used to test froth wash at GHS.
b. To determine whether froth washing on coal flotation cells at GHS flotation plant can bring about a yield increase while maintaining the product quality required, thereby determining if the current plant yield achieved with the current plant configuration could be out performed by a froth wash installation.
c. To investigate froth wash performance with increasing reagent dosages.
d. To investigate the effects of applying froth wash to both primary and secondary cells.

e. To investigate the effects of applying froth wash to primary cells only (PWO) and secondary cells only (SWO).
f. To investigate the froth wash performance with different coal feed types (to be discussed in more detail in the literature review section of the report), specifically the effect when processing difficult-floating coal (to be discussed in more detail in the literature review section of the report).
g. To discuss the possible mechanisms driving the froth washing process.
h. To determine the configuration of lip washing that can offer a practical and effective solution for GHS flotation plant.

Project Scope

The project scope can be summarized in stages:

- Stage 1: Froth wash system design
- Stage 2: Sampling Campaign
- Stage 3: Experimental design
- Stage 4: Sampling
- Stage 5: Analysis
- Stage 6: Results interpretation

CHAPTER 2 - LITERATURE REVIEW

The literature review starts by looking at the basic flotation principles before discussing flotation dynamics. The dynamics of coal flotation in South Africa is highlighted. The role of flotation reagents are discussed in detail with emphasis on the factors that are important to interpret the results from the investigation. Next, functions of the froth phase are discussed before the literature of froth washing is discussed. Lastly the literature review discusses GHS plant. The flotation plant at GHS is discussed followed by a discussion on the reagent mix at GHS flotation plant and the flotation cell design.

2. 1 Flotation principles

Originally patented in 1906, flotation has allowed the recovery of valuable minerals from low-grade and complex ores which was previously thought of as uneconomical. Flotation is a selective process in which a variety of minerals such as sulphides of copper, lead and zinc can be recovered (Wills and Napier-Munn, 2006). Flotation utilizes the difference in hydrophobicity between the valuable mineral and discard material to separate the product from the discard. For the purpose of the current project, emphasis will be placed on flotation of ultra-fine coal.

Feed slurry, reagent and air are fed to a flotation cell and these three inputs are mixed and dispersed through the cell. Figure 1 shows a schematic diagram of a typical flotation cell, and illustrates the principles associated with flotation in a mechanical flotation cell. Hydrophobic coal particles attach to the surface of the rising air bubbles and are carried towards the top of the cell and enter into the base of the froth layer. Coal particles will be transported on the air bubbles and exit the flotation cell at its top in the form of overflowing froth. The froth overflows over the lip of the flotation cell and is collected as a product . The hydrophilic non-valuable material will not attach to the air bubbles, remaining in the pulp. The hydrophilic residue material is collected at the bottom of the cell with most of the water.

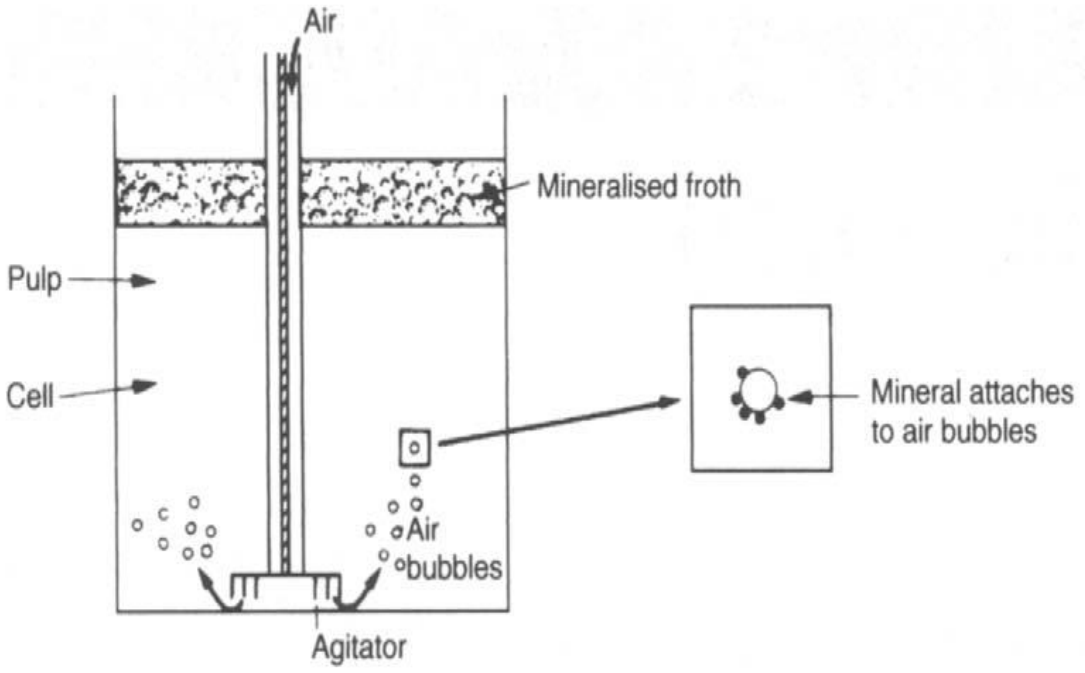


Figure 1: Typical operation of a mechanical flotation cell (Wills and Napier-Munn, 2006)

Early improvements in the flotation process were brought about through a better understanding of the chemical properties of the flotation process. More recently the physics of the process has become better understood. It has been shown that for the same chemical conditions, the flotation performance can be greatly improved through the optimization of factors such as bubble size, froth depth and gas flow rate which are more related to the physics of the process. **Error! Reference s ource not found.** shows several inter-related factors that influence the flotation process, the relationship of these factors need to be considered in froth flotation operations as they have a synergistic effect (Klimpel, 1995).

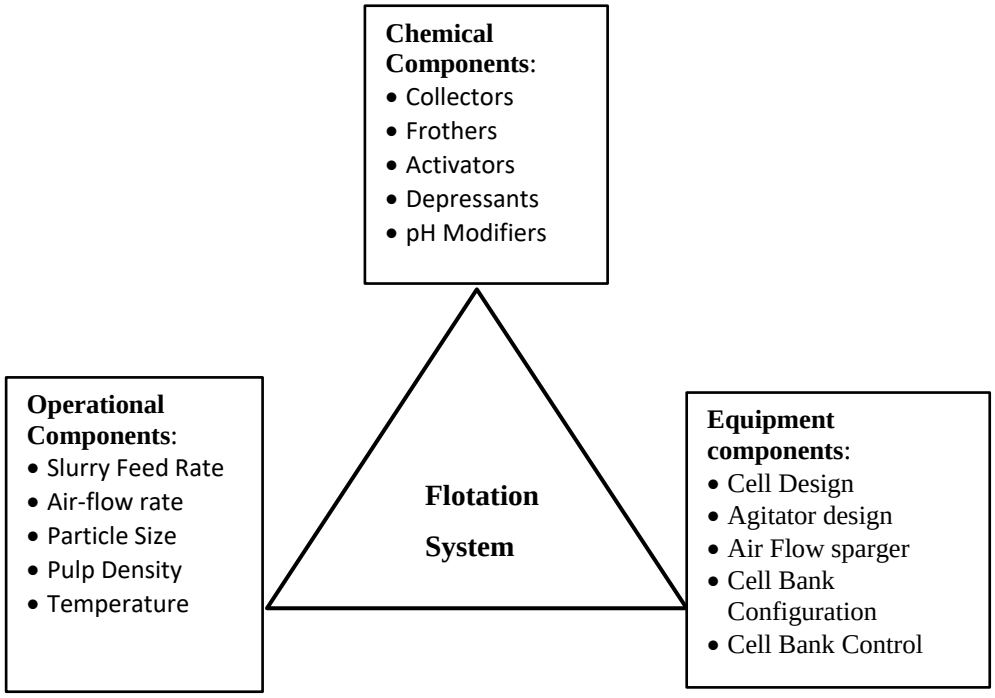


Figure 2: Schematic diagram of factors influencing flotation. Adapted (Klimpel, 1995)

In flotation the desired mineral is recovered from the feed pulp by the following three mechanisms:

i. True flotation, i.e. selective attachment of the mineral to the air bubbles.
ii. Entrainment with gangue particles in the pulp water layers between bubbles in the froth.
iii. Physical entrapment between particles in the froth attached to air bubbles, which is commonly known as aggregation.

True flotation is generally the dominant mechanism of recovery, though the degree of entrainment and entrapment also plays a role in the flotation performance (Wills and Napier-Munn, 2006).

2. 2 Flotation dynamics

The most effective and recognized method to separate ultra-fine coal (-212µm particles) is froth flotation (Allum and Whelan, 1954). Froth flotation is the main technique being implemented for the beneficiation of ultra-fine coal and is applied widely in the international mining industry.

Coal is naturally hydrophobic and can therefore easily be wetted by non-polar materials (ideal for the coal flotation process that utilizes hydrocarbon based reagents). Typical unwanted gangue

minerals found in the ROM (run of mine) coal are shales, mudstones and clays. All these minerals have a polar nature and are therefore preferentially wetted by water instead.

Hindermarch and Waters (1951) reported that coal is heteropolar as it possesses a hydrophobic carbon skeleton as well as hydrophilic surface functional groups. Woollacott and Eric (1994) illustrated the difference in hydrophobicity by means of Figure 3:

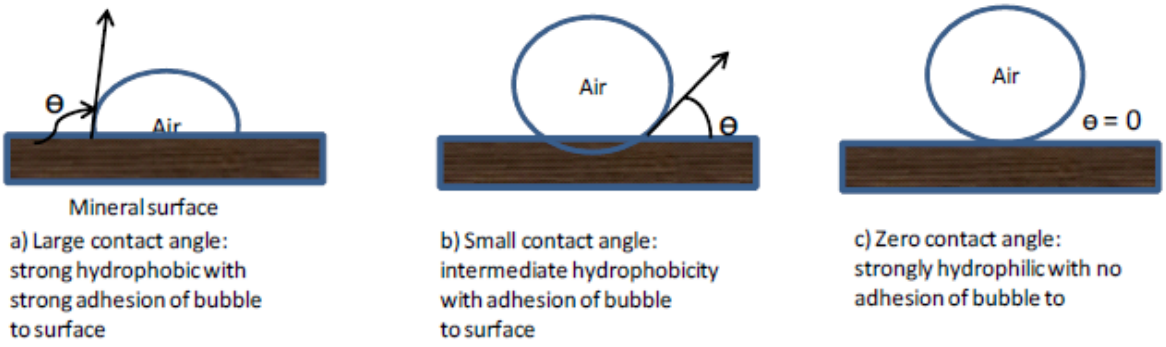


Figure 3: Woollaccott and Eric (1994) illustration of hydrophobicity with contact angle between air and mineral

Wills and Napier-Munn (2006) also state that the greater the contact angle the greater is the work of adhesion between particle and bubble, the hydrophobicity of a mineral therefore increases with the contact angle. The terms hydrophobicity and floatability are often used interchangeably. There is however a difference between these two terms. Hydrophobicity refers to the thermodynamic properties whereas floatability incorporates particle properties that affect flotation amenability and is therefore a kinetic characteristic (Leja, 1982; Laskowski, 1986; Woods, 1994).

Several factors influence the natural hydrophobicity and floatability of coal. Coal is generally hydrophobic in nature, however its natural floatability in water with respect to the origin and rank is variable (Fuerstenau and Pradip, 1992). According to Wheeler and Keys (1986), a higher rank coal particle will float more easily than a lower rank coal for any given size class. The ease of floatability decreases as the rank decreases due to both a decrease in carbon content and an increase in oxygen content (Horsfall, 1992). Ye et al. (1989) also states that the floatability of coal increases with rank due to the lower oxygen content in higher rank coals. Coal oxidation has a strong

influence on coal floatability. According to Sun (1954) this is once again related to coal rank to some extent: an increase in the surface functional groups occurs as the degree of oxidation increases leading to a decrease in floatability. The oxidation susceptibility of coal has also been found to decrease with an increase in rank (Taylor et al, 1981). The petrographic composition of the coal also has an influence on the floatability of coal. Barnwal et al. (2000) reported that the flotation rate is related to the different coal macerals, with vitrinite having the highest flotation rate, followed by liptinite and lastly inertinite.

2.2.1 Coal flotation dynamics in South Africa

Historically, beneficiation of the ultra-fine coal fraction has not been common practice in South Africa and has been generally limited to coking coal applications. South African coals are generally difficult to float (Peatfield, 2003). A number of factors contribute to the challenges associated with floating South African coals. Horsfall et al. (1986) suggested that the problem with South African coals is the lack of selectivity in the flotation process. South African coals differ from other coal seams around the world, as the petrographic composition is less favorable for flotation and the degree of oxidation and the surface functional groups present in South African coals negatively influence the flotation thermodynamics and kinetics. As a result South African coals are very difficult to float compared to coal seams found in the rest of the world, and require significantly higher amounts of flotation reagents to be floated successfully. This inevitably results in high reagent costs per ton of coal washed. The economic imperative is that flotation devices need to have high efficiencies to ensure that the process remains viable (Peatfield, 2002). The application of ultrafine coal flotation for Witbank coal has been limited due to lack of an appropriate frother and ultimately by process economics (cost, dewatering, etc.). Until the early nineties, it was believed that Witbank coal was not amenable to froth flotation (Hand, 2000). Subsequently, this was found to be incorrect and, driven by environmental and economic pressures the processing of ultra-fine coal began to receive more attention in the mid-1990s. At the turn of the century, approximately 12% of the South African coal washing plants utilized flotation to beneficiate ultra-fines (de Korte, 2000). The majority of ultra-fine coal produced in washing plants is still disposed of into slurry ponds or underground (South African Coal Roadmap, 2012).

2.3 Flotation Reagents

In the flotation process, valuable minerals can only attach to the air bubbles if they are water-repellent or hydrophobic to some extent. When the valuable minerals attach to the air bubbles, the air bubbles can only continue to support the mineral particles if they can form a stable froth. Without a stable froth, the air bubbles will burst and release the mineral particles. To ensure that these conditions are achieved, chemical compounds known as collectors and frothers are used. There are three main groups of the reagents that are used in flotation to optimize the flotation process, namely: collectors, frothers and modifying agents, which are classified in respect to their action during flotation separation. The common reagents applied in coal flotation are summarized in Table 1

Table 1: Common reagents, frothers and modifiers used in coal flotation. (Laskowski, 1996)

Type	Use	Functional Group	Examples	Action
Non-polar (water-insoluble)	Collectors		Kerosene Fuel oil	Collects through selective wetting and adhesion of oil drops to coal particles
Surface active (water-soluble)	Frothers	Hydroxyl Nitrogenous	Aliphatic alcohols Pyridene containing tar oils	May also improve collecting ability of oily collectors
Emulsifiers	Promoters	Hydroxyl Carboxyl Nitrogenous	Polyethoxylated alcohols Fatty acids	Facilitate collector emulsification and its spread over coal surface
Inorganic	Modifiers	Water soluble salts	NaCl, $CaCl_2$, H_2SO_4, CaO	Promoters pH regulators Sulphide depressants
Protective colloids	Depressants	Hydroxyl Carboxyl	Polymers: starch, dextrin, carboxymethyl cellulose	Modifiers Coal depressants

Collectors are the reagents added to modify, in a selective manner, the hydrophilic/hydrophobic properties of various mineral grains to facilitate their attachment to rising air bubbles in flotation separation. Collectors are a large group of organic chemical compounds, which differ in chemical composition and function. The basic purpose of the collector in coal flotation is to selectively form a hydrophobic layer on the coal particle surface in the flotation pulp and thus provide conditions for the attachment of the hydrophobic particles to air bubbles and recovery of such particles in the froth product. Collector molecules may be ionizing compounds, which dissociate into ions in

water, or non-ionizing compounds, which are practically insoluble, and render the mineral water-repellent by covering its surface with a thin film. The mechanism of adsorption is now widely accepted as being hydrophobic bonding between the collector molecules and associated groups on the coal surface. This is a physical rather than a chemical bond (Woollacott and Eric, 1994). Brown et al., (1958) noted that conditioning of coals using oily collectors is also strongly dependent upon coal surface properties. From a thermodynamic point of view, the spreading of an oil film on a coal surface requires an energy input, termed the work of spreading. Oils spread more easily over high rank coals than over low rank coals.

Frothers, on the other hand, are heteropolar surface-active compounds that lower the surface tension of water and have the ability to adsorb on the air bubble-water interface. Their presence in the liquid phase increases the film strength of the air bubbles, thus providing better attachment of hydrophobic particles to the bubbles. Frothers stabilize the froth by reducing the surface tension between the slurry and the bubble (Michaud, 2015). Frothers also increase the dispersion degree of the air introduced into flotation cells through diminishing diameters of the bubbles formed and preventing their coalescence resulting in the formation of a dynamic adsorption layer (Makhotla, 2015). As a result of lowering the bubbles velocity, the time of contact of the colliding bubbles and grains is increased and probability of forming the bubble-grain aggregates is higher. A frother therefore assures the formation of a froth layer with a definite stability, ideally forming a reasonably stable froth that also allows selective drainage from the froth of entrained gangue. Ultimately the frother increases flotation kinetics (Klimpel, 1995). Frother selection depends on coal floatability characteristics, generally coals with favourable floatability characteristics require only alcohol type frothers. As the natural floatability of the coal decreases, stronger frothers such as polyglycols and polyether alcohols may be more suitable and strong frothers are recommended for oxidized coals (Powell, 2016). Strong frothers cause a robust, slow draining froth to form. With weak frothers this is not observed, the froth matrix is not held as rigidly as with strong frothers, and therefore selectivity is increased. South African coals generally require strong frothers to be used resulting in the lack of selectivity in the flotation process as observed by Horsfall et al (1986).

2.4 Functions of the froth phase

The most important stage in the mineral recovery mechanism is the attachment of the valuable minerals to the air bubbles in the pulp phase (known as true flotation). The efficiency of the separation is however greatly influenced by entrainment and physical entrapment. In ultra-fine coal flotation, non-floatable hydrophilic material can also be recovered to the product stream as a result of entrainment, entrapment and slime coating. All these are non-selective mechanisms that tend to reduce the performance of the cell by reducing product quality. Once in the froth phase the discard material is transported in the liquid between bubbles (Atkinson et al, 2001). Figure 4 illustrates hydraulic entrainment in the froth layer.

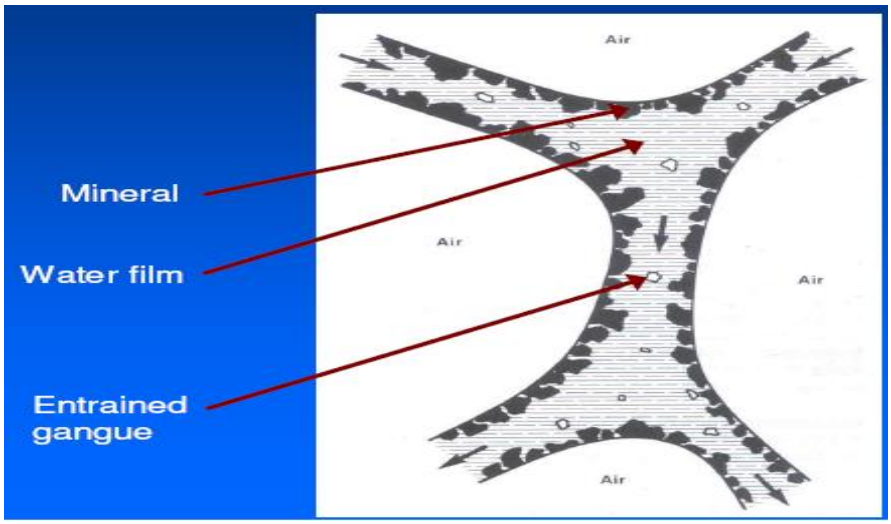


Figure 4: Schematic diagram to illustrate hydraulic entrainment in the froth layer. Adapted from Wills and Napier-Munn (2006)

The cleaning stage taking place in the froth layer is referred to as the secondary cleaning stage. In the secondary cleaning stage water drains from the froth, carrying unwanted entrained material back into the pulp. One of the functions of the froth phase is to enhance the overall selectivity of the process by froth drainage as mentioned in the previous section. The froth achieves this by reducing the recovery of entrained material to the concentrate stream, while preferentially retaining the attached minerals. This increases the product quality but decreases yield. Yield in coal preparation is defined as product tons divided by feed tons. If material that would have reported as product has been removed from the product stream the yield will decrease, and because the quality of the material removed from the product stream is low, the overall product quality will

improve. The froth stage is a key determining factor of the grade and recovery of the flotation process (Wills, Napier-Munn, 2006).

Klassen and Tikhonov (1964) proposed that the thickness of the liquid film that surrounds the bubbles directly correlates to the amount of entrainment. As bubbles crowd closer together with increasing height above the the pulp a product ash differential is set up through the froth profile, where the product ash is highest closest to the pulp and decreases as the height above the pulp increases.

The amount of froth drainage is highly dependent upon the froth residence time as shown by Bisshop and White (1976) and Cutting et al. (1986). Both agreed that the amount of recovery of material by the froth is strongly dependent on the residence time of the froth. Considering the work of Cutting et al. (1986), Kuzkin et al. (1983), Moys (1984) and Subrahmanyam and Forssberg (1988), there is agreement that while froth drainage is good, it can lead to instability. Froth drainage can therefore help and hinder the secondary cleaning stage taking place in the froth layer. While froth drainage ensures that a higher quality product is produced, well drained froths are generally unstable because of the increase in coalescence. As the froth drains coalescence occurs increasingly up through the froth layer. Coalescence causes shocks in the froth phase, which causes detachment of mineral particles from the bubbles. Coalescence also reduces the bubble surface area, reducing the surface available for mineral attachment resulting in a reduction in the recovery of the mineral. Well-drained froths do not flow well and this in turn greatly decreases recovery. During coal flotation, unless the rate of ash entrainment is reduced, the penalty for the improvement in recovery is increased product ash. One technique that has been suggested to reduce hydraulic entrainment in the froth layer is known as froth washing (Atkinson et al, 2001).

2.5 Froth washing principles

Early improvements in the flotation process were brought about through a better understanding of the chemical properties of the flotation process. More recently the physics of the process has become better understood. It has been shown that for the same chemical conditions, the flotation performance can be greatly improved through the optimization of factors such as bubble size, froth depth and gas flow rate. Whilst the optimization of these variables has led to an increase in the

efficiency of flotation of the desired material (in this case coal), it has also led to an increase in the entrainment of unwanted discard material that needs to be removed from the froth otherwise the product quality gets severely affected.

Wash water is used with the goal of removing impurities that report to the froth layer. In principle froth washing is the process whereby water is injected into the froth or sprayed over the froth to increase the grade of the concentrate by removing gangue particles which accumulate in the froth by hydraulic entrainment (Finch and Dobby, 1990). Adding wash water to flotation cells provides a method to wash out entrained impurities in the froth phase. Froth washing has the ability to reduce the hydraulic ash entrainment that was not drained from the froth during the secondary cleaning phase. The ultimate goal of froth washing is to displace the water between bubbles containing entrained material back into the pulp phase and replace the water film between bubbles with clean water.

Wash water has been used mainly in column flotation and no reason has been put forward prohibiting its adoption on mechanical cell systems where limited work has been reported (Finch, 1994). The exact behavior and mechanisms of froth cleaning using wash water is currently not adequately understood as demonstrated by limited published information on the subject matter (Ireland et al, 2006).

Several wash water systems have been tried in the past for both coal and mineral flotation systems. Literature from these earlier studies suggests that the wash water should be added as a light rain, and not a jet, so that air bubbles containing the valuable mineral are preserved (Kaya et al., 1990). Finch (1994) suggested that wash water should travel through the froth and cross the froth/pulp interface for the froth wash process to be effective. To accomplish this a vertical spray of water is introduced over the froth or parts of the froth at a velocity high enough to move through the given froth depth to the pulp phase, but at a velocity low enough to not compromise the froth layer by bursting air bubbles that carry the valuable mineral. The water droplets that move through the froth will drag entrained particles down with it back into the slurry (or pulp phase). This in effect makes a channel through the froth for impurities to exit. The hydrophilic discard particles attach to wash water droplets and get removed from the froth layer to the underflow of the cell. The wash water

velocity is important only in as much as it must be sufficient to penetrate the froth and cross the froth interphase to the pulp. Mist addition does not work because the water tends to flow across the froth into the product launder. Because wash water addition should be done by a method that protects the froth integrity, jets are not appropriate and a light rain is recommended by most work reported in literature. Wash water is customarily applied through a large number of small holes, drilled in piping or in shallow pans, and may be suspended above or within the froth layer. Because of the relatively shallow froths that form on mechanical flotation cells, it is generally not possible to install an immersed distribution system. In a shallow froth, there is insufficient volume for the wash water to diffuse laterally in the froth from an immersed distributor (Atkinson et al, 2001).

Wash water can either be introduced over the whole froth area, or just the lip area of the cell where the froth overflows. This leads to a distinction between the two types of wash water addition systems:

i. Lip washing - where wash water is applied on the peripheral of the flotation cell just inside the froth overflow lip.
ii. Froth washing - where wash water is applied over the whole area of the flotation cell to cover the whole froth area of the flotation cell.

Adding wash water to the cell lip is one of the most crucial places for wash water addition because the entrainment is most severe at that point (Moys, 1978). The height of the wash water addition above the froth should be minimized to increase froth stability (Kaya et al., 1990).

Wash water has been found to reduce overloading, which can increase drainage without reducing froth stability (Kaya et al., 1990). Kaya et al, (1990) suggests that wash water flow rates should be between 7% and 12% of water in the feed. This however was recommended for column cells with high froth heights and ample space for wash water dispersion. In mechanical cells the froth height is significantly lower, therefore lower wash water flowrates may be sufficient to achieve the desired results.

2.6 Goedehoop South Plant background

GHS plant is an Anglo American coal handling and preparation plant (CHPP) located in Mpumalanga that washes coal from coal seams mined at Goedehoop (GH) mine. GHS plant receives coal from the “South side” mining sections at GH mine. The coal supplied for the test work was mined from three different shafts, namely the Vlaklaagte shaft, North East shaft, and Block 7 shaft. Bituminous coal is mined from the 4 seam, the coal field forms part of the Witbank coal fields. The coal mined mineralogy and coal quality from these three shafts have been found to vary significantly. Dykes, sills and other geological intrusions influence the coal minerology. The volatilization, carbon content, oxidation, ash and CV of the coal is affected by the geological factors. The ash content of the ROM coal (feed material) processed during test work ranged from 30-37%. There is one overland conveyor that conveys coal from all three sections to the plant stockpiles, and hence coal from the three shafts arrive at the flotation plant stockpiles as a mix or a blend. The washing plant is then fed from these stockpiles. The washing plant is made up of three modules. Each module consists of a dense medium separation (DMS) drum plant, DMS cyclone plant, spiral fines plant and a flotation plant. Each of the modules is fed at a rate of 500-600 tph. The +12 mm particles are treated in the DMS drum plants, the -12 +0.5 mm particles are treated in the DMS cyclone plants, and the -0.5 +0.212 mm particles are treated in the fines plant consisting of spiral separators. The smallest size fraction of the ROM material, the -0.212 mm particles (also referred to as ultra-fines), are treated in the flotation plant. The percentage ultra-fines in the feed vary between 5-10%. Of the separation processes at GHS, the treatment of ultra-fines is the most expensive separation process by far, both in terms of operational and capital costs.

2.7 Flotation at Goedehoop South Plant

The GHS flotation plant operates three identical modules. Each module comprises of a thickener, three primary cells and three secondary cells. The three modules share two product filter presses. Figure 5 shows the process flow diagram of one module.

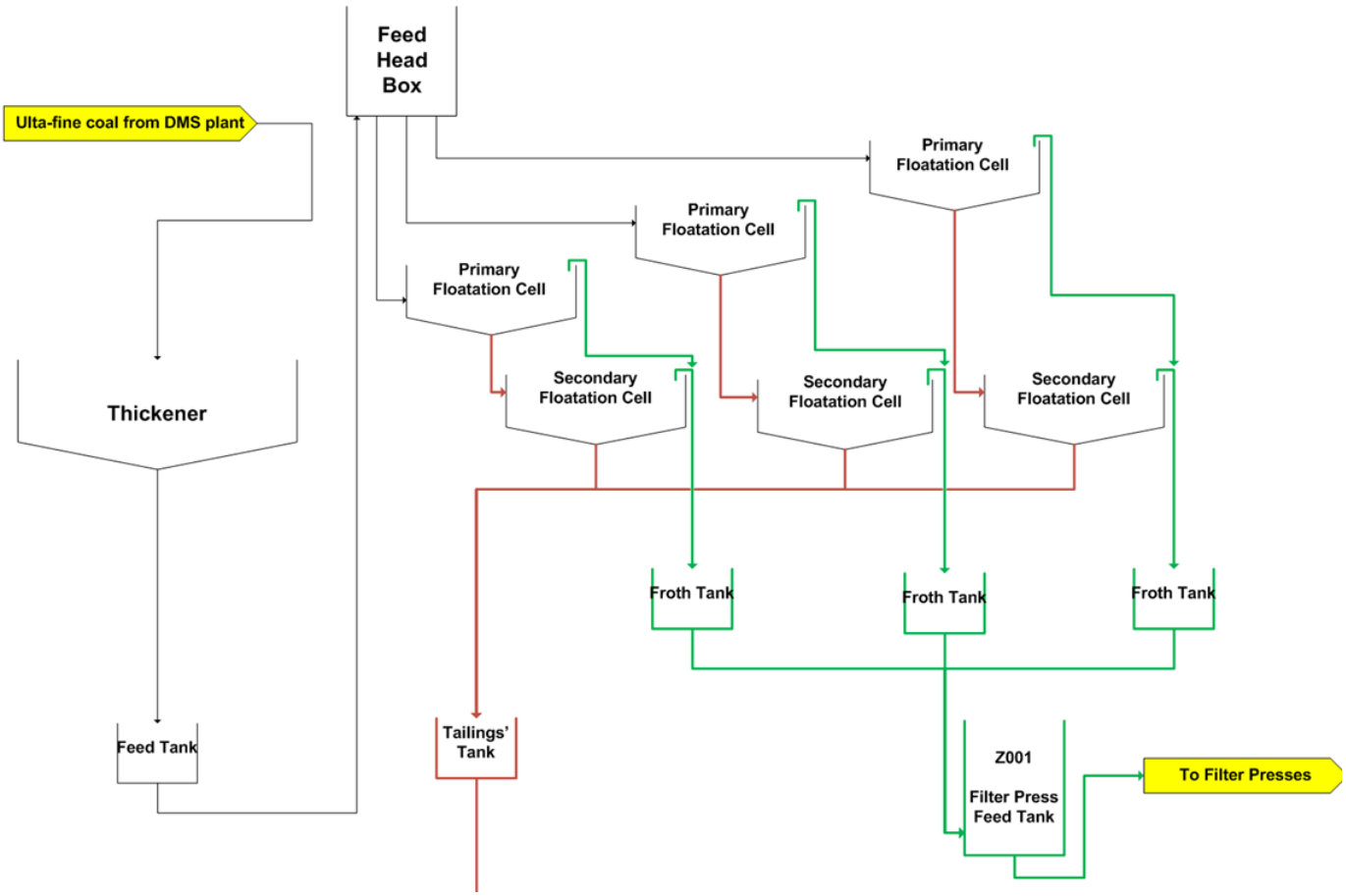


Figure 5: Process flow diagram of a flotation module at GHS

Coal below 212 µm from the main DMS plants reports to three thickeners and from the thickeners, the ultra-fine coal is pumped into the flotation plant feed tanks where it is diluted with water to achieve the desired feed density of 1.022 ton/m^3. From the feed tank, the slurry is pumped into a head box which serves to distribute the slurry into three primary flotation cells by gravitational feed. In the primary cells, fast floating coal is recovered as product and the discard slurry is fed to the secondary cells. In the secondary cells, the slow floating coal is recovered as product. The product material from the primary cell is gravity fed to the secondary cell product launder. The combined product from the primary and secondary cells is pumped to the product filter feed tank

and then dewatered using the Ishigaki Lasta filter presses. Tailings from the secondary cells are pumped to the tailings thickener, the underflow from the tailings thickener is dewatered using the Jing Jin filter presses and discarded on the discard dump (dry disposal).

The operation of the flotation plant has been optimized and all three modules are being operated at plant parameters shown in Table 2.

Table 2: Flotation plant operating parameters

Parameter	Value	Unit
Header box density	1.022	t/m^3
Feed slurry flow rate	200	m^3/h
Air flow rate	30	Standard cubic feet per minute (SCFM)
Reagent dosage	1.3	kg/t
Reagent split (volume): (Primary : Secondary)	75:25	-
Reagent ratio: (Collector: Frother)	80:20	-
Reagent ratio: (CGH7 : CGM4)	75:25	-

Operating the plant using the current technology at the parameters mentioned in Table 2 results in achievement of maximum yield of product at the AAC quality specifications (CV= 27.3 MJ/kg adb). Yields in the flotation plant average at 54% but can vary from 10% to 70% depending on the quality of coal being fed to the flotation plant.

Product quality is evaluated twice per shift (with three shifts daily). A feed, product and discard slurry sample is taken once per shift for each module to evaluate product quality and yield.

Filter cake samples from the product filtration presses are also taken once per shift to evaluate the product quality and moisture content. Product quality should remain around the target CV of 27.3 MJ/kg (adb). If the product quality drops below 26.5 MJ/kg (adb) for more than 2 shifts further investigation into plant performance is required. If it is found that all areas of the plant are functioning correctly the reagent dosage may be decreased to bring the product quality up with permission from the process engineering team. It is well known that a decrease in reagent dosage on the flotation cells will increase the selectivity of the process and produce a higher quality product at a lower yield. If the product quality produced is more than 27.8 MJ/kg (adb) reagent dosage may be increased, this will result in a decrease in product quality and an increase in plant yield. An increase in reagent dosage will lead to a decrease in product quality and increase in yield. The inverse of this statement also applies.

2.7.1 Flotation Reagents at GHS

Goedehoop south flotation plant used a single flotation reagent called CGH 7 in the past, which is a mixture of hydrocarbon, alcohol and glycol compound groups. The reagent has 20% frother and 80% collector ratio. Previous tests at GHS have shown that CGH 7 operates optimally at this specified ratio. CGH 7 is known for its high selectivity of product material over discard material in industry. In 2013, a new reagent called CGM 4 was tested. CGM 4 is also a mixture of hydrocarbon, alcohol and glycol compound groups and is also 20% frother and 80% collector. CGM 4 is similar to CGH 7 with the only difference being the molecular weight of the glycol component. The exact composition of the reagents (CGM 7 and CGM4) are unknown as its formulation is an intellectual property of the supplier. However, it is known that the glycol component of CGM 4 has a higher molecular weight than CGH 7. Therefore CGM 4 has a stronger frother component than CGH 7. Due to the higher molecular weight, CGM 4 has a higher carrying capacity that may possibly result in higher yields. CGM 4 was tested at the flotation plant and, contrary to expectation, higher yields were not achieved. During the test of CGM 4, the froth that formed at the top of the slurry was found to be too stable (the frother component was too strong) and hindered material from overflowing into the product launders of the flotation cells. Even though the reagent had the capacity to recover more product material, the stable froth hindered flow and could not break down sufficiently to gravitate into the product launders.

A project was conducted to investigate the effects of mixing CGH 7 and CGM 4 to explore the possibility of optimizing the reagent deployment. The goal was to harness the high carrying capacity of CGM 4 with the selectivity and flowability of CGH 7 by varying the CGH 7 to CGM 4 ratio. Various mixtures were investigated to determine which mixture would offer the highest yields. The results of the project has led to the current reagent mix used at GHS plant. The plant is currently dosing the reagents at a ratio of 3:1 (i.e. 75% CGH7 & 25% CGM4).

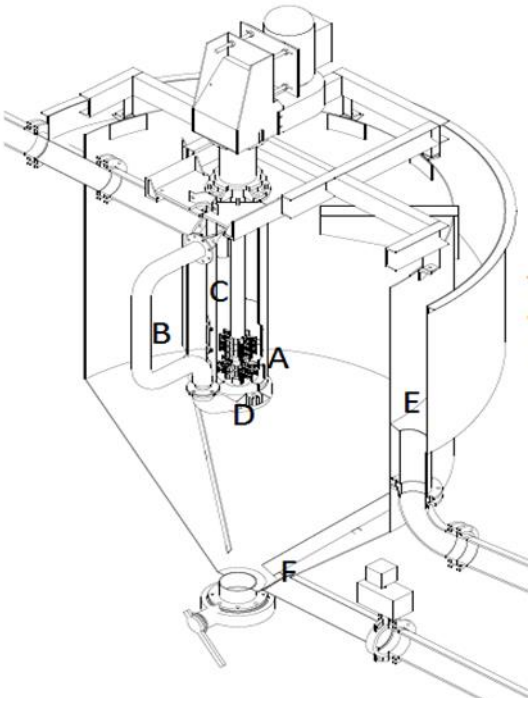
Test work at GHS flotation plant shows that an increase in reagent dosage leads to an increase in yield as expected from literature. With the increase in yield comes a decrease in product quality. The plant is run at a dosage of 1.3 kg reagent per ton of solids fed producing a product with a CV of 27.3 MJ/Kg, which is the target product quality requirement for the Anglo American AAC product. The plant dosage is re-evaluated every 3 months by means of sample analysis from an external laboratory to ensure that the optimum plant dosage is at 1.3kg/ton. Plant dosage is also re-evaluated if product qualities from the flotation plant indicate quality concerns.

2.7.2 Cell design at GHS flotation

Before building and commissioning the GHS flotation plant, test work was done to determine the best option for a flotation cell and circuit at GHS. Throughout the test work on characterizing flotation at GHS, Opperman et al. (2002) found that high mixing energy is essential to accomplish satisfactory recoveries and lower reagent consumption. Very small bubbles are produced if high energy mixing is applied correctly. This in turn increases the bubble–solid contact area and allows a higher carrying capacity in the cell. The probability of bubble–solids collisions is also increased. All these factors contribute to higher recoveries and lower reagent consumption to those achieved with low intensity mixing and big bubbles regime. Opperman et al (2002) found that the mixing power through the orifice plate in the down-comer of a Jameson cell was not sufficient to achieve acceptable recoveries in the fine coal flotation plant at GHS plant. This led to the development of the Multi-cell at GHS, the Multi-cell circuit being a flotation circuit patented by Anglo American in 2000. When the GHS flotation plant was commissioned in 2007, the Multi-cell circuit was used. The Dual cell circuit was then designed as an improvement to the Multi-cell circuit. Test work

showed that the Dual cell outperformed the Multi-cell and therefore the Multi-cell was replaced by the Dual cell.

The Dual cell, which was designed and patented by Enprotec, optimizes agitation in the cells which is aimed at assisting with increased yields. Dual cell pumps are installed on both the primary and secondary cells to enhance mixing. Figure 6 shows a schematic diagram of the Dual cell.



A- Mechanism paddles
B- Recirculation line
C- Mechanism Shaft
D- Mechanism Wet End
E- Froth/Product Launder
F- Discard/Tailings line

Figure 6: Schematic diagram of the Dual cell patented by Enprotec

The Dual cell system gravitates the feed material through both the primary and secondary flotation units. The primary unit is fed from a header box to ensure that a constant hydraulic head is kept at all times. Air is introduced into the wet end of the mechanism through a unique air manifold, aiding in creating bubble surface area by creating finer bubbles. The high rotational speed of the mechanism together with the unique paddle system which is attached to the mechanism's shaft increases dispersion efficiency as well as collision efficiency between particles and bubbles. The material is fed directly into a specifically designed barrel such that the material is introduced into the system at the same point as the reagents and the aerated recirculation stream. The material, bubbles and reagent progressing through the barrel towards the paddle initiates the flotation process before entering the flotation cell. The wet end of the mechanism has an open core and also

allows for suction of material at the bottom of the wet end. This allows particles (in the pulp zone of the cell) to be reintroduced to the system effectively giving the particles further opportunity to collide and attach with air bubbles. The froth depth is also a critical process parameter and is controlled with a control valve situated at the cell's discharge. The control valve is controlled via a level transmitter which utilizes a floating ball level bracket attached to a shaft and detection disk. The shaft moves freely within a guide to keep the reflective plate (detection disk), which is attached

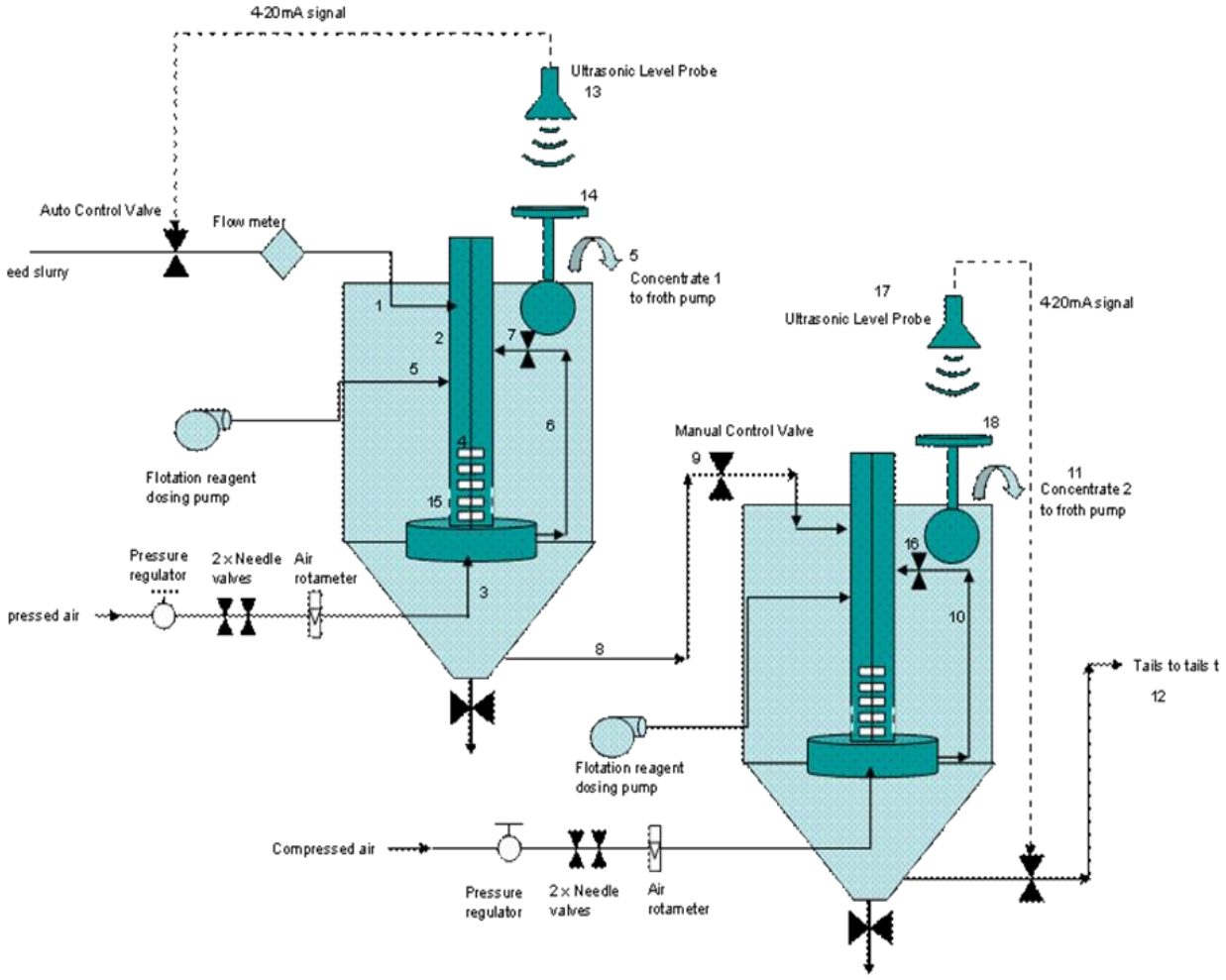


Figure 7: Dual cell process flow and control diagram

to the other end of the shaft, in place. The ultrasonic level transmitter reads the level of the reflective plate effectively indicating and controlling the froth depth. The process flow and control is illustrated in Figure 7.

The flotation product from both the primary and secondary cells is gravitated to a froth pump which is used to break down the froth phase and pump it to a concentrate tank. The flotation tails are gravitated to a tails tank and pumped to the next downstream process.

Chapter summary

Coal particles smaller than 212 µm are treated through the flotation plant at GHS plant. The flotation plant consists of mechanical flotation cells known as Dual cells. The feed to the flotation plant is fed to the primary flotation cells, and the discard arising from primary flotation cells is fed to secondary flotation cells for additional mineral recovery. Reagents increase the flotation kinetics, hydrophobicity and floatability for the mineral. Usually in coal flotation, the higher the reagent dosage the higher the yield and lower the product quality. The reagents used at GHS flotation plant is a combination of CGM 4 and CGH 7, a strong frother component is required due to the challenging flotation characteristics of the feed. The resulting froth is a stable froth with a low flowability and therefore a higher residence time. The secondary cleaning stage of flotation is the froth draining stage, where water containing entrained ash particles is drained from the froth before the froth overflows to the product launder. The high residence time of the froth results in a cleaner product at a lower yield. The flotation efficiency is negatively influenced if the degree of froth drainage is too high. Well drained froths are generally unstable because of the increase in coalescence. Coalescence causes shocks in the froth phase, reducing mineral recovery amd yield. Well-drained froths do not flow well and this in turn greatly decreases recovery

Wash water is applied to flotation cells to remove ash particles contained in the froth by hydraulic entrainment. The use of wash water usually results in a higher product qulity being produced combined with a lower yield. Wash water should be applied as a light rain over the froth at a velocity high enough to move through the froth into the pulp without compromising the froth layer or breaking the bubbles that carry the product.

CHAPTER 3 – DESIGN AND TEST METHODOLOGY

Conventionally wash water is used to improve product quality rather than yield. However the goal of applying the wash water system at GHS flotation plant is to increase the yield while maintaining the current product quality which is already sufficient. This could be possible if the reagent dosage can be increased to increase the flotation intensity while the introduction of the wash water helps to reject the excess low-grade material that has floated due to the higher reagent dosage rates. The result could potentially produce a higher yield with a product quality comparable to the one currently being produced. The experimental program was designed with an objective to investigate this possibility.

3 .1 Stage 1: Froth wash system design

The physical design of the froth wash systems was based on a trial and error approach since there is limited literature available on the subject. A decision was made to design both a froth wash system as well as a lip wash system. By a trial and error approach the wash water system achieved consistency of light rain spray over the froth area. The spray designs, water flow rates and the head were varied until a light rain was achieved. Visual inspection and adjustment of the system was done until it was determined that the wash water system was in compliance with all the requirements of washing as set out in literature. Wash water was made to enter the froth phase at a flow rate high enough to get the required penetration into the froth without compromising the integrity of the froth. Wash water flow rate was increased to ensure that water did not remain on top of the froth to be carried to the product launders with the froth, but instead moved through the froth phase into the pulp phase.

3.1.1 Froth wash tray design

For the froth wash design, a tray distributor was designed from high density poly ethylene (HDPE). This material was chosen due to the corrosion resistance and inert nature of HDPE, low cost of HPDE compared to other materials such as stainless steel, and the simplicity of constructing and modifying designs made with HDPE. For the froth wash tray design, 5 mm holes were drilled every 15 mm in a triangular pattern. The trays were 50 mm in depth to ensure enough head to produce a light rain through the holes when filled with water. The depth was determined by filling

the tray with water to different heights until a light rain was produced from the holes. The trays were mounted onto the flotation cells as high above the froth as the structure directly above the flotation cell would allow. However, the froth height at the center of the cell rose too high such that when the trays were fitted onto the cells, the gap between the trays and the froth became too small to the point that the froth pushed up against the tray blocking the holes. The perforated tray became a flow barrier for the froth, and it was clear that practically the froth wash design was not a solution because retrofitting it into the current GHS flotation plant infrastructure was not possible. In the practical sense, shower trays would tend to block up and would require frequent cleaning. It was challenging to run a cell continuously for more than ten minutes without a blockage. The restriction to froth flow created by the trays would negatively influence yields and flotation dynamics. This proved that the HDPE tray installation was not a practical and viable solution for GHS flotation plant and therefore the froth washing test work was abandoned and only lip wash test work was continued.

3.1.2 Lip wash design

The lip wash design proved to be a much more viable option for GHS flotation plant. Figure 8 illustrates the lip wash design fitted to a Dual cell in the GHS flotation plant.

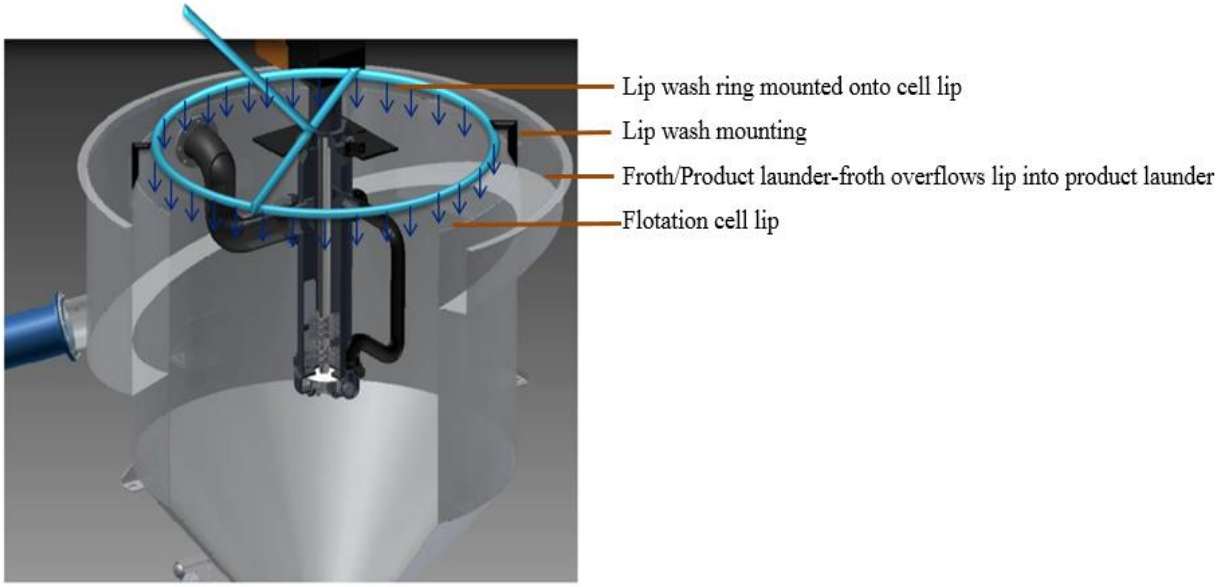


Figure 8: Lip wash design and installation onto a Dual cell (cut-away view of the flotation cell)

The design of the lip wash system consists of a 16 mm (inner diameter) HDPE ring installed around the cell lip. The ring was positioned 50 mm inside the cell lip and mounted 100 mm above the cell lip by means of HDPE mounts onto the cell lip (as high above the cell as possible, just below the structure above the flotation cell). Holes with a diameter of 4 mm were drilled 10 mm apart around the ring to inject wash water downward. The water was introduced above the froth layer directly downwards to wash entrained discard material out of the product froth before the product discharges over the cell lip. The water flow was adjusted to 4.5m^3/h, producing a steady stream of water that was evenly distributed through the whole ring. All test work was conducted at this water flow rate.

3.2 Stage 2: Experimental design

Test work was done on flotation line A1 and A2 at GHS flotation plant. The main objective of the test work was to compare the current plant flotation practice with flotation incorporating lip washing. The flotation plant practice (without lip washing) was used as a baseline. To achieve this, two identical lines were chosen that feed from the same head box and therefore receiving the same feed. The flotation cells on one of these flotation lines was modified and retrofitted with lip wash rings i.e. A2 line. The other line, A1, referred to as the baseline was operated at the same settings at which the plant routinely runs at, i.e. optimized settings, and on that line there was no form of froth washing.

For every single test run, the settings on the baseline flotation line were kept constant. The baseline cells were dosed at 1.3 kg/t, which is the operational dosage of the current optimum plant settings. While the settings on the baseline were fixed, various parameters were varied on the lip wash flotation cell line. This allowed comparison of lip wash performance, at different settings, to the current flotation plant performance. The overall project goal was to achieve higher yields than the baseline cells while achieving similar product qualities. Figure 9 shows a schematic process flow diagram to illustrate the sampling points and the lip wash installation on A2 line. The feed Sampling point is indicated by the red circle marked F on the diagram, the two discard sampling points are brown circles marked with D, and the two product samples are represented by green circles marked with P.

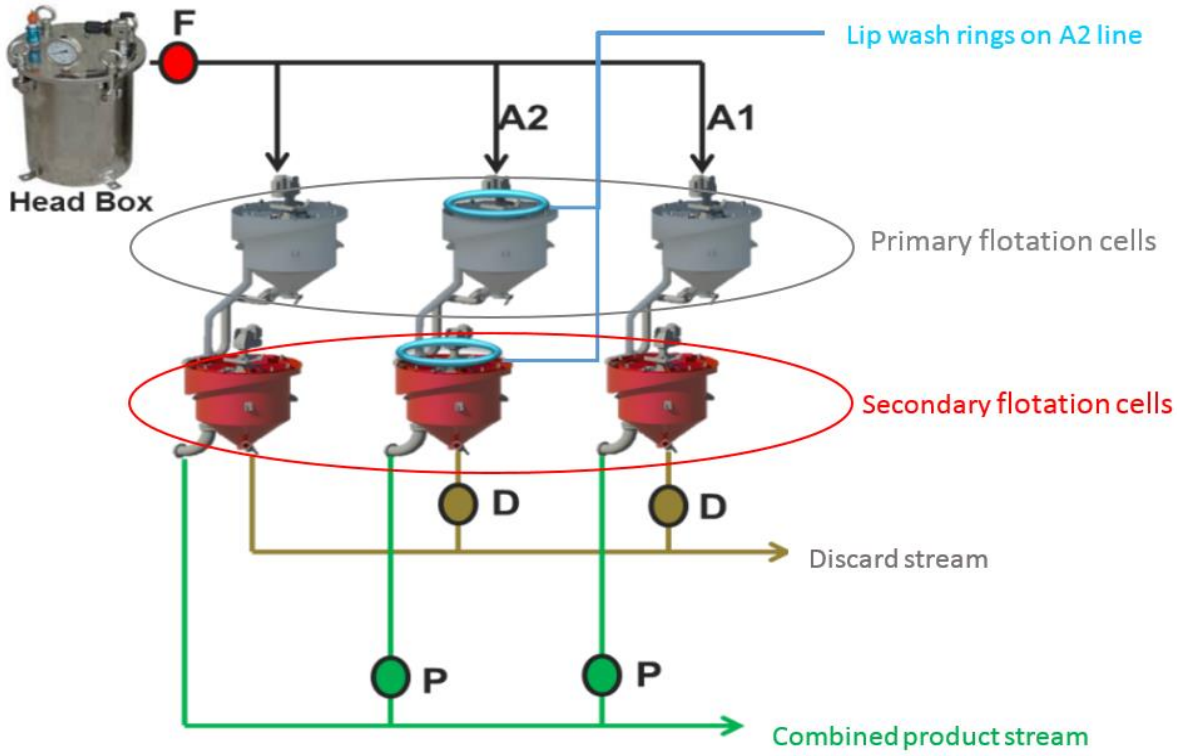


Figure 9: Schematic diagram showing sampling points for test work

In an attempt to understand the effects of a single factor such as reagent dosage on the lip wash flotation line, all other parameters were kept constant on both lines (except dosage). Table 3 summarizes the operating parameters that were kept constant.

Table 3: Standard constant flotation operating parameters

Head box Density	***1.020 t/m^3***
Feed slurry flow rate	200 m^3/h
Solids tons to primary cell	12 t/h
Current reagent dosage	1.3 kg/t
Air flow rate	30 SCFM
Wash water flow rate (A2)	4.5 m^3/h

Prior to each sampling campaign, the flotation cells were individually inspected during a plant shutdown to ensure that the equipment was in an acceptable condition, i.e. Paddles not worn, valves functioning correctly, and so on.

3.3 Stage 3: Experimental runs

3.3.1 Experimental runs 1-4: Combined lip wash on primary and secondary cells vs baseline cells

Conventionally froth washing is used to improve product quality. The aim of installing froth wash at GHS flotation plant is to maximize yield and not to improve product quality. The first and most important question is to understand by how much lip wash can increase the yield while maintaining the required product quality. The first 4 runs were designed to determine the effect, on yield and quality, of varying reagent dosage on the A2 line while applying lip wash on both primary and secondary cells (combined PW and SW) compared to the baseline flotation cell performance (Current plant performance).

Reagent dosages were varied on A2 (lip wash cells) while keeping the reagent dosages constant on A1 (Baseline cells). Table 4 summarizes the settings for the first experimental runs (i.e. run 1 – 4).

Table 4: Settings for the first experimental run: Combined (PW and SW) with varying reagent dosages on lip wash line A2.

	Reagent dosage rate (kg reagent/t dry solids fed)			
Cell	Run 1	Run 2	Run 3	Run 4
A2	1.3	1.45	1.6	1.75
A1	1.3	1.3	1.3	1.3

3.3.2 Experimental Runs 5-7: Repeat Runs on different feed material

After the first four runs were completed some conditions were tested again to determine the influence of wash water on the different types of feed that the plant is receiving. In this research low yielding coals or a low quality feed specifically refers to a coal feed that results in low yields in the current flotation plant. The difference in feed quality could most accurately be evaluated by the performance/yield of the conventional flotation cells with a specific feed. If the conventional cells achieve much lower yields than what is usually observed this indicates that the floatability and hydrophobic properties of the coal feed is less favorable than usual; this is then defined as a low yielding coal in this research. It indicates that the coal being processed through the flotation plant originated from mining in areas where the floatability characteristics of the coal are less favorable. It is difficult to determine with precision exactly where the flotation plant feed originated from as coal from all 6 underground sections come to the plant on the same overland conveyor before being stacked onto the plant stockpiles by means of stackers. The coal received on the plant ROM stockpiles is therefore a blend between coals from the 6 underground mining sections. These ROM feed stockpiles have a live capacity of about 80 000 tons. As mentioned earlier the mineralogy and coal quality tends to vary significantly between the 6 mining sections.

The DMS plant separates coal based on density, whereas flotation separates coal based on surface properties. Therefore, the yield achieved in the DMS plant cannot be used as a measure or means to quantify coal quality feed to the flotation plant. Differences in coal feed quality will therefore be based on the conventional flotation plant performance as a basis, in an attempt to quantify the floatability characteristics of the coal. Low yielding coals or low-quality feed specifically refers to flotation plant yields and flotation plant feed quality in this report. Conditions for Runs 5-7 were chosen as follows:

- Runs 5 and 6: are repeat runs for run 3 on Table 4 i.e. with a reagent dosage rate of 1.6 kg/t and Baseline cells (A1) dosage at 1.3 kg/t.
- Run 7: Repeat run of run 1 on Table 4 with a reagent dosage rate of 1.3 kg/t. and Baseline cells (A1) dosage at 1.3 kg/t.

3.3.3 Experimental Runs 8-11: PWO and SWO vs baseline flotation cells

Primary wash only (PWO) and secondary wash only (SWO) were tested against baseline flotation cells in runs 8-11, at reagent dosage rates of 1.3 kg/t and 1.45 kg/t. PWO is where lip wash is only applied to the primary cell on line A2, and SWO is where lip wash is only applied to secondary cells on line A2. Table 5 summarizes the experimental matrix for PWO and SWO. Baseline cells (A1) were dosed at 1.3 kg/t.

Table 5: PWO and SWO reagent dosage rates

	Reagent Dosage rate (kg/t) on A2	
PWO	1.3 (run 8)	1.45 (run 10)
SWO	1.3 (run9)	1.45 (run 11)

*Increased dosage only applied to cells with lip washing

3.3.4 Experimental Runs 12 and 13: plant performance of lip wash cells against baseline cells when running the plant in AUTO.

The last two runs (runs 12 and 13) were done while running the plant on AUTO completely. In run 12, lip wash was applied to primary and secondary cells. In run 13, lip wash was applied to primary cells only. The AUTO setting applies the following control to the process: The solids are controlled at 15 tph to each cell by a proportional–integral–derivative (PID) controller that measures the thickener underflow flow rate and density to control the tons solids reporting to each line. The thickener underflow pump is a variable speed drive (VSD) pump and is sped up or slowed down to control the solids fed to the flotation plant. The reagent is dosed to the cells at the required flow rate to ensure 1.3 kg/ton dosage. Reagent dosage is automatically adjusted depending on the tph solids fed to each cell (tph reading at that specific point in time because the flotation plant was run in the “AUTO” setting reagent dosage was controlled at 1.3 kg/t for both flotation lines (A1 and A2). The plant usually runs in AUTO when all instrumentation devices are working correctly; the AUTO setting automatically ensures that the cells are all dosed at a specified set point (in this case 1.3 kg reagent/ton coal fed to each cell line). The optimum dosage during test work was

1.3 kg/ton but this set point can be changed so that the AUTO setting controls the dosage to any set point specified. The AUTO setting was not used for all test work because reagent dosage to all cells in the module are controlled to the same set point when running the plant in AUTO. The project investigated the performance of the optimum current flotation plant (dosed at 1.3 kg/ton) to different reagent dosages on the lip wash cells. In order to keep one test line on a 1.3 kg/ton dosage but increase the dosage on another test line, the AUTO setting could not be used for all test work.

3.4 Stage 4: Sampling & Analysis

3.4.1 Sampling Procedures for manual sampling of Slurries

The SANS 20904:2007 standard is a South African National Standard (SANS) for the sampling of slurry material. This national standard is identical in implementation to ISO 20904:2006 which was developed by the International Standards Organization (ISO). Therefore, the sampling procedure used complies with ISO and SANS standards.

The basic principle behind this sampling standard is that all parts of the slurry in the lot should have an equal opportunity of being selected and appearing in the lot sample for testing. Any deviation from this basic principle can result in an unacceptable loss of accuracy.

SANS 20904:2007 describes procedures that are designed to acquire samples that are representative of the slurry solids and particle size distribution of the slurry under examination. For the purposes of this standard, a slurry is defined as fine coal, coal rejects or tailings of nominal top size < 1 mm that is mixed with water, which is frequently used as a convenient form of media to transport coal, rejects or tailings through plant circuits by means of pumps and pipelines and under gravity in launders or chutes or through long distances in slurry pipelines.

The first aspect to consider when sampling is the sampling location. According to SANS 20904:2007, the sampling location should:

i. Afford complete operator safety
ii. Afford access to the complete slurry stream

iii. Allow no apparent visual segregation of the slurry stream

iv. Be as close as possible to the point where the quality characteristics are determined

In most cases, the only sampling location that satisfies the above criteria is a transfer point. For manual sampling, ladles are acceptable. The cutting aperture of the ladle should be at least 3 times the nominal top size of the particles in the slurry. Table 6 shows the values for the minimum mass of solids for general analysis for a precision of 0.2% with regards to ash.

Table 6: Minimum mass of solids in a lot sample for general analysis (South African Coal Processing Society, 2002)

Nominal top size of solids in slurry (mm)	Minimum mass of solids required for general analysis samples and common samples (kg)
4.0	1.6
2.8	0.65
2.0	0.25
1	0.1

3.4.2 Test work sampling

Sampling in the plant test-work was done according to the South African National Standards (SANS) procedure for sampling slurries (SANS 20904:2007) described in section 3.4.1.

Feed samples were taken in 32 sample increments, while product and discard samples were taken in 16 increments as per the standard requirements. A minimum mass of 100 g solids is required for each increment. To achieve the minimum mass requirements product increments were taken in 1 L increments, discard samples on baseline cells were 2.5 L increments, discard samples on lip wash cells were taken in 5 L increments (to account for the density change in underflow because of the lip wash application) and feed samples were taken in 2 L increments. Samples were taken every 2.5 minutes on the feed and every 5 minutes on the product and discard streams. The total time required to sample one run was 80 minutes. During the 80 minutes of sampling each run the

plant conditions were closely monitored by the control room operator and all persons sampling and working in the plant to ensure that the plant was operating efficiently and running at steady conditions. Whenever deviations in the plant performance were identified sampling was immediately stopped and the incremental samples were discarded, the run was then redone as soon as the plant could run efficiently at steady conditions. Between different runs (therefore different plant settings) the plant was run for 10 minutes before sampling to ensure that the plant was running at steady state before sampling for the next condition (or run) was resumed. The residence time per cell is 3 minutes, therefore, the system has ample time to reach steady state at the new run settings. Each run consisted of 5 samples; the total feed sample for each run was 32 L, the two product samples were 16 L each, the baseline discard samples were 40L each and the lip wash discard sample was 80 L. In total there were 65 samples for the 13 runs.

3.4.3 Sample preparation and analysis

After samples were taken, they were prepared for analysis using the protocol outlined in this section. Sample preparation was done carefully so that the analyzed sub-sample remained representative of the whole sampled material.

The preparation of each sample involved the following stages:

- Filtration
- Drying
    - The cake from the filtration step was then dried in an oven at 40 °C to remove moisture. As soon as the cake was dry, it was removed from the oven to prevent the degradation of the ultra-fine solids under heat.
- Reducing the sample size by cone and quartering
- Crushing the reduced sample amount (except the portion that undergoes a size analysis)
- Analysis of sample

3.4.3.1 Sample analysis

To evaluate the effect of the lip wash cells and compare it to the baseline cells the following analyses were done:

- Size analysis of each sample through wet screening. Done according to the SANS 1953:1994 standard.
    - With the following screen sizes: 500 µm, 300 µm, 212 µm, 125 µm, 106 µm, 75 µm, 63 µm, 45 µm, 25 µm.
- Ash analysis on each size increment of every sample. Done according to the SANS 131:2011 standard.
- Ash analysis on all samples (composite ash). Done according to the SANS 131:2011 standard
- CV analysis on product samples (composite CV). Done according to the SANS 1928:2009 standard)

Yields can be determined by an ash balance. It is assumed that the ash in the feed is distributed between the clean coal and the discard in proportion of their yields (South African coal processing society, 2002) so the yield can be calculated by a mass balance. Product quality can be evaluated on the basis of product ash or product CV on an air-dry basis (adb).

A composite sample is obtained by splitting and reducing the large, filtered and dried sample, combining different parts of the large sample to obtain a smaller representative sample of the entire sample. Before ash and CV analysis is done, samples were dried in an oven at 40°C, and milled to -212µm with a grinding mill. Cal-2K bomb calorimeters were used to measure CV. A sample of 0.5000g is weighed and placed inside the bomb, then the bomb is pressurized to 3000 kPa before being placed into the Cal-2K calorimeter. Ash analysis is done by placing 1.000g of sample into an oven which operates at 800°C for 1 hour. The weight of the material left after the sample has been in the oven for an hour (ash of the sample) is recorded and converted to a percentage.

CHAPTER 4 - RESULTS AND DISCUSSION

Wash water is conventionally used to improve product quality rather than yield. However, the goal of applying a wash water system at GHS flotation plant is to try and increase the yield while maintaining the current product quality which is already sufficiently good. The hypothesis of the current research is that an increase in product yield could be achieved by applying lip wash while increasing flotation reagent dosage that increases the flotation rate. The increase in reagent dosage increases yield by floating more low-grade coal, and the addition of wash water increases the product quality by removing hydraulic entrainment. The net effect of these two processes occurring simultaneously could result in a higher plant yield with a product quality comparable to the one currently being produced. The coal feed processed during test work is bitumious coal from the 4 seam Witbank coal fields, with an ash content of between 30-37%.

4.1 CV-ASH correlation

In coal processing it is well-known that there is a direct correlation between product CV and product ash. For thermal coal the higher the ash content in the product the lower the product CV and product quality. Figure 10 shows a plot of the product CV (adb) against the product ash for all samples analyzed from runs 1 – 13.

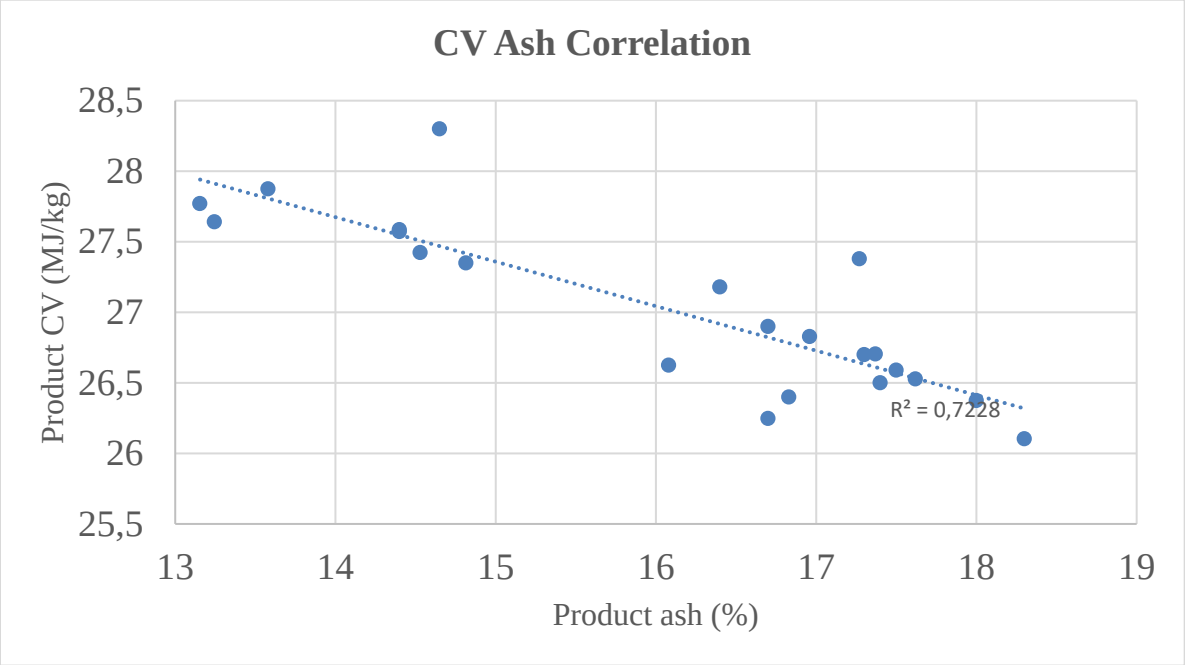


Figure 10: CV vs Ash for all product samples analysed for runs 1-13

The results in Figure 10 show the expected trend in which the coal product CV is inversely proportional to the ash content. Figure 10 also shows that the product quality for many of the samples was slightly lower than the target CV of 27.3 MJ/kg (adb). The comparison of product quality will be based on the baseline cells product quality rather than a strict value of 27.3 MJ/kg (adb), such that when baseline cell product ash value (quality) is similar to lip wash product ash value then the goal of achieving a similar quality via the lip washing route would have been met.

4.2 Combined primary wash (PW) and secondary wash (SW) vs baseline flotation: Experimental runs 1 -4

4.2.1 Effect of varying reagent dosage on yield

In the experimental runs 1-4, the flotation reagent dosage on the baseline flotation line was kept constant at 1.3 kg/t while the dosage on the lip wash line was varied as indicated in Table 4: Run 1 - 1.3 kg/t, Run 2 - 1.45 kg/t, Run 3 - 1.6 kg/t and Run 4 - 1.75 kg/t. All other flotation conditions were kept the same on both lines, see Table 3.

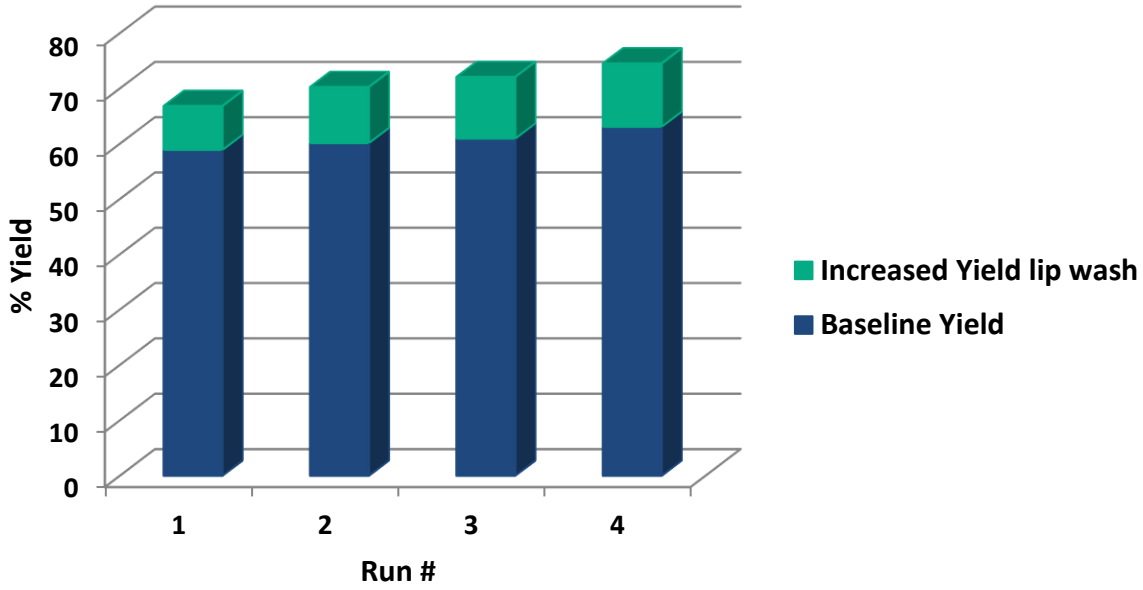


Figure 11: Baseline flotation yield and increased lip wash yield for run 1-4

The yields presented in the results were calculated from an ash balance, a common practice in coal preparation. With an ash balance it is assumed that ash in the feed is distributed between the product and the discard in the proportion of the yields (The South African coal processing society, 2002), and the yield is calculated with a simple mass balance. The results from Figure 11 show a constant yield of about 58 – 60 % on the baseline flotation line across runs 1 – 4.

This validates the reliability of the test work as runs 1-4 were conducted using similar coal feed material and therefore there was an expectation that the yield will be similar. The results also clearly demonstrate that there is a marked increase in the yield when lip washing is utilized. In Run 1 where the flotation reagent dosage of 1.3 kg/t was used on both the baseline flotation line and the lip wash line it can be seen that the yield on the lip wash line improved to about 67% which represents a significant improvement in the yield of about 8%. A further increase in the flotation reagent dosage in runs 2, 3 and 4 (reagent dosage increases of 0.15 kg/t reagent per run) resulted in further improvement in the yield. A yield of up to 73% was recorded at the maximum dosage of 1.75 kg/t with lip wash. Higher reagent dosages generally result in higher yields. It could therefore be inferred that lip washing has a positive effect of improving the yield on coal fines

flotation and that the increase in the reagent dosage further increases the yield albeit not in direct proportion.

An optimum reagent dosage needs to be identified where the product quality should not be compromised. Flotation reagent costs are a major operational cost driver in the flotation process and therefore this will also need to be considered to determine the optimum reagent dosage. The optimum reagent dosage will be the dosages where the product quality (or product ash) of baseline cells and lip wash cells are similar. The product quality is compromised if the product ash of the lip wash cells is higher than the product ash of the baseline cells. If increased yields are not accompanied by a similar product ash it is not a viable option for the plant as product quality is compromised to achieve the increase in yield.

4.2.2 Effect of varying reagent dosage on product quality

Figure 11 shows that the lip wash cells produced a higher yield than baseline cells for each run. The effect of the lip wash and increased reagent dosages on product quality will be evaluated. The product quality was compared in terms of the percentage ash in the product instead of product CV. It was however demonstrated in Figure 8 that there is a direct relationship between % ash and CV so both these characteristics can be used interchangeably as a measure of thermal coal quality. Figure 12 shows a plot of % yield for both baseline flotation and lip wash flotation on the left vertical axis, and % ash of product from both baseline flotation and lip wash flotation on the right vertical axis. Figure 13 is identical to Figure 12 except that it excludes the baseline flotation yield so that focus may be clearly placed on the product quality that was achieved in each run. Figure 11 and 12 illustrate the yield increase achieved by lip wash. Figure 12 and 13 further illustrate the product qualities achieved for each flotation line in runs 1-4.

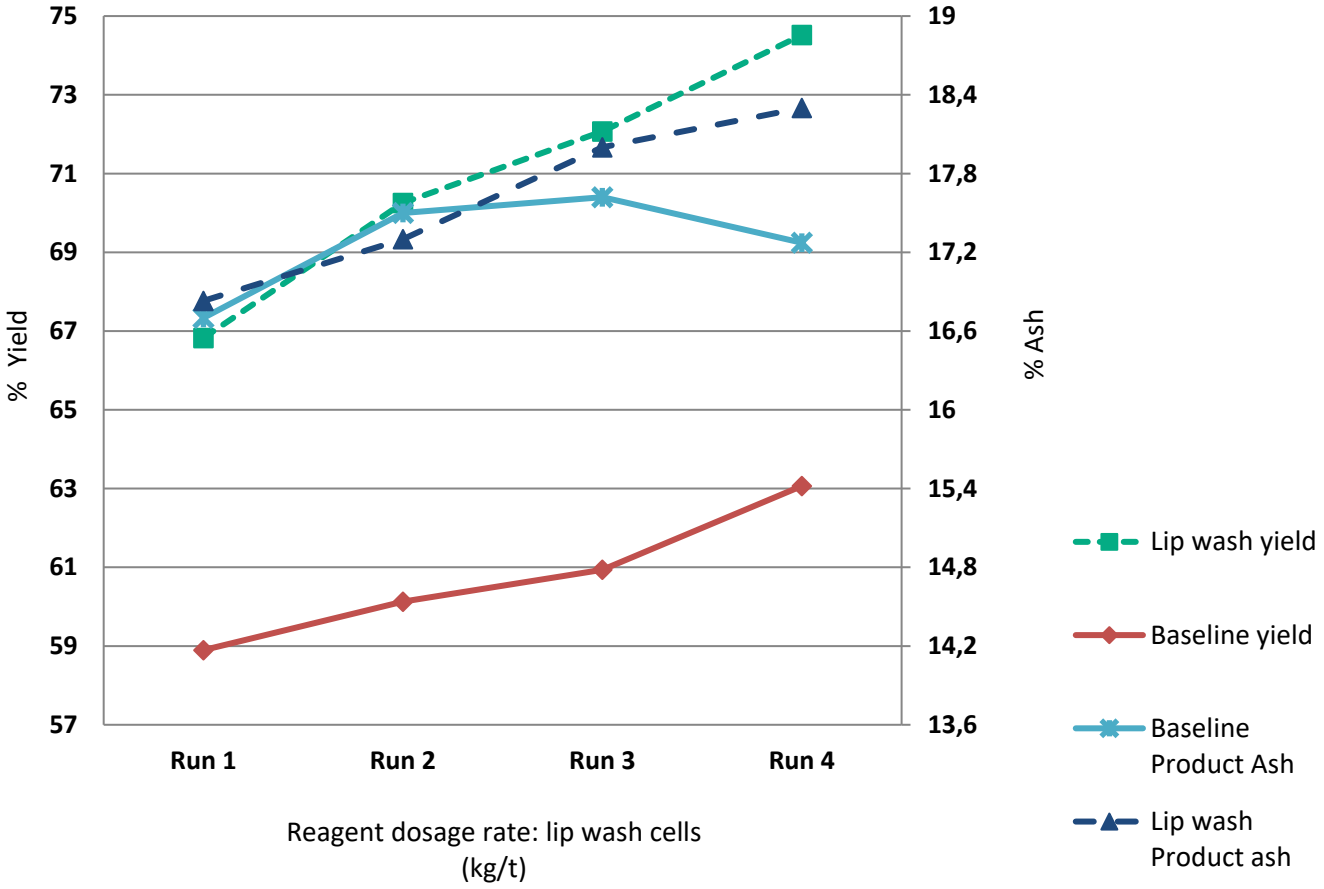


Figure 12: Effect of flotation reagent dosage on % product ash and yield

An increase in reagent dosage does increase froth stability as more frother is dosed to the flotation cell. This contributes to the increased yields observed at higher reagent dosages. Without lip washing the froth stability at high reagent dosages compromises yield as the froth is too stable to gravitate into the product launders, and forms a plug above the flotation cell.

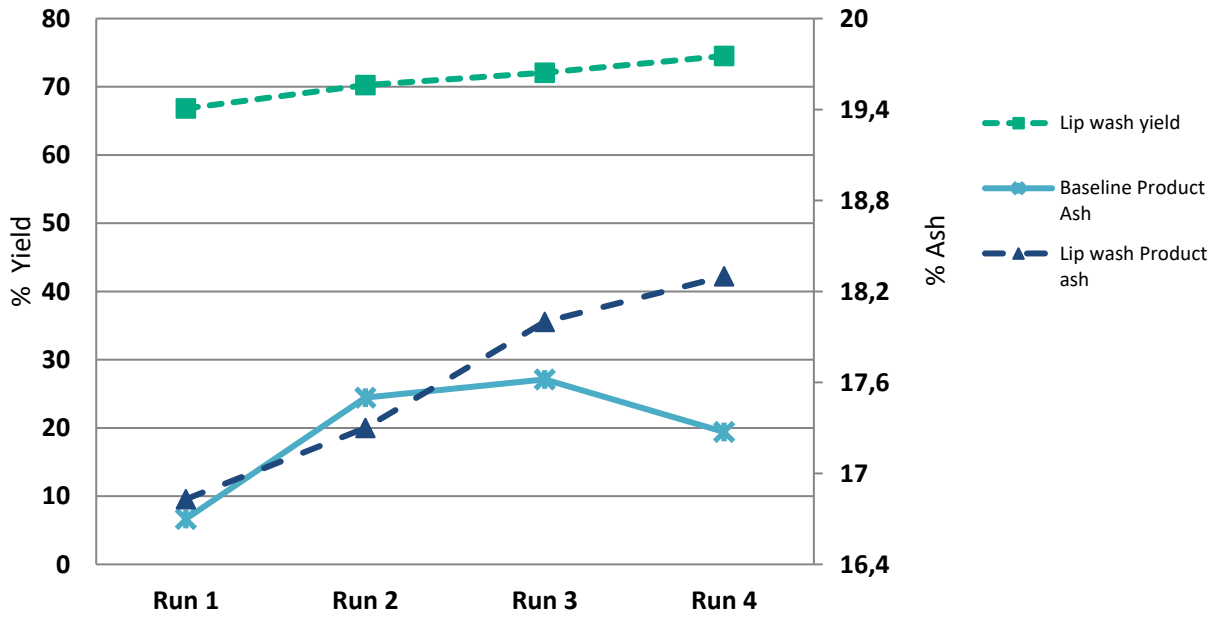


Figure 13: Product quality comparison between Baseline and Lip wash flotation cells for runs 1-4

In the previous section it was established that lip wash yield was higher than baseline cells yield for runs 1-4. It was also shown that the yield on the lip wash cells increased as the reagent dosage increased. The goal now becomes the identification of the dosage where the highest yield increase is achieved while maintaining similar product qualities (or product ash values). The results in Figure 13 also show that the product quality produced from baseline flotation and lip wash flotation as measured by the ash content is comparable up to the reagent dosage of 1.45 kg/t. This implies that when the reagent dosages are between 1.3 -1.45 kg/t (on the lip wash flotation line) product quality on lip wash cells are similar to product quality on baseline flotation cells. Therefore, at these reagent dosages lip wash cells produce a much higher yield than the baseline flotation cells without compromising product quality. When the reagent dosage is increased above 1.45 kg/t the results in Figure 13 show that the ash content of the lip wash product increases significantly as a result of the increased reagent dosage. This means that at dosages higher than 1.45 kg/t the coal product quality from lip washing drops considerably though the yield is still improving. Therefore, a tradeoff needs to be made between yield and product quality when reagent dosage is increased and lip wash is applied. To realize maximum yield gains and still obtain product quality comparable to that achieved using the conventional baseline flotation, then reagent

dosages of 1.45 kg/t or less need to be used at this plant. The economics of yield gain against reagent cost should be established to determine the most profitable reagent dosage.

These results are significantly different from any that is published in literature on froth washing. Most froth washing applications reported in literature show that froth washing generally increases the product quality (by decreasing product ash) while yield normally decreases, and this trend is consistent in all literature available on the subject. However, the approach and the results in this present work indicate that it is possible that a yield increase can occur without a change or a minimal change in product quality by froth washing. For run 1 where both the baseline cells and lip wash cells were dosed at a reagent dosage of 1.3 kg reagent/ton coal feed an increase in yield was observed where lip wash was applied without affecting product quality. When flotation intensity is increased by increasing flotation reagent dosages (to 1.45kg reagent/ton coal feed) a further increase in yield was observed without compromising product quality (as was hypothesized in this research).

Visual observations of flotation cells at GHS that run with lip wash compared to other cells that do not have lip washing in the plant showed a distinct difference in the froth behavior. There is a significantly visible increase in froth mobility when lip wash is applied to the cells. The reason for the increased froth mobility is the additional water present in the froth phase due to the lip wash. As a result of this increase in froth mobility the froth is moved to the product launders much faster than usual. Usually increased froth mobility has a negative effect on the natural secondary cleaning stage that happens in the froth phase, as the residence time for froth drainage is decreased with the increased froth mobility. Under normal circumstances this should increase yield, but since the secondary cleaning stage residence time would be reduced, froth drainage and removal of ash and gangue material would not be effective resulting in the decrease of product quality. However, in this case the installation of lip washing has a dual action, it increases froth mobility while also washing down entrained ash from the froth layer before the product gravitates into the product launder. This results in increased yield without compromising product quality even when lip wash cells are dosed at the same reagent dosage as the conventional plant dosage (i.e. 1.3kg/t).

4.2.3 Yield and quality as a function of particle size

Figure 14 shows a plot of the yield and product ash as a function of particle size for flotation Run 1 conducted at reagent dosage of 1.3 kg/t for both baseline flotation and lip wash flotation.

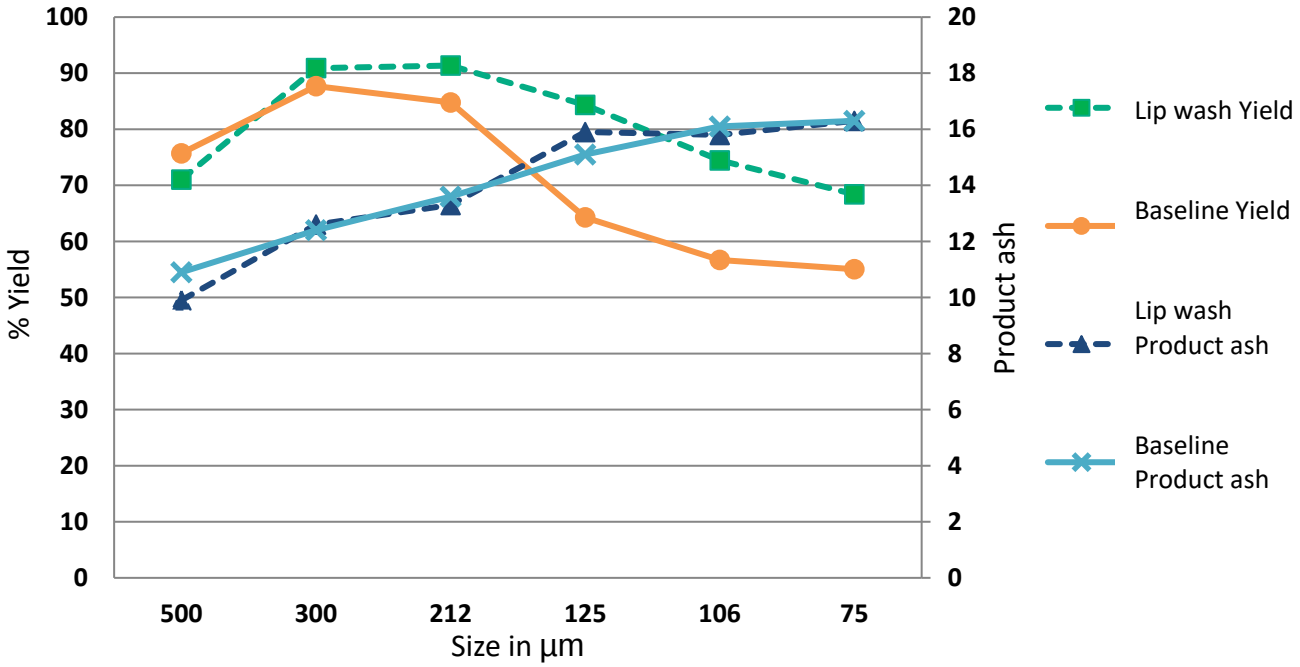


Figure 14: Yield and quality as a function of particle size for run 1

The results in Figure 14 show that the % yield by size generally increases as particle size decreases from 500 to 300 µm and then decreases as the particle size decreases below 300 µm for both baseline flotation and lip wash flotation. The ash content in the product increases with a decrease in particle size, meaning that the finer particles are generally associated with higher ash content than coarser particles. It is also instructive to note that ash content for all the sizes is below 16 wt% which corresponds to an acceptable minimum quality of 27 MJ/kg according to Figure 10 that demonstrates the CV-ash correlation.

Figure 14 also shows that flotation of particles in the size class – 500 µm + 300 µm, regardless of whether baseline flotation and lip wash flotation is used, does not result in an appreciable yield difference. However, as particles get finer, i.e. < 212 µm, lip wash flotation causes a significant increase in the yield of the respective particle sizes. The ash content, however, appears to be

comparable across the entire particle size spectrum for both baseline flotation and lip wash flotation products, meaning that quality is maintained while yield is being increased. It can also be inferred that as long as the flotation plant does not receive oversize material, i.e. > 212 µm particles, lip washing will produce higher yields and required product quality when a reagent dosage of 1.3 kg/t is used. During test work small amounts of oversize material were reporting to the flotation plant, this is due to wear on the classifying cyclones that separate the spiral plant material from the flotation plant material. The amount of oversize material received in the flotation plant during test work was very low and well within the range of what the flotation plant can tolerate and should therefore not be a concern.

4.3 Combined primary and secondary wash vs baseline flotation: Experimental runs 5 -7

4.3.1 Effect of varying reagent dosage on yield on a different coal feed material

To investigate the effect of lip washing on different coal feed materials, selected flotation test-work re-runs were performed at identical conditions used for Run 1 and 3. Figure 15 shows the comparison of the yield obtained for Run 1 and 3, which were conducted at reagent dosages of 1.3 kg/t and 1.6 kg/t, and the parallel runs done on a poorer coal feed (re-do's) conducted at the same flotation conditions.

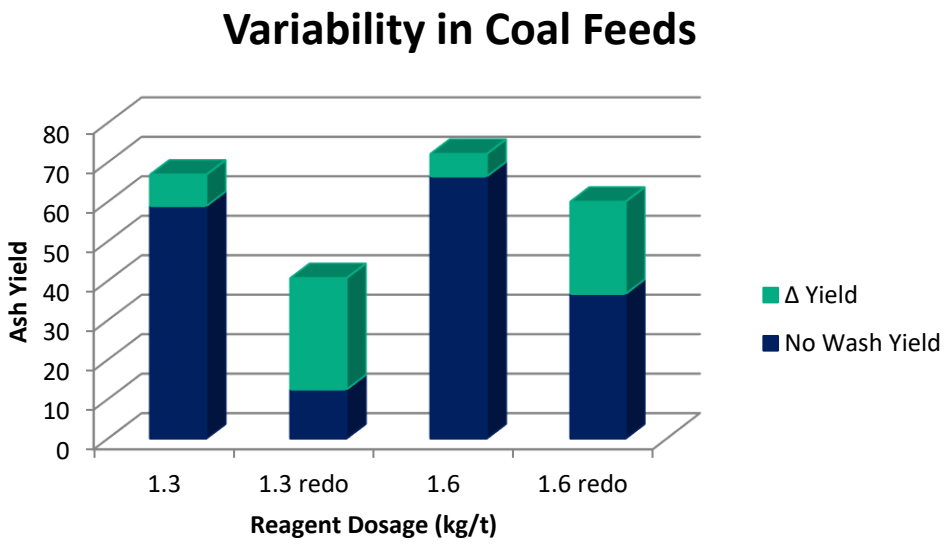


Figure 15: Comparison of lip wash on different coal feed qualities

The results illustrate how severely the flotation plant can be affected by the type of feed it receives. On one specific day a yield of 54% can be achieved in the current flotation plant (baseline cells) but on another day when a different feed is received into the flotation plant, only a 10% yield can be achieved. A coal feed that results in low yields on baseline cells is referred to as low quality feed. Results shown on Figure 15 suggest that much bigger increases in yield are possible with lip wash when the plant is fed with a low-quality feed. In this case a feed that achieves 54% yield in baseline cells records a yield increase of 8% with lip wash applied, whilst a feed which recorded 10% yield in the baseline cells registers an increase of almost 30% in yield when lip wash is applied. Therefore, lip wash was able to realize an 8-30% yield increase above the current flotation plant yield.

With the challenging floatability and hydrophobicity properties of low yield coals (during a flotation application) the chances that coal particles will be recovered once they have detached from bubbles in the froth phase are slim. Bubbles in the froth layer are not all of equal size, as they tend to increase in diameter as they approach the surface, due to froth drainage and coalescence. As the bubble size increases with height the available surface area for particle attachment decreases (Michaud, 2016). This leads to greater competition for free bubble sites which in turn leads to mineral loss to the pulp phase. As observed by Atkinson et al (2001) with the use of wash-water bubble size remained uniform because of the reduction in coalescence, in turn reducing the competition for bubble sites. Froth stability is also improved because bubble coalescence is reduced by the use of wash water. Coalescence also causes shocks in the froth phase that leads to further mineral losses to the pulp (Atkinson et al, 2001). For this reason, the yield increase possible with lip wash when floating low yield coals is significantly higher, as it is much more difficult to recover detached coal particles if the flotation kinetics and flotation thermodynamics of the coal are significantly lower than ideal. This further reinforces the need to introduce lip washing at GHS, as it can help realize substantial gains if the coal feed qualities drop drastically. The value of lip wash becomes more significant as coal reserves deplete and lower quality coal deposits need to be mined to extend the Life of Mine (LOM).

4.4 Comparison of the Effect of Primary Wash Only (PWO) & Secondary Wash Only (SWO) vs Baseline Flotation: Experimental Runs 8-11

In this section the baseline flotation performance (flotation on standard cells) was compared to two lip wash scenarios. The first lip wash scenario was when lip washing was applied on the 1st or primary cell, while no lip washing was applied on the secondary cell. The second lip wash scenario was the case where no lip washing was applied on the primary cell while only applying lip wash on the secondary cell, which is fed by the underflow (discard) of the primary cell. These test-work runs were conducted at two flotation reagent dosages of 1.3 kg/t and 1.45 kg/t.

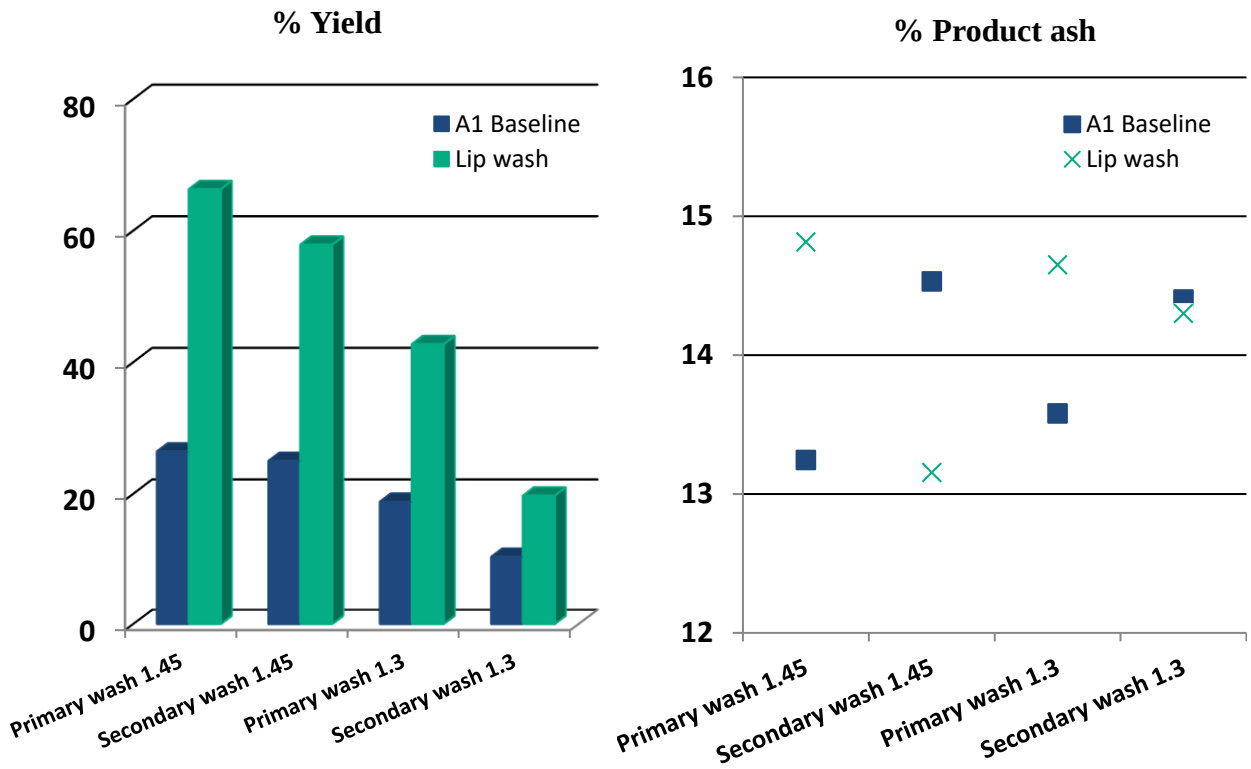


Figure 16: Comparison of Primary Wash Only (PWO) and Secondary Wash Only (SWO)

The results of the comparison of PWO and SWO with baseline flotation are shown in Figure 16. The plot to the left is the yield results and it shows that PWO achieved higher yields than SWO at the respective reagent dosages used. It is also clear that lip wash cells achieved significantly higher yields than baseline cells, and that the feed quality to the flotation plant was low at the time of sampling. As observed earlier, higher reagent dosages produce higher yields.

The plot to the right of Figure 16 is the product ash results, and it shows that product ash for PWO is higher than baseline cells. The product ash produced with PWO is also higher than with SWO applied (for both reagent dosages). The results in Figure 16 show that while higher yields can be achieved with PWO, product qualities will be compromised (lower product qualities than baseline cells and therefore lower product qualities than current flotation plant performance). SWO appears to be more favorable as yields are still much higher than those obtained from baseline cells while a higher product quality (lower product ash) is achieved.

The possible reason for lower product quality (or higher product ash content) when PWO is applied is that during PWO lip wash, wash cleaning is done on the primary cells resulting in the production of a fairly clean concentrate product while apparently all the washed down and rejected ash forms part of the feed to the secondary cell. In the secondary cell, which now floats a poorer feed (with a higher ash content) than the primary cells, no lip washing was applied resulting in the production of a contaminated product with higher ash content which was then combined with the product of the primary cells. The result is a product stream with a significant amount of ash. On the other hand, when SWO was applied, a fairly good quality product was produced from the primary cell. It has already been noted that both baseline/standard flotation line and lip wash cells produce a product of comparable quality when fed with the same feed material. However, in the SWO the feed into the secondary cells (discard/underflow from the primary cells) is cleaner than that produced during PWO and above this lip wash is applied on the secondary cells resulting in further improvement in the overall quality of the SWO product. The combined product stream with SWO therefore has a higher product quality than baseline cells.

4.5 Experimental runs 12 and 13: Plant performance lip wash cells against baseline cells when running the plant in AUTO

The last two runs (runs 12 and 13) were conducted while running the plant on the AUTO setting at a 1.3 kg/t dosage. In run 12, lip wash was applied to primary and secondary cells. In run 13, lip wash was applied to primary cells only. Therefore, these runs allow for a comparison between PWO and combined primary and secondary cell washing. In Section 4.3 of the results it was shown that yields for PWO are higher than that of SWO, but product quality is compromised with PWO. This section will compare the performance of PWO to combined washing. Figure 17 shows the yield and quality results for experimental runs 12 and 13.

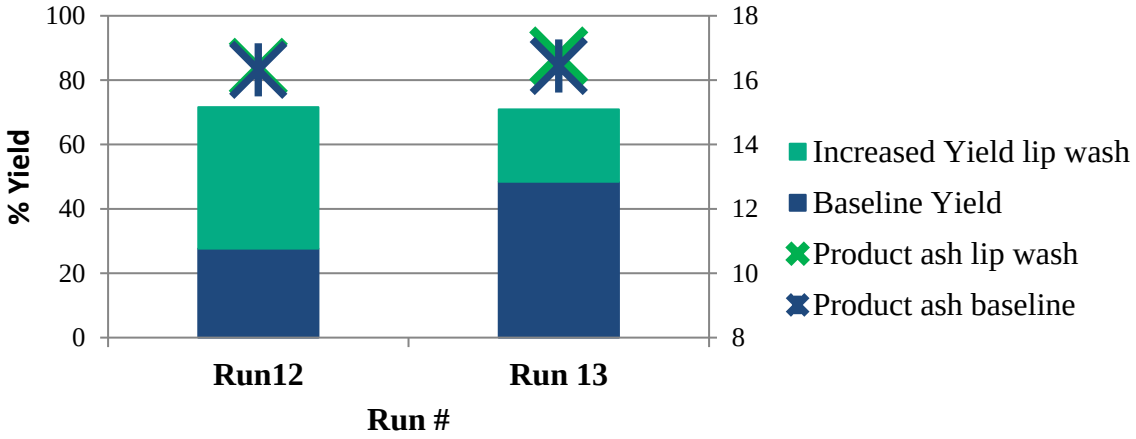


Figure 17: Lip wash results when running the plant in AUTO

The graph in Figure 17 once again shows that applying lip wash to flotation cells increased the yield while not compromising product quality for a reagent dosage of 1.3 kg/t. The yields achieved with combined wash and PWO were similar although the product quality for combined wash was better than that of PWO. The increase in yield achieved with lip wash was higher with the combined wash, but this is more likely due to feed quality. Because the effect of low quality feed plays a major role in the increase in yield possible we are not able to conclude that the yield increase with combined wash is higher than with PWO. Results in Figure 16 and 17 show that the product ash for PWO was higher than product ash for baseline cells, suggesting that product quality is compromised to achieve the increase in yield observed.

It is possible to conclude that combined washing on primary and secondary is preferable to SWO from the results in Figures 16 and 17, and the results presented in section 4.3. Results showed that

SWO achieved lower yields than PWO although product qualities with PWO were lower than baseline cells (and SWO). Figure 17 shows that combined washing produces similar yields to PWO, and that product qualities are similar to baseline cells (as shown for all runs where 1.3kg/t reagent is dosed to the lip wash line). The results therefore suggest that combined washing is more favorable than SWO as it achieves the higher yield that PWO achieves, without compromising product quality.

4.6 Possible mechanisms: froth washing at GHS

The results have shown that an increase in yield is possible without decreasing product quality, contrary to findings and observations in literature where lip and froth wash result in higher product qualities accompanied by lower yields (Atkinson et al, 2001; Finch, 1994; Kaya et al,1990; Moys,1978). The mechanisms responsible for the unique results observed in this study is a combination of various factors. The first important observation to note is the significant increase in froth mobility when lip wash is applied. With the increased froth mobility the froth residence time decreases dramatically, impacting the secondary cleaning stage. The amount of froth drainage is highly dependent on froth residence time as shown by Bisshop and White (1976) and Cutting et al (1986). The froth reaching the cell lip now contains more ash particles in the water between bubbles. The lip wash water presumably removes roughly the same amount of material that would usually be drained from the froth during the secondary cleaning stage. Therefore, the quality of the lip wash cells and conventional flotation cells are similar, and because of the increased froth mobility the yields of the lip wash cells are higher than the conventional flotation cells. Another factor that would contribute to the increase in yield observed is a reduction in coalescence due to the increase in froth mobility. As mentioned in section 2.4 of the literature study coalescence increases as the secondary cleaning stage residence time increases and the froth drainage increases (Cutting et al, 1986; Kuzkin et al, 1983; Moys, 1984; Subrahmanyam and Forssberg ,1988).

The magnitude of the yield increase possible with lip wash depends on the type of coal (feed type) that is processed. Coal feeds that achieve higher yields in the conventional flotation cells have shown that yield increases of between 8-12% are possible with lip wash, while coal feeds that achieve lower yields in the conventional flotation cells could realize yield increases between 30-40% with lip wash. The reason for this is presumed to be the flotation thermodynamics and

kinetics. When the floatability characteristics of the coal feed is less favourable, the probability to recover a coal particle once it detaches from an air bubble is significantly lower. Coalescence results in the detachment of coal particles due to the decreased surface area after coalescence. Coalescence also creates shocks in the froth phase that could result in further mineral detachment (Atkinson et al, 2001). Therefore it is presumed that the higher yield increases possible when floating low yield feeds is due to the decrease in coalescence that results in coal particles being removed before they detach, and the chances for recovery a second time is significantly less. The increased froth mobility could also contribute to the higher yield increases possible as mineral particles are removed to the product stream faster, before they have a chance to detach.

CHAPTER 5 – CONCLUSIONS AND RECOMMENDATIONS

Test work has shown that a yield increase between 8-40 % is possible when applying lip wash, compared to the current performance of flotation cells. The flotation cells with lip wash achieved a higher yield than the baseline cells which represent the current flotation plant performance.

5.1 Froth wash design

The most suitable design for a froth wash system at GHS plant was found to be a lip wash configuration. This was the most practical solution considering the small clearance available above the froth. The walkway mounted above the cell limited the space available above the froth significantly, especially toward the centre of the cell where the froth height was at its highest. The system was constructed out of HDPE, a non-corrosive, abrasion resistant inert material. HDPE is also an inexpensive material and the simplicity of construction and modifications of systems and designs with HDPE is another benefit. The design of the lip wash system consists of a 16 mm (ID) HDPE ring installed around the cell lip. The ring was positioned 50 mm inside the cell lip and mounted 100 mm above the lip level. Holes with a diameter of 4 mm were drilled every 10 mm around the ring to inject wash water downward. The water flow was adjusted to 4.5m^3/h, to produce a steady stream of water that was evenly distributed through the whole ring. As suggested by literature the lip-wash water flow resembled a light rain at this flow rate.

5.2 Lip wash test work

Froth washing on coal flotation cells at GHS flotation plant can bring about a yield increase while maintaining the product quality required, therefore the current plant performance can be improved by introducing lip wash.

In the case of primary and secondary wash, if the reagent dosage is between 1.3-1.45 kg/t, test work shows that a product quality better than or similar to the product quality of the baseline cells was produced by applying lip wash. As reagent dosage increases the yield increases, and at reagent dosages of 1.6 kg/t and 1.75 kg/t product quality was compromised. The maximum yields possible when applying lip wash, while ensuring acceptable product qualities, were found to be up to 70%.

Test work also shows that high yield increases are possible if the feed introduced to the flotation units is coal with challenging flotation kinetics and thermodynamics (the type of coal that would usually result in low yields in the conventional flotation plant). Therefore lip wash increases the range of coal qualities that could be more efficiently processed in the flotation plant.

The comparison of the PWO to the SWO showed that higher increases in yield are achievable using PWO rather than SWO, however, a lower product quality was produced with PWO compared to that produced by SWO and baseline flotation cells. SWO produces a product with the highest quality. The possible reason for the result is that when applying lip wash to the primary flotation cell only, a cleaner product is produced in the primary flotation cell but the underflow of the primary cell (which is the feed to the secondary cell) is of a much poorer quality than usual as most of the entrainment has been washed to the underflow of the primary flotation cell. This will result in a higher ash product from the secondary cell, because of a significant amount of gangue material reporting to the product stream due to hydraulic entrainment. The combined product for the primary and secondary cells then contains a significant amount of ash. When lip wash is applied to secondary cells only, a high product quality is produced from the primary cell. It has already been noted that both baseline/standard flotation line and lip wash cells produce a product of comparable quality when fed with the same feed material. However, in the SWO the feed into the secondary cells (which is the underflow from the primary cells) is not as dirty as that produced during the PWO and further to that lip wash is applied on the secondary cells resulting in further improvement in the overall quality of the SWO product.

In the GHS flotation plant, wash water serves two purposes. The major purpose is to displace pulp water (and hence entrained contaminants) from the froth. Another purpose is to improve the froth mobility through maintaining a high water content in the froth.

An interesting observation was that lip wash increased yields while achieving similar product qualities at the current plant's optimum reagent dosage of 1.3 kg/ton. Therefore, the hypothesis that it would be necessary to increase reagent dosage to achieve an increased yield with uncompromised product qualities was not completely true, as it is not necessary to increase reagent dosage to achieve the goal of this project.

This research has enabled a better understanding of the dynamics and the influence of a lip wash system on the Dual flotation cells at GHS flotation plant. The mechanisms responsible for the increase in yield are most likely due to the increased froth mobility and the regulated bubble size by reduction of coalescence. The residence time of the froth phase is dramatically decreased by increased froth mobility which increases the yield. However, froth drainage is significantly reduced when froth mobility is increased and this has an effect of compromising the product quality. The hydraulically entrained ash and waste is removed by the lip wash water, therefore, compensating for the reduced secondary cleaning phase. It is presumed that this is why an increase in yield is possible with product qualities remaining similar to the baseline cells product qualities with a longer secondary cleaning stage (and froth residence time).

5.3 Recommendations

1. A lip wash configuration is recommended for GHS flotation plant. The lip wash system should consist of a 16 mm (ID) HDPE ring installed around the cell as per the design for test work in this study. The ring should be positioned 50 mm inside the cell lip and mounted 100 mm above the cell lip. Holes with a diameter of 4 mm should be drilled every 10 mm around the ring to inject wash water downward.

2. From the results achieved with the test work it is recommended that all 18 flotation cells in the flotation plant be fitted with a lip wash installation to increase the plant yield.

3. It is recommended that lip wash be applied to both primary and secondary flotation cells as the research has shown that lip wash has a positive effect on the flotation dynamics at GHS flotation plant.

4. An economic analysis should be done to determine the most profitable reagent dosage to run the plant at. It is suggested that it will be between 1.3-1.45 kg/ton.

5. The viability of this lip wash system should be tested in other flotation plants to determine if similar benefits are possible.

REFERENCES

Allum, J.A. and Whelan, P.F. (1954). Journal of the Energy Institute, Vol 27 p 142.

Atkinson, B., Lambert, N., Jameson, G. (2001). Froth washing in mechanical cells. Australian Coal Association Research Report. ACARP project no C7041. University of Newcastle

Barnwal, J.P., Patil, Durga D., Rao, T.C. and Kawata, S.K. (2000). Enrichment of coal macerals using froth flotation. Minerals and Metallurgical Processing, Vol 17 (1) pp 56-61

Bisshop, J.P. and White, M.E. (1976). Study of Particle Entrainment in Flotation Froths. Transactions Issue Mathematics, Vol. 85, pp. C191-C194.

Brown, D.J., Gray, V.R. and Jackson, A.W. (1985). The Spreading of Oil on Wet Coal. Journal of Applied Chemistry,Vol 8, pp 752-759.

Cutting, G.W., Barber, S.P. and Newton, S. (1986). "Effects of Froth Structure and Mobility on the Performance and Simulation of Continuously Operated Flotation Cells". International Journal of Mineral Processing, Vol. 16, pp. 43-61.

de Korte, G.J. (2000). Economic Evaluation of Fine Coal Beneficiation, Progress Report for Coaltech 2020; Report No. 2000-0422.

de Korte, G.J. (2006). Determination and use of washability curves. Available online: http://www.sacoalprep.co.za/ Papers%20Vryheid.htm, accessed December 2017.

Finch, J.A. and Dobby, G.S. (1990). Column Flotation. Pergamon Press: Oxford Pergamon

Finch, J. (1994). Column flotation: a selected review - part iv: novel flotation devices. Minerals Engineering, Volume 8, Issue 6, pp. 587-602.

Fuerstenau, D.W. and Pradip, A. (1982). Adsorption of frothers at coal-water interfaces, Colloids and Surfaces, 4, pp. 229-243.

Hand, P.E. (2000). Dewatering and drying of fine coal to a saleable product. Report for Coaltech 2020.

Hindermarch, E. and Waters, P.I. (1951). Froth flotation of coal, Transactions of the Institution of Mining and Metallurgy. 111 (3377), pp. 221-235.

Horsfall, D. W. (1992). Coal Preparation and Usage: Coal Processing For Management. Coal Publications (Pty) Ltd, Johannesburg, Chapter 19.

Ireland, P., Cunningham, R. and Jameson, G. J. (2006). The behaviour of wash water injected into a froth. . International Journal of Mineral Processing. Volume 84. Pages 99-107.

Kaya, H., and Laplante, A.R. (1990). "Froth Washing and Froth Vibration in Mechanical Flotation Machines". Department of Mining and Metallurgical Engineering Department, McGill University, Montreal, Canada. Presented at the 1990 SME Annual General Meeting , Salt Lake City, Utah. 19.

Klassen, V.I. and Mokrousov, V.A. (1963). An Introduction to the Theory of Flotation. Butterworths, London.

Klimpel, R.R. (1995). The Influence of Frother Structure on Industrial Coal Flotation. High-Efficiency Coal Preperation (Kawatra, ed.). Society for Mining, Metallurgy and Exploration, Littleton, CO, pp141-151

Kuzkin, A.S., Kolyada, V.D. and Pugovkina, V.I. (1983). "An Investigation of Flotation Cell Froth Layer Structure". Non-ferrous Metals/Tsvetn. Metall., pp. 100-103.

Laskowski, J.S. (1986). The relationship between flotability and hydrophobicity, in Advances in Minerals Processing, ed. P. Somarsundaran, SME, Littleton, Colorado, pp. 189-208.

Laskowski, J.S. (1996). Seminar notes: Coal Flotation: Fundamentals And Engineering Aspects, Mintek auditorium, Randburg, South Africa, p 36.

Leja, J. (1982). Surface Chemistry of Froth Flotation, Plenum Press, New York, p 758.

Makhotla, N., Hearn, S., and Boskovic, S. (2015). The Huntsman Approach to Flotation Frothers. Copper Cobalt Africa, incorporating the 8th Southern African Base Metals Conference Livingstone, Zambia, 6–8 July 2015

Michaud, L.D. (2015). "Flotation Frothers- Frothing Agents", https://www.911metallurgist.com/blog/flotation-frothers-frothing-agents (accessed 13 June 2018)

Michaud, L.D. (2016). "Column flotation cells", https://www.911metallurgist.com/blog/column-flotation-cell (accessed 13 June 2018)

Moys, M.H. (1978). “A Study of a Plug-Flow Model for Flotation Froth Behaviour”. International Journal of Mineral Processing, Vol. 5, Amsterdam, pp. 21-38.

Moys, M.H. (1984).“Residence Time Distribution and Mass Transport in the Froth Phase of the Flotation Process”. International Journal of Mineral Processing, Vol. 13, Amsterdam, pp. 117-142.

Opperman, S.N., Nebbe, D. and Power, D. (2002). "Flotation at Goedehoop Colliery" The Journal of The South African Institute of Mining and Metallurgy, Vol 102, No. 7.

Peatfield, D. (2003). "Coal and coal preparation in South Africa—A 2002 review". The Journal of The South African Institute of Mining and Metallurgy, Vol 103, Issue 6, pp. 355-372

Powell, D.M. (1999). A process model for a free jet column cell. Master of Science in Engineering Project Report, University of the Witwatersrand, Johannesburg.

Powell, D.M. (2016) "A techno-economic evaluation of the production of hard coking coal from Tshikondeni coal discards". Thesis submitted in fulfilment of the requirements for the degree Philosophiae Doctor in Chemical Engineering. North-West University. Available online:https://dspace.nwu.ac.za/bitstream/handle/10394/20453/Powell_DM_2016.pdf?sequence=1&isAllowed=y, accessed December 2017.

South Africaan coal roadmap (2011). Overview of the South African coal value chain. Prepared as a basis for the development of the South African coal roadmap

Subrahmanyam, T.V. and Forssberg, E. (1988). “Froth Stability, Particle Entrainment and Drainage in Flotation—A Review”. International Journal of Mineral Processing, vol. 23, Elsevier Science Publishers B.V., Amsterdam, pp. 33-51.

Sun, S.C. and Zimmerman, R.F. (1950). The mechanism of coarse coal and mineral froth flotation. Transactions of the Metallurgical Society of AIME, 187, pp. 516-522.

Sun, S.C. (1954). Effects of oxidation of coals on their flotation properties. Transactions of the American Institute of Mining and Metallurgical Engineers, pp. 396-401.

Taylor, S.R., Miller, K.J. and Deurbrouk, A.W. (1981). Surface chemical problems in coal flotation, AIP Conference Proceedings, 70, pp. 344-356.

The South African coal processing society (2002). Coal preparation in South Africa. Natal Witness Commercial Printers, Pietermaritzburg.

Wheeler, T.A. and Keys,R.D. (1986). Factors influencing the choice of coal flotation reagents.

Ye, Y., Khandrika, S.M. and Miller, J.D. (1989). Induction time measurements at a particle bed, International Journal of Mineral Processing, 25, pp. 221-240.

Wills, B. A., and Napier-Munn, T. (2006). Wills' Mineral Processing Technology. Elsevier Science & Technology Books, pp. 267-343.

Woods, R. (1994). "Chemisorption of thiols and its role in flotation" Proceedings of IV Meeting of Southern Hemisphere on Mineral Technology, Chile, pp. 1-14.

Woollacott, L.C and Eric, R.H. (1994). Mineral and Metal Extraction: An Overview. The South African Institute of Mining and Metallurgy, Monograph Series M8. Johannesburg.

APPENDICES

Appendix A: Composite analysis results for experimental runs

Summary of analysis results for composite samples, details on date of sampling, wash water (WW) flow rate & sample number.

		Cell	*WW*	*Reag dos*	*Feed ash*	*Product ash*	*discard ash*	*CV Product*	*Yield*
29-Jun	Reagent dosage constant @ 1.3 kg/ton	A1	NO WASH	1.3	33.01	16.7	56.38	26.247	58.90
	WW flowrate= full	A2	LIP WASH	1.3	33.01	16.83	65.6	26.4	66.82
	Run1								
30-Jun	Reagent dosage constant on 1.45 kg/t	A1	NO WASH	1.45	32.5	17.5	55.12	26.59	60.13
	WW flowrate= full	A2	LIP WASH		32.5	17.3	68.4	26.7	70.25
	Run 2								
	Reagent dosage constant on 1.6 kg/t	A1	NO WASH	1.6	32.3	17.62	55.2	26.528	60.94
	WW flowrate= full	A2	LIP WASH		32.3	18	69.2	26.374	72.07
	Run3								
	Reagent dosage constant on 1.75 kg/t	A1	NO WASH	1.75	31.5				
	Varying WW	A2	LIP WASH		31.5	18.3	70.1	26.104	74.52
	Run 4								

		Cell	*WW*	*Reag dos*	*Feed ash*	*Product ash*	*discard ash*	*CV Product*	*Yield*
05-Aug	Reagent dosage 1.6 kg/ton	A1	NO WASH	1.6	37.7	16.08	50.2	26.625	36.64
	WW flowrate= full	A2	LIP WASH		37.7	17.27	68.3	27.379	59.96
	run 5								
	Reagent dosage 1.6 kg/t	A1	NO WASH	1.6	37.5	16.96	60.8	26.828	53.15
	WW flowrate= low pressure in ring	A2	LIP WASH		37.5	17.37	72.1	26.704	63.22
	run 6								
	Reagent dosage 1.3 kg/t	A1	NO WASH	1.3	32.2	16.7	34.4	26.9	12.43
	WW flowrate= full	A2	LIP WASH		32.2	16.4	43	27.18	40.60
	run 7								
19-Aug	Reagent dosage 1.45 kg/t	A1	NO WASH	1.45	30.2	13.245	36.295	27.641	26.44
	WW flowrate= full. Primary wash only	A2	LIP WASH		30.2	14.815	60.48	27.35	66.31
	Run 8								
	Reagent dosage 1.45 kg/ton	A1	NO WASH	1.45	31.1	14.53	36.625	27.424	25.01
	WW flowrate= full. Secondary wash only	A2	LIP WASH		31.1	13.155	55.75	27.77	57.87
	run 9								
22-Aug	Reagent dosage 1.3 kg/t		NO WASH	1.3	30.77	13.58	34.75	27.875	18.80
	WW flowrate= full Primary wash only	A2	LIP WASH		30.77	14.65	42.81	28.3	42.76
	run 10								
	Reagent dosage 1.3 kg/t	A1	NO WASH	1.3	30.72	14.4	32.6	27.572	10.33
	WW flowrate= full. Secondary wash only	A2	LIP WASH		30.72	14.4	34.73	27.586	19.72
	run 11								

		Cell	*WW*	*Reag dos*	*Feed ash*	*Product ash*	*discard ash*	*CV Product*	*Yield*
26-Aug	Reagent dosage 1.3	A1	NO WASH	1.3	30.73	16.32	32.6		27.66
	WW flowrate= full. P+S wash AUTO AUTO	A2	LIP WASH		30.73	16.4	66.9		71.62
	run 12								
	Reagent dosage 1.3 kg/t	A1	NO WASH	1.3	31.58	16.44	45.79		48.42
	WW flowrate= full. Primary wash only	A2	LIP WASH		31.58	16.75	67.775		70.94
	run 13								

Appendix B: Analysis by size

Size analysis and ash analysis for each size increment

Run 1: Primary & Secondary wash ; Reagent Dosage= 1.3 kg/t

Sample: Feed 1						A2	A1	
Size	Wts	%Wts	Cumm Wts	Ash	% Passing	Ash Yield	Ash Yield	Size
500	3.8	1.6	1.6	15.2	98.4	71.04	75.71	500
300	10.0	4.2	5.8	14.0	94.2	90.91	87.69	300
212	12.2	5.1	11.0	15.7	89.0	91.37	84.78	212
125	31.8	13.4	24.4	22.6	75.6	84.35	64.29	125
106	4.6	1.9	26.3	28.7	73.7	74.46	56.70	106
75	21.9	9.2	35.6	32.8	64.4	68.39	55.04	75
63	5.6	2.4	37.9	35.3	62.1			
45	14.8	6.2	44.2	36.0	55.8			
-45	132.4	55.8	100.0	36.0	0.0			
		0.0	100.0		0.0			

Sample A2 Product P2					
Size	Wts	% Wts	Cumm Wts	Ash	% Passing
500	7.2	1.6	1.6	9.9	98.4
300	38.4	8.4	10.0	12.6	90.0
212	27.7	6.1	16.0	13.3	84.0
125	66.1	14.5	30.5	15.9	69.5
106	8.7	1.9	32.4	15.8	67.6
75	44.6	9.8	42.2	16.3	57.8
63	264.0	3.6	45.8	18.53	54.2
45	20.0	4.4	50.1	17.8	49.9
45	227.7	49.9	100.0	18.7	0.0

Sample: A1 Product P3					
Size	Wts	%Wts	Cumm Wts	Ash	% Passing
500	3.3	1.7	1.7	10.9	98.3
300	9.2	4.8	6.5	12.4	93.5
212	12.3	6.4	12.9	13.6	87.1
125	20.9	10.9	23.8	15.1	76.2
106	5.3	2.8	26.5	16.1	73.5
75	16.9	8.8	35.3	16.3	64.7
63	10.7	5.6	40.9	18.22	59.1
45	12.3	6.4	47.3	17.4	52.7
45	101.3	52.7	100.0	19.4	0.0

	A2 Discard D4				
Size	Wts	%Wts	Cumm Wts	Ash	% Passing
500	5.3	3.5	3.5	28.2	96.5
300	4.5	3.0	6.5	28.0	93.5
212	2.2	1.5	8.0	41.1	92.0
125	5.7	3.8	11.8	58.7	88.2
106	3.3	2.2	14.0	66.3	86.0
75	12.1	8.1	22.1	68.5	77.9
75	116.9	77.9	100.0	67.7	0.0
		0.0	100.0		0.0
		0.0	100.0		0.0
		0.0	100.0		0.0

	A1 Discard D5				
Size	Wts	%Wts	Cumm Wts	Ash	% Passing
500	7.0	3.0	3.0	28.6	97.0
300	7.5	3.2	6.2	25.4	93.8
212	5.2	2.2	8.4	27.4	91.6
125	15.0	6.4	14.8	36.1	85.2
106	5.8	2.5	17.3	45.2	82.7
75	15.4	6.6	23.8	53.0	76.2
75	178.7	76.2	100.0	59.9	0.0
		0.0	100.0		0.0
		0.0	100.0		0.0
		0.0	100.0		0.0

Run2: Primary & Secondary wash ; Reagent Dosage= 1.45 kg/t

Sample	Feed F6					A2	A1	
Size	Wts	%Wts	Cumm Wts	Ash	% Passing	Ash Yield	Ash Yield	Size
500	23.2	6.4	6.4	18.6	93.6	79.03	83.06	500
300	25.1	6.9	13.3	17.1	86.7	91.96	94.62	300
212	24.5	6.7	20.0	19.2	80.0	92.97	92.08	212
125	37.9	10.4	30.4	20.8	69.6	90.86	91.34	125
106	9.3	2.6	32.9	25.6	67.1	84.57	82.67	106
75	33.4	9.2	42.1	31.3	57.9	76.72	72.59	75
63	12.3	3.4	45.5	33.5	54.5	71.69	70.38	63
45	19.1	5.2	50.7	38.6	49.3	61.59	58.26	45
45	179.5	49.3	100.0	40.3	0.0	58.55	52.60	45

	A2 Product P7				
Size	Wts	%Wts	Cumm Wts	Ash	% Passing
500	14.9	4.9	4.9	11.7	95.1
300	28.6	9.5	14.4	12.9	85.6
212	19.6	6.5	20.9	15.1	79.1
125	46.0	15.3	36.2	15.2	63.8
106	8.1	2.7	38.9	16.3	61.1
75	22.3	7.4	46.3	17.7	53.7
63	13.0	4.3	50.6	16.5	49.4
45	16.5	5.5	56.1	16.9	43.9
45	132.2	43.9	100.0	19.8	0.0
		0.0	100.0		

	A1 Product P8				
Size	Wts	%Wts	Cumm Wts	Ash	% Passing
500	26.6	9.1	9.1	12.3	90.9
300	34.2	11.7	20.8	14.1	79.2
212	23.2	7.9	28.7	15.1	71.3
125	36.9	12.6	41.3	16.1	58.7
106	10.5	3.6	44.9	16.0	55.1
75	21.2	7.2	52.1	16.3	47.9
63	9.1	3.1	55.2	17.1	44.8
45	21.9	7.5	62.7	16.1	37.3
25	16.1	5.5	68.2	17.5	31.8
25	93.0	31.8	100.0	20.6	0.0

	A2 Discard D9				
Size	Wts	% Wts	Cumm Wts	Ash	% Passing
500	46.4	11.5	11.5	44.61	88.5
300	18.8	4.6	16.1	65.13	83.9
212	11.6	2.9	19.0	73.4	81.0
125	22.6	5.6	24.6	76.44	75.4
106	14.0	3.5	28.0	76.58	72.0
75	33.0	8.2	36.2	76.11	63.8
63	17.5	4.3	40.5	76.56	59.5
45	42.9	10.6	51.1	73.4	48.9
-45	197.8	48.9	100.0	69.26	0.0
		0.0	100.0	62.39	
Totals	404.6	100.0			

	A1 Discard D10				
Size	Wts	%Wts	Cumm Wts	Ash	% Passing
500	41.9	17.0	17.0	49.5	83.0
300	11.8	4.8	21.7	69.9	78.3
212	5.1	2.1	23.8	66.9	76.2
125	9.7	3.9	27.7	70.4	72.3
106	3.9	1.6	29.3	71.4	70.7
75	15.5	6.3	35.6	71.0	64.4
63	8.2	3.3	38.9	72.5	61.1
45	20.8	8.4	47.3	70.0	52.7
-45	130.0	52.7	100.0	65.6	
		0.0	100.0		
Totals	246.9	100.0			

Run 3: Primary & Secondary wash; Reagent Dosage= 1.6 kg/t

	Feed F11				
Size	Wts	% Wts	Cumm Wts	Ash	% Passing
500	14.9	5.3	5.3	19.7	94.7
300	20.6	7.4	12.7	17.2	87.3
212	16.1	5.7	18.4	18.0	81.6
125	27.6	9.9	28.3	21.4	71.7
106	9.9	3.5	31.8	26.6	68.2
75	20.9	7.5	39.3	31.1	60.7
63	17.2	6.1	45.4	34.0	54.6
45	16.8	6.0	51.4	38.7	48.6
25	21.8	7.8	59.2	35.6	40.8
0	114.3	40.8	100.0	38.7	0.0

A2	A1	
Ash Yield	Ash Yield	Size
80.28	88.98	500
94.08	92.74	300
92.52	92.29	212
90.70	87.82	125
82.62	82.12	106
76.89	72.64	75
71.44	69.74	63
64.05	63.89	45
67.82	63.20	25
64.23	56.90	-25

	P12 A2 product				
Size	Wts	%Wts	Cumm Wts	Ash	% Passing
500	16.3	5.6	5.6	12.1	94.4
300	24.2	8.3	13.9	14.1	86.1
212	19.8	6.8	20.7	13.4	79.3
125	36.1	12.4	33.1	15.7	66.9
106	10.9	3.7	36.8	15.9	63.2
75	23.6	8.1	45.0	17.1	55.0
63	12.1	4.2	49.1	16.9	50.9
45	19.0	6.5	55.6	17.9	44.4
25	20.4	7.0	62.6	17.8	37.4
-25	108.8	37.4	100.0	21.8	0.0

	P13 A1 product				
Size	Wts	%Wts	Cumm Wts	Ash	% Passing
500	25.7	6.8	6.8	11.4	93.2
300	39.1	10.3	17.1	13.7	82.9
212	32.8	8.7	25.8	14.0	74.2
125	44.1	11.7	37.5	15.3	62.5
106	16.3	4.3	41.8	16.5	58.2
75	34.3	9.1	50.9	16.7	49.1
63	6.8	1.8	52.7	17.5	47.3
45	26.8	7.1	59.8	17.0	40.2
25	26.1	6.9	66.7	17.9	33.3
-25	126.0	33.3	100.0	21.7	0.0

	A2 Discard D14				
Size	Wts	% Wts	Cumm Wts	Ash	% Passing
500	55.6	15.4	15.4	50.64	84.6
300	14.4	4.0	19.3	66.44	80.7
212	5.7	1.6	20.9	74.91	79.1
125	12.3	3.4	24.3	77.01	75.7
106	11.4	3.2	27.5	77.46	72.5
75	32.3	8.9	36.4	77.68	63.6
63	16.7	4.6	41.0	76.78	59.0
45	21.9	6.1	47.1	75.76	52.9
25	30.5	8.4	55.5	73.12	44.5
-25	161.1	44.5	100.0	69.04	

	A1 Discard D15				
Size	Wts	%Wts	Cumm Wts	Ash	% Passing
500	79.1	32.0	32.0	86.7	68.0
300	21.6	8.7	40.7	61.9	59.3
212	7.6	3.1	43.8	65.9	56.2
125	11.2	4.5	48.3	65.4	51.7
106	6.1	2.5	50.8	73.0	49.2
75	16.3	6.6	57.4	69.3	42.6
63	11.1	4.5	61.9	72.0	38.1
45	13.3	5.4	67.2	77.1	32.8
25	15.9	6.4	73.7	66.0	26.3
-25	65.1	26.3	100.0	61.1	

Run 4: Primary & Secondary wash; Reagent Dosage= 1.75 kg/t

	Feed F16			
Size	Wts	%Wts	Cumm Wts	Ash
500	12.8	6.3	6.3	18.74
300	16.5	8.1	14.5	18.31
212	12.4	6.1	20.6	19.76
125	20.8	10.3	30.8	23.08
106	5.3	2.6	33.5	27.15
75	19.2	9.5	42.9	32.73
63	5.5	2.7	45.7	36.49
45	13.9	6.9	52.5	37.75
25	16.6	8.2	60.7	35.17
-25	79.6	39.3	100.0	38.31
Totals	202.6	100.0		

	A2 Product P17			
Size	Wts	%Wts	Cumm Wts	Ash
500	39.6	7.6	7.6	11.81
300	59.5	11.4	19.0	13.74
212	39.9	7.6	26.6	15.27
125	72.1	13.8	40.4	16.48
106	11.7	2.2	42.7	16.07
75	42.7	8.2	50.8	17.28
63	10.3	2.0	52.8	16.69
45	43.9	8.4	61.2	17.86
25	22.5	4.3	65.5	17.11
-25	180.0	34.5	100.0	22.76
Totals	522.2	100.0		

	A1 Product P13				
Size	Wts	%Wts	Cumm Wts	Ash	% Passing
500	25.7	6.8	6.8	11.4	93.2
300	39.1	10.3	17.1	13.7	82.9
212	32.8	8.7	25.8	14.0	74.2
125	44.1	11.7	37.5	15.3	62.5
106	16.3	4.3	41.8	16.5	58.2
75	34.3	9.1	50.9	16.7	49.1
63	6.8	1.8	52.7	17.5	47.3
45	26.8	7.1	59.8	17.0	40.2
25	26.1	6.9	66.7	17.9	33.3
-25	126.0	33.3	100.0	21.7	0.0
Totals	378	100.0			

Sample	A2 Discard D19			
Size	Wts	%Wts	Cumm Wts	Ash
500	50.9	16.3	16.3	50.5
300	19.5	6.3	22.6	70.58
212	8.3	2.7	25.3	73.8
125	17.4	5.6	30.9	77.63
106	8.6	2.8	33.6	78.06
75	27.1	8.7	42.3	77.27
63	11.3	3.6	46.0	77.67
45	22.4	7.2	53.1	76.48
25	21.6	6.9	60.1	71.24
-25	124.3	39.9	100.0	
Totals	311.4	100.0		

Sample	A1 Discard D20			
Size	Wts	%Wts	Cumm Wts	Ash
500	25.7	13.3	13.3	48.3
300	10.4	5.4	18.7	61.3
212	4.4	2.3	20.9	64.7
125	9.7	5.0	25.9	67.5
106	3.5	1.8	27.8	67.7
75	14.1	7.3	35.0	68.8
63	8.6	4.4	39.5	67.7
45	13.4	6.9	46.4	67.7
25	17.0	8.8	55.2	62.4
-25	86.7	44.8	100.0	61.4
Totals	193.5	100.0		

Run 5: Primary & Secondary wash ; Reagent Dosage= 1.6 kg/t repeat

Sample	Feed F21			
Size	Wts	%Wts	Cumm Wts	Ash
500	8.5	2.2	2.2	23.5
300	11.1	2.8	5.0	18.5
212	12.1	3.1	8.1	16.3
125	31.5	8.1	16.2	18.9
106	8.7	2.2	18.4	24.1
75	39.6	10.1	28.5	32.9
63	10.1	2.6	31.1	34.9
45	33.6	8.6	39.7	39.4
25	31.1	7.9	47.6	35.7
25	205.0	52.4	100.0	41.6

A2	A1	
Ash Yield	Ash Yield	Size
60.79	64.60	500
82.45	75.21	300
89.45	75.66	212
87.11	64.94	125
79.49	43.31	106
66.08	34.13	75
66.26	38.47	63
58.57	32.92	45
64.29	44.59	25
214.88	25.17	-25

	A2 Product P22			
Size	Wts	%Wts	Cumm Wts	Ash
500	1.4	0.6	0.6	7.66
300	6.0	2.4	3.0	9.93
212	7.4	3.0	6.0	10.58
125	21.1	8.5	14.5	12.04
106	6.7	2.7	17.2	12.95
75	22.7	9.2	26.4	14.15
63	7.9	3.2	29.6	15.45
45	20.4	8.2	37.8	15.92
25	25.9	10.5	48.3	17.05
-25	127.9	51.7	100.0	19.36

A1 Product P23			
Wts	%Wts	Cumm Wts	Ash
4.4	1.7	1.7	7.7
11.3	4.6	6.2	9.1
11.3	4.6	10.8	9.8
25.8	10.4	21.2	11.2
8.0	3.2	24.4	12.1
18.9	7.6	32.1	13.4
7.3	3.0	35.0	14.3
21.2	8.6	43.6	15.2
19.9	8.0	51.7	16.1
138.2	55.9	107.5	

Sample	A2 Discard D24			
Size	Wts	%Wts	Cumm Wts	Ash
500	18.5	4.2	4.2	48.06
300	7.3	1.7	5.9	58.76
212	4.4	1.0	6.9	64.82
125	14.4	3.3	10.2	65.24
106	6.0	1.4	11.5	67.32
75	35.0	8.0	19.5	69.43
63	15.0	3.4	22.9	73.1
45	51.7	11.8	34.7	72.59
25	32.9	7.5	42.2	69.28
-25	254.1	57.8	100.0	
Totals	439.3	100.0		

A1 Discard D25			
Wts	%Wts	Cumm Wts	Ash
30.7	7.3	7.3	52.4
15.4	3.7	11.0	46.9
11.0	2.6	13.6	36.5
29.7	7.1	20.7	33.2
13.9	3.3	24.0	33.3
37.8	9.0	33.0	43.0
20.8	5.0	37.9	47.8
27.4	6.5	44.4	51.3
34.2	8.1	52.6	51.5
199.2	47.4	100.0	55.6
420.1	100.0		

Run 6: Primary & Secondary wash (wash water pressure low; Reagent Dosage= 1.6 kg/t

	Feed F26			
Size	Wts	%Wts	Cumm Wts	Ash
500	6.4	1.6	1.6	29.1
300	10.9	2.7	4.3	21.6
212	11.9	2.9	7.2	20.1
125	34.8	8.6	15.8	20.8
106	11.4	2.8	18.6	25.3
75	38.8	9.6	28.1	33.5
75	13.1	3.2	31.4	35.5
45	42.9	10.6	42.0	41.0
25	24.5	6.0	48.0	35.1
-25	211.0	52.0	100.0	41.1

Ash Yield		Size
A2	A1	
55.86	67.81	500
83.22	83.64	300
88.02	85.53	212
87.38	79.91	125
82.21	68.36	106
69.74	56.96	75
69.15	57.09	63
60.04	48.65	45
68.66	57.54	25
63.53	52.08	-25

	A2 Product P27			
Size	Wts	%Wts	Cumm Wts	Ash
500	1.5	5.6	5.6	9.5
300	6.2	8.3	13.9	11.54
212	9.1	6.8	20.7	12.14
125	24.2	12.4	33.1	12.28
106	15.0	3.7	36.8	14.07
75	19.8	8.1	45.0	15.28
63	17.5	4.2	49.1	16.09
45	18.1	6.5	55.6	17.04
25	22.3	7.0	62.6	17.57
-25	126.2	37.4	100.0	19.92

A1 Product P28			
Wts	%Wts	Cumm Wts	Ash
3.0	6.8	6.8	10.7
8.0	10.3	17.1	12.4
9.9	8.7	25.8	12.0
27.5	11.7	37.5	12.2
7.3	4.3	41.8	12.9
24.6	9.1	50.9	14.3
6.4	1.8	52.7	15.6
18.6	7.1	59.8	15.9
19.7	6.9	66.7	16.3
107.8	33.3	100.0	20.0

Sample	A2 Discard D29				A1 Discard D30			
Size	Wts	%Wts	Cumm Wts	Ash	Wts	%Wts	Cumm Wts	Ash
500	55.6	15.4	15.4	53.9	79.1	32.0	32.0	67.9
300	14.4	4.0	19.3	71.5	21.6	8.7	40.7	68.6
212	5.7	1.6	20.9	78.6	7.6	3.1	43.8	68.2
125	12.3	3.4	24.3	79.8	11.2	4.5	48.3	55.2
106	11.4	3.2	27.5	77.2	6.1	2.5	50.8	52.0
75	32.3	8.9	36.4	75.5	16.3	6.6	57.4	58.9
63	16.7	4.6	41.0	79	11.1	4.5	61.9	62.0
45	21.9	6.1	47.1	77	13.3	5.4	67.2	64.8
25	30.5	8.4	55.5	73.5	15.9	6.4	73.7	60.6
-25	161.1	44.5	100.0	78	65.1	26.3	100.0	64.0

Size analysis: Run 7: Primary & Secondary wash; Reagent Dosage= 1.3 kg/t repeat run

	Feed F31			
Size	Wts	%Wts	Cumm Wts	Ash
500	4.6	1.9	1.9	15.9
300	5.9	2.4	4.3	15.6
212	5.6	2.3	6.5	14.8
125	14.6	5.9	12.5	14.9
106	9.8	4.0	16.4	19.7
75	19.5	7.9	24.3	23.5
63	8.9	3.6	28.0	27.5
45	22.3	9.0	37.0	31.5
25	21.5	8.7	45.7	32.6
-25	133.8	54.3	100.0	36.9

\	P32 A2 Product			
Size	Wts	%Wts	Cumm Wts	Ash
500	2.1	5.6	5.6	10.4
300	5.2	8.3	13.9	10.61
212	6.5	6.8	20.7	9.6
125	21.3	12.4	33.1	10.43
106	8.6	3.7	36.8	10.97
75	16.4	8.1	45.0	12.96
63	7.8	4.2	49.1	13.96
45	19.9	6.5	55.6	15.25
25	18.7	7.0	62.6	15.89
-25	150.7	37.4	100.0	19.58

\	P33 A1 Product			
Size	Wts	%Wts	Cumm Wts	Ash
500	0.8	6.8	6.8	
300	2.5	10.3	17.1	10.6
212	2.6	8.7	25.8	9.6
125	6.2	11.7	37.5	10.4
106	2.3	4.3	41.8	11.0
75	7.4	9.1	50.9	13.0
63	3.3	1.8	52.7	14.0
45	10.4	7.1	59.8	15.3
25	16.2	6.9	66.7	15.9
-25	185.4	33.3	100.0	21.7

	D34 A2 Discard			
Size	Wts	%Wts	Cumm Wts	Ash
500	11.2	3.0	3.0	19.97
300	8.2	2.2	5.2	21.33
212	6.7	1.8	7.0	19.38
125	24.7	6.6	13.6	21.48
106	13.2	3.5	17.1	25.28
75	30.9	8.3	25.4	32.29
63	13.3	3.6	28.9	36.44
45	35.3	9.4	38.4	41.71
25	36.7	9.8	48.2	42.6
-25	193.8	51.8	100.0	50.2

	A1 Discard D35			
Size	Wts	%Wts	Cumm Wts	Ash
500	9.1	3.0	3.0	20.39
300	8.5	2.8	5.8	
212	7.8	2.6	8.4	
125	25.4	8.4	16.8	
106	8.2	2.7	19.5	
75	35.8	11.8	31.3	27.79
63	9.0	3.0	34.3	31.28
45	27.1	9.0	43.3	34.34
25	25.8	8.5	51.8	34.2
-25	145.9	48.2	100.0	42.4

Size analysis: Run 8: Primary wash only; Reagent Dosage= 1.45 kg/t

Sample	Feed F36			
Size	Wts	%Wts	Cumm Wts	Ash
500	0.2	0.1	0.1	-
300	1.0	0.5	0.6	-
212	3.3	1.6	2.2	10.8
125	17.6	8.5	10.7	12.0
106	6.6	3.2	13.9	16.9
75	18.3	8.9	22.8	22.3
63	6.3	3.1	25.8	28.1
45	17.9	8.7	34.5	33.2
25	20.0	9.7	44.2	30.0
25	115.3	55.8	100.0	31.0

A2	A1	
Ash Yield	Ash Yield	Size
-	-	500
-	-	300
94.39	49.32	212
94.20	49.23	125
86.63	42.74	106
76.30	22.56	75
67.30	12.64	63
59.86	20.41	45
66.09	29.15	25
65.06	26.43	-25

	P37 A2 Product			
Size	Wts	%Wts	Cumm Wts	Ash
500	0.1	0.0	0.0	-
300	0.8	0.3	0.4	-
212	2.9	1.1	1.5	8.5
125	125.8	49.7	51.2	10.3
106	6.4	2.5	53.7	12.1
75	14.2	5.6	59.3	12.7
63	8.9	3.5	62.8	14.4
45	10.9	4.3	67.1	15.5
25	13.4	5.3	72.4	16.2
-25	69.9	27.6	100.0	16.5

P39 A1 Product			
Wts	%Wts	Cumm Wts	Ash
0.0	0.0	0.0	-
0.7	0.3	0.3	-
2.2	0.9	1.1	7.1
8.3	3.3	4.4	8.7
3.0	1.2	5.6	10.2
9.6	3.8	9.4	12.0
4.2	1.7	11.1	12.9
11.3	4.5	15.5	13.7
14.3	5.6	21.2	14.2
98.2	38.8	59.9	14.3

	A2 Discard D39			
Size	Wts	%Wts	Cumm Wts	Ash
500	2.4	0.7	0.7	69.9
300	1.6	0.4	1.1	65.4
212	1.6	0.4	1.5	49.5
125	10.0	2.8	4.3	39.6
106	5.5	1.5	5.8	48
75	37.6	10.4	16.2	53.2
63	11.3	3.1	19.4	56.3
45	37.1	10.3	29.6	59.6
25	32.8	9.1	38.7	56.9
-25	221.7	61.3	100.0	58
Totals	361.6	100.0		

A1 Discard D40			
Wts	%Wts	Cumm Wts	Ash
1.1	0.3	0.3	55.0
2.8	0.8	1.1	27.3
6.9	2.0	3.1	14.4
26.2	7.4	10.5	15.2
20.9	5.9	16.4	21.9
28.8	8.2	24.6	25.3
23.3	6.6	31.2	30.3
29.8	8.5	39.7	38.2
35.7	10.1	49.8	36.5
176.8	50.2	100.0	37.0
352.3	100.0		

Size analysis: Run 9: Secondary wash only; Reagent Dosage= 1.45 kg/t

Feed 41					
Size	Wts	% Wts	Cumm Wts	Ash	% Passing
500	0.5	0.1	0.1		99.9
300	1.1	0.3	0.5		99.5
212	3.1	0.9	1.3	11.3	98.7
125	15.7	4.4	5.8	12.3	94.2
106	10.0	2.8	8.6	18.4	91.4
75	22.9	6.5	15.0	14.4	85.0
63	18.6	5.3	20.3	23.1	79.7
45	23.2	6.5	26.8	27.6	73.2
25	45.1	12.7	39.6	29.3	60.4
-25	214.0	60.4	100.0	35.7	0.0

A2 Product P42					
Size	Wts	% Wts	Cumm Wts	Ash	% Passing
500	0.1	0.0	0.0		100.0
300	0.8	0.3	0.3		99.7
212	2.2	0.7	1.0	7.25	99.0
125	10.3	3.4	4.5	8.23	95.5
106	5.3	1.8	6.3	10.95	93.7
75	14.1	4.7	11.0	11.71	89.0
63	6.5	2.2	13.1	13.42	86.9
45	17.4	5.8	19.0	13.86	81.0
25	27.8	9.3	28.3	13.44	71.7
-25	214.4	71.7	100.0		0.0

A1 Product P43					
Size	Wts	%Wts	Cumm Wts	Ash	% Passing
500	0.2	0.1	0.1		99.9
300	1.1	0.8	1.0		99.0
212	2.6	1.9	2.9	9.7	97.1
125	11.9	8.7	11.6	10.57	88.4
106	5.9	4.3	15.9	11.48	84.1
75	11.4	8.4	24.2	12.8	75.8
63	9.2	6.7	31.0	13.8	69.0
45	9.3	6.8	37.8	15.3	62.2
25	13.9	10.2	48.0	16.25	52.0
-25	71.0	52.0	100.0	15.14	0.0

A2 Discard D44					
Size	Wts	%Wts	Cumm Wts	Ash	% Passing
500	2.2	0.5	0.5	63.2	99.5
300	1.5	0.3	0.8		99.2
212	1.4	0.3	1.1	46.7	98.9
125	7.9	1.8	2.9	31.6	97.1
106	5.2	1.2	4.1	31.5	95.9
75	28.2	6.3	10.3	34.0	89.7
63	22.8	5.1	15.4	44.0	84.6
45	34.9	7.8	23.2	49.7	76.8
25	48.2	10.7	33.9	53.0	66.1
-25	296.5	66.1	100.0		0.0

A1 Discard D45					
Size	Wts	%Wts	Cumm Wts	Ash	% Passing
500	4.8	1.3	1.3	60.7	98.7
300	3.8	1.1	2.4	45.7	97.6
212	5.3	1.5	3.9	23.0	96.1
125	24.6	6.9	10.7	16.7	89.3
106	13.2	3.7	14.4	17.9	85.6
75	34.0	9.5	23.9	23.4	76.1
63	19.5	5.4	29.3	28.8	70.7
45	29.2	8.1	37.5	33.6	62.5
25	35.6	9.9	47.4	34.7	52.6
-25	188.8	52.6	100.0	44.3	0.0