

The influence of magnetic fields on the flotation of sulphide minerals

Arnoldus Carel Swarts

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By

Arnoldus Carel Swarts

Study leader: Professor R.F. Sandenbergh
Department: Metallurgical Engineering
Degree: Magister Engineering (Metallurgical)

Abstract

Oscillating magnetic fields have the potential to affect the flotation behaviour of magnetically susceptible minerals. The idea was evaluated by studying the flotation separation of pyrrhotite from a pentlandite, chalcopyrite and pyrite feed. Various analytical, flotation and visual observation techniques were used to establish the effect of an oscillating magnetic field on the flotation process. Oscillating magnetic fields were applied to a Hallimond flotation tube, a bench scale column, and a pilot scale flotation column to test the effect of a magnetic field on flotation of sulphide minerals. It was found that the flotation of non-magnetic minerals was not affected by the magnetic field. In general it was found that the flotation of magnetically susceptible minerals could be depressed by mechanically rotating the particles using an external magnetic field. Magnetic field strength, frequency, and the orientation of the field lines (relative to the particle) were identified as important parameters controlling rotation of the magnetic particles. In some cases the rotating particle dislodged itself from the air bubble to which it was attached and consequently the flotation recovery of the magnetic particles decreased. This has a significant impact on nickel flotation, where pyrrhotite can be selectively depressed during flotation. Chrysotile, a mineral frequently associated with nickel sulphide ores, had a negative effect on flotation recovery of the sulphide minerals. In the presence of chrysotile, the depressing effect of an oscillating magnetic field on pyrrhotite recovery was enhanced. It was also found that quartz could be depressed from the flotation concentrate using an oscillating magnetic field. Pilot scale column work indicated that it is possible to depress pyrrhotite flotation by applying an oscillating magnetic field to a flotation column.

Keywords: *flotation, sulphide minerals, pyrrhotite, low grade nickel deposit, magnetic fields.*

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1 INTRODUCTION

Nickel is produced from either lateritic or sulphide ore bodies. Generally sulphide nickel deposits are mined and upgraded to produce a nickel sulphide concentrate, which is either hydrometallurgically or pyrometallurgically treated to recover the nickel. With sulphide orebodies the nickel occurs predominantly in pentlandite, a nickel-iron-sulphide mineral. Pyrrhotite, an iron-sulphide, is almost always associated with the nickel bearing pentlandite. These sulphide minerals are hosted in minerals like gabbros, micas, dolomites and serpentine minerals.

Flotation is used to separate the sulphide minerals from the host (gangue) minerals. The surfaces of the sulphide minerals are typically rendered hydrophobic by the addition of flotation collectors such as xanthates. In a flotation cell, the hydrophobic sulphides are floated while the gangue minerals remain in the pulp. Serpentinized minerals like chrysotile, lizardite and talc inhibits the flotation of the sulphide minerals by also collecting at the air bubbles and preventing adherence at the sulphides. Various reagents like carboxymethylcellulose, starches and guar gums can be added to depress the flotation of these gangue minerals and to increase the flotation recovery of the sulphide minerals and the grade of the concentrate. The use of magnetic fields may possibly be used to oscillate magnetically susceptible sulphides to remove these gangue materials from the surfaces of sulphide minerals.

Although pyrrhotite is a sulphide mineral which contains small amounts of nickel as either finely intergrown pentlandite or as nickel in solid solution in the crystal matrix, it is seen as a mineral that dilutes the nickel grade of the flotation concentrate. Pyrrhotite can be depressed by manipulating the chemistry during flotation. However, pyrrhotite occurs in two crystal forms, monoclinic and hexagonal pyrrhotite. Monoclinic pyrrhotite is magnetically susceptible and offers

the possibility to separate the monoclinic pyrrhotite magnetically from the other sulphide minerals but this usually results in unacceptable nickel losses.

Combining flotation and magnetic separation techniques in a single device may offer some beneficial effect; for example applying a magnetic field to a flotation column might enhance the recovery and concentration of the flotation concentrate.

1.1 Testwork

Various experimental set-ups, including micro flotation (Hallimond tube), mini column flotation, pilot scale column flotation, visual observation and chemical analysing techniques were used to determine the effect of an oscillating magnetic field on the chemistry, movement and flotation response of magnetic and non-magnetic minerals.

The first aim of this work was to establish the behaviour of the magnetic minerals in the presence of an oscillating magnetic field. A visual (observation by microscope) laboratory experimental set-up was used to observe the effect of an oscillating magnetic field on magnetically susceptible particles attached to the air bubbles.

The second aim was to determine the effect of the oscillating magnetic field on the flotation performance of the minerals and this was established using various flotation techniques. Laboratory flotation testwork was done in a Hallimond flotation tube and in a 300mm long and 25mm diameter column. Various parameters like magnetic field properties, chemical reagents and the addition of gangue minerals, were also investigated in the laboratory.

The possibility that the oscillating magnetic field will influence the chemical reactions between sulphide minerals and potassium amyl xanthate (flotation collector) was also investigated. UV spectrophotometry was used to measure the concentration of various aqueous xanthate species formed during the conditioning of pyrite in a xanthate solution with and without the application of a magnetic field.

Finally, to prove this technique, an oscillating magnetic field was applied to a pilot flotation column at an operating nickel mine to determine the effect of the magnetic field on the flotation process. The pilot testwork was done at Nkomati Mine in the Mpumalanga province of South Africa. A pilot flotation column from Baker Hughes was used and material from the cleaner flotation circuit was used as feed for the pilot column.

2 MINERALOGY, MAGNETIC PROPERTIES AND PROCESSING OF LOW GRADE NICKEL SULPHIDE ORES

2.1 Introduction

A deposit's mineralogy is probably the most important feature to consider when evaluating the development of a low grade ore body. The mode of occurrence and the physical properties of the valuable minerals will determine the metallurgical extraction route. For low grade nickel deposits, froth flotation is traditionally used to produce a sulphide concentrate, but the complex mineralogy often makes it difficult to successfully concentrate these ores (Sizgoric, 1981).

In this study the occurrence and distribution of nickel minerals are explored. It is also important to understand which minerals associated with the nickel ores will influence the flotation performance of the valuable sulphide minerals. Finally, the magnetic properties of minerals relevant to this study are discussed.

2.2 Mineralogy of nickel bearing minerals

Economic quantities of nickel occur in either sulphide deposits, laterite deposits or deep-sea manganese nodules. In sulphide deposits nickel is present in the sulphide minerals, while in laterite ores the nickel occurs in oxide minerals. Nickel is primarily produced from sulphide minerals and to a lesser extent from laterite ores. According to Terry et al. (1987) the recovery of nickel from deep-sea manganese nodules will not be economically possible until well into the 21st century. Low-grade nickel sulphide ore bodies typically contain an average nickel grade of below 1%. The nickel is primarily present as pentlandite, a nickel sulphide mineral.

The successful extraction of nickel from an ore is dependent on the mineralogy of the ore body. When the primary nickel sulphides are altered, it may result in a reduction in flotation recovery. For example, the alteration of pentlandite to violerite and magnetite is usually accompanied by the transformation of pyrrhotite to nickelferrous pyrite and magnetite (Alcock, 1988). During liberation, violerite maintains its association with magnetite which forms a rim around the violerite; this shields the violerite surface during flotation causing the violerite to be lost to the residue. Sulphide minerals are invariably intergrown with each other and with the gangue minerals. Where the intergrowth is fine grained and complex, liberation and concentration of the sulphides are problematic.

The host rock, associated with the nickel sulphide minerals, can affect the recovery, grade, and the character of the sulphide flotation concentrate. The host rock of nickel sulphide deposits is either serpentized dunite, serpentized peridotite or gabbros. The gangue minerals of the serpentized dunite and serpentized peridotite typically contain fibrous or asbestiform silicates such as antigorite or chrysotile serpentine, or platy silicate minerals such as talc or chlorites which are difficult to reject during flotation. Gabbro host rock minerals consist predominantly of feldspar and pyroxene, with minor amounts of chlorites, biotite, muscovite mica, and asbestiform amphibole as troublesome silicates (Alcock, 1988).

2.3 Magnetic properties of materials and minerals pertinent to the present study.

The orbital motion of electrons around the nucleus of an atom, and the spin of the electron around its own axis creates a microscopic current loop, which generates its own magnetic dipole moment. These magnetic dipole moments of materials react in various ways in the presence of an external magnetic field.

Diamagnetic materials do not have permanent magnetic moments as is shown in figure 2-1 (a). However, in the presence of a magnetic field, the electrons are slightly unbalanced and small magnetic moments that oppose the external

magnetic field are created. Diamagnetic materials are repelled by a magnetic field and reduce the external magnetic field. Magnetic susceptibility is negative in this case. Quartz (SiO_2) is an example of a diamagnetic material (Lawver and Hopstock, 1985).

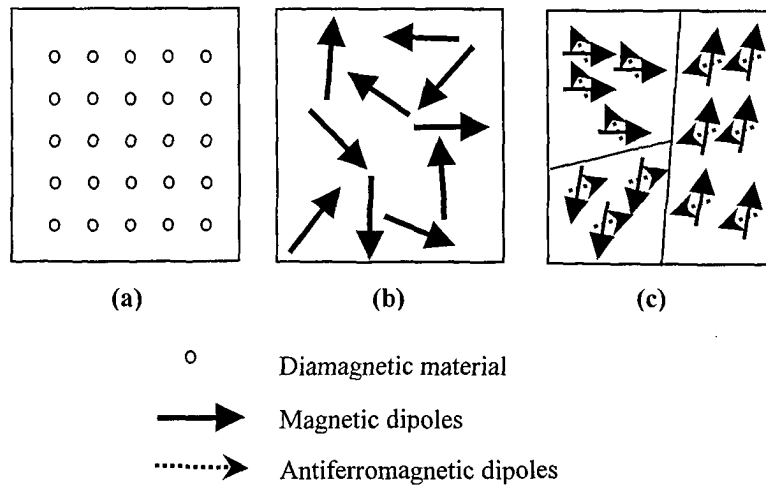


Figure 2-1 :Schematic representation of magnetic structures of materials, a) Diamagnetism (quartz), b) Paramagnetism (pyrite), c) Ferromagnetism (pyrrhotite)

In the presence of an external magnetic field, the magnetic dipole moments of paramagnetic materials align themselves parallel to the external field. When the magnetic field is removed, the magnetic dipole moments return to a random distribution as shown in figure 2-1 (b). Pyrite (FeS_2) is paramagnetic with a specific magnetic susceptibility of 0.004×10^{-6} to 0.013×10^{-6} (Lawver and Hopstock, 1985).

While paramagnetism and diamagnetism are only induced in the presence of an external magnetic field, ferromagnetism can exist in the absence of an external magnetic field. Domains exist where the magnetic dipole moments are aligned in the same direction and the antiferromagnetic dipole moments are aligned in a different direction; several domains can co-exist in a single particle and this is shown in figure 2-1 (c). In the presence of an external magnetic field, the magnetic dipole moments align themselves parallel and non-parallel to the external magnetic field.

Pyrrhotite is a non-stoichiometric compound and can be represented as $\text{Fe}_{(1-x)}\text{S}$ where x varies from 0 to 0.13 in natural samples. Monoclinic pyrrhotite has the highest metal deficiency, while hexagonal pyrrhotite has the lowest (Lawver and Hopstock, 1985). The iron deficient or monoclinic pyrrhotite is highly ferromagnetic.

2.4 Processing of nickel sulphide ores

The first processing step after mining of the ore is the liberation of the valuable sulphides from the gangue minerals by crushing and grinding. The sulphides are usually concentrated by froth flotation. The flotation concentrate is further treated pyrometallurgically and/or hydrometallurgically to produce nickel metal.

Conventional nickel flotation circuits are made up of rougher and scavenger stages followed by a cleaning stage. The exact configuration of the flotation plant is determined by the mineralogy of the ore body. Xanthate collectors are predominantly used for the flotation of nickel sulphide minerals. Various reagents like sodium carbonate, sodium cyanide, carboxymethylcellulose (CMC) and sodium chloride can be used to selectively depress or disperse different gangue minerals present in the ore.

Fine pentlandite intergrowths in the pyrrhotite result in high nickel losses when monoclinic pyrrhotite is magnetically rejected. On the other hand, excessive amounts of pyrrhotite in the flotation concentrate cause high SO_2 emissions during the pyrometallurgical treatment of the flotation concentrate. To counter this, flotation circuits are typically modified to include a pyrrhotite rejection stage. Various methods are used to depress the flotation of pyrrhotite, which include the exploitation of particle size, coupled to a pH change and reagent control, as reported by Senior et al (1995). The addition of sodium cyanide is a good depressant for slightly oxidised pyrrhotite (Agar, 1991).

According to Agar (1991), talc is a naturally floatable mineral and when present in sulphide flotation, it produces a voluminous froth with low sulphide recoveries. Talc is depressed using CMC, but with low-grade ores the high dosages of CMC necessary to successfully depress the talc, makes the process uneconomical (Wellham et al, 1992).

Serpentine minerals, which include chrysotile and lizardite, are also reported to reduce the flotation recovery of nickel sulphides (Edwards et al, 1980). The serpentine minerals form a slime coating on the sulphide surfaces thereby inhibiting the flotation of sulphides. CMC and NaCl could be used to disperse the slime coating and improve flotation (Wellham et al, 1992).

Talc and serpentine minerals, present in the flotation concentrate, lower the concentrate grade and increase the magnesium content of the concentrate. During the pyrometallurgical treatment of the concentrate, especially with the use of a reverberatory furnace, the magnesium raises the melting temperature as well as the viscosity of the slag; consequently the nickel losses to the slag are increased (Agar, 1991).

2.5 Application of magnetic fields in separating processes

Magnetically susceptible minerals, like magnetite and monoclinic pyrrhotite are frequently associated with nickel deposits. Sulphide minerals, with the exception of monoclinic pyrrhotite, are all non-magnetic. Magnetic intergrowths of magnetite or pyrrhotite may render some of the valuable sulphide particles magnetic.

The difference in the magnetic properties of minerals is frequently used to concentrate or separate the nickel rich minerals from the gangue minerals. Low intensity magnetic separators are sometimes used to remove monoclinic pyrrhotite and magnetite from the flotation concentrate.

Yalcin (1993) explored the possibility of magnetoflotation, a process involving a magnetic drum at the froth collection zone, which feeds back any magnetic material that reports in the concentrate of the flotation cell.

Applying an oscillating magnetic field to a flotation column will affect the movement of the magnetically susceptible materials during flotation. The movement of the magnetic particles may increase the possibility of a hydrophobic surface on the particle attaching to the bubble. The movement may also cause the particle and bubble to lose contact with each other. The slime coating caused by serpentine minerals such as chrysotile could possibly be dispersed by the rotation of the particles. The magnetic field may also affect the chemical interactions between the sulphide minerals and the collector. In the present study, the possible effects of magnetic fields on the flotation process with special reference to nickel sulphide minerals were investigated.

3 EFFECT OF A MAGNETIC FIELD ON THE MOVEMENT AND FLOTATION RESPONSE OF A FERRIMAGNETIC PARTICLE

3.1 Introduction

During flotation, hydrophobic particles attach to air bubbles and float. Applying an oscillating magnetic field to a flotation column, where magnetically susceptible particles are present, will not only affect the movement of the magnetically susceptible particles, but will also affect the flotation response of these particles.

The properties of the applied magnetic field, e.g. frequency, field strength and orientation of the magnetic field relative to the particle, determine the behaviour of the magnetic particles in the magnetic field. Under specific conditions, the magnetic field can be used to oscillate the magnetic susceptible particles. Depending on the orientation of the magnetic field, some of the particles attached to the air bubble may even lose contact with the air bubble.

The behaviour of a magnetically susceptible particle in an oscillating magnetic field and its effect on flotation are investigated in this chapter. Various combinations of magnetic field strengths and frequencies were used in flotation and visual experiments. To prevent the magnetic field from retaining the magnetic particles in the magnetic field, experiments were done at various frequencies to determine the minimum magnetic field strength required to retain any magnetic susceptible particles in the field. Flotation tests, with varying magnetic field strengths and frequencies, were done in a Hallimond tube to establish the effect of the magnetic field on the flotation of sulphide particles. Orientation of the magnetic field, either parallel or perpendicular to a rising bubble, was investigated using a Hallimond tube.

A laboratory flotation column was used to investigate the effect of positioning the magnetic field in both the particle collection zone and in the middle of the column. In the collection zone at the bottom of the column, the hydrophobic particles attach themselves to the air bubbles. These particles are then transported to the top of the column by the rising bubbles. By varying the position of the electro-magnet on the column flotation cell, the effect of a magnetic field on the collection and rising stages of bubbles was investigated.

The strength of the bond between the bubble and the particle is of importance in flotation. Increasing the strength of the bond between the particle and the bubble, by adding increasing amounts of collector to the system, should prevent the particle and bubble from losing contact even when oscillated by an oscillating magnetic field. Flotation tests in a Hallimond tube with sulphide minerals and varying amounts of collector was done in the presence of an oscillating magnetic field to examine the effect of collector on the flotation performance of the sulphide minerals.

Finally, the effect of residence time of a magnetically susceptible particle in an oscillating magnetic field on flotation was investigated. The residence time in a magnetic field will determine the number of oscillations induced on a pyrrhotite particle, which will also influence the flotation of pyrrhotite in a magnetic field.

3.2 Experimental set-up and procedures

3.2.1 Mineral sample preparation

A nickel sulphide sample was ground in a pulverising mill. The -150 μ m fraction was removed from the milled product by dry sieving. Oversized material, +150 μ m, was recycled to the mill. This procedure was repeated until the whole sample passed through a 150 μ m screen. The -63 μ m fraction was also removed by

dry sieving. The -150 +63 μ m samples were stored in airtight containers to minimise surface oxidation.

Optical techniques were used to determine the mineralogical composition of the samples as shown in table 3-1. The sample was also assayed for nickel, copper and iron by the Nkomati Mine laboratory. Iron (28%) was the major component with lesser amounts of nickel (0.9%) and copper (0.5%).

Table 3-1: Mineralogical composition of the sulphide sample.

Pyrrhotite	85%
Chalcopyrite	2%
Pentlandite	4%
Pyrite	1%
Magnetite	5%
Silicate minerals	3%

3.2.2 Reagent preparation procedure

Potassium amyl xanthate (PAX) obtained from Senmin was used as a collector for the sulphides. To ensure the quality of the PAX, it was purified by dissolving the crystals in acetone and removing the undissolved crystals and impurities from solution by filtration. The PAX was recrystallised by evaporating the solvent under vacuum and the crystals were stored in an airtight container to prevent oxidation.

3.2.3 Conditioning procedure

Just prior to the flotation experiments, oxidation products were removed from the surface of the particles, by conditioning in a hydrochloric acid solution. One gram of sample was mixed with 50ml of a 10-volume percent hydrochloric acid solution before exposing it to an ultrasonic bath for 2 minutes. After this treatment, the sample was rinsed 3 times with 100ml of distilled water.

One gram of the sample was conditioned in 100ml of 10 mg/l PAX solution. A perspex stirrer and impeller were used to agitate the mixture to prevent the particles from settling out and to improve the mass transfer of the collector. During the conditioning of the sample in the PAX solution, the temperature was kept constant by immersing the conditioning beaker in a water bath at 20°C. The pH was controlled at 7.4 by the addition of a potassium dihydrogen ortho phosphate/ disodium hydrogen ortho phosphate pH buffer to the conditioning solution. The conditioning time was kept constant at 10 minutes for all the experiments.

3.2.4 Experimental set-up for the generation of magnetic fields

Electromagnets were coupled to an alternating current source to produce magnetic fields. Magnetic fields, oscillating either parallel or perpendicular to the rising bubbles, were generated with frequencies between 1 and 160Hz and a magnetic field strength of up to 1600 Gauss.

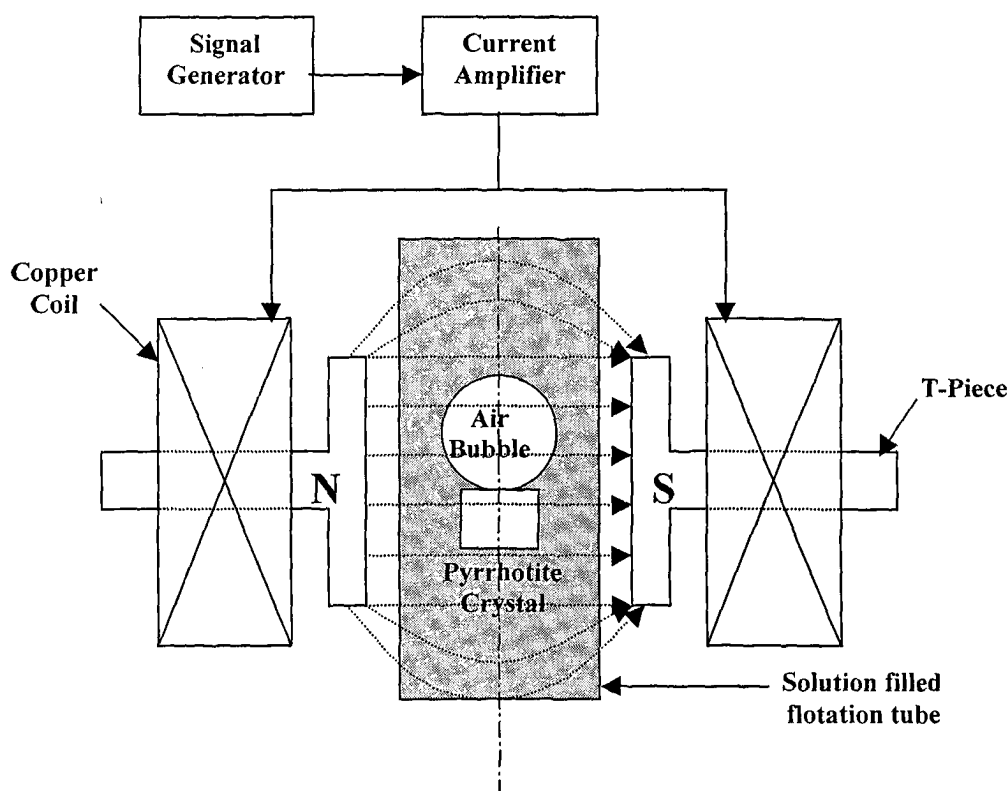


Figure 3-1: Experimental set-up used to produce a linear magnetic field perpendicular to a rising bubble.

The copper coils were driven by a sinusoidal voltage signal, produced by a Krohn-Hite 1000A function generator and amplified by a PA 500 power amplifier, as shown in figure 3-1. The function generator allowed for the variation of current and frequency of the input signal to the electromagnets. The strength of the magnetic field was measured using a Hall probe.

A magnetic field, perpendicular to the rising bubble, was produced by winding copper coils around two mild steel T-pieces. The uniformity of the magnetic field produced between the two T-pieces is shown in figure 3-2. At the edges of the plates, the magnetic field lines were concentrated and the magnetic field strength increased. This is also reflected in the magnetic field profile in figure 3-2, which shows the magnetic field strength along the length of the plates and at two different radial positions (centerline and at radius 20mm from the centerline). The plates were 45mm long and 20mm wide.

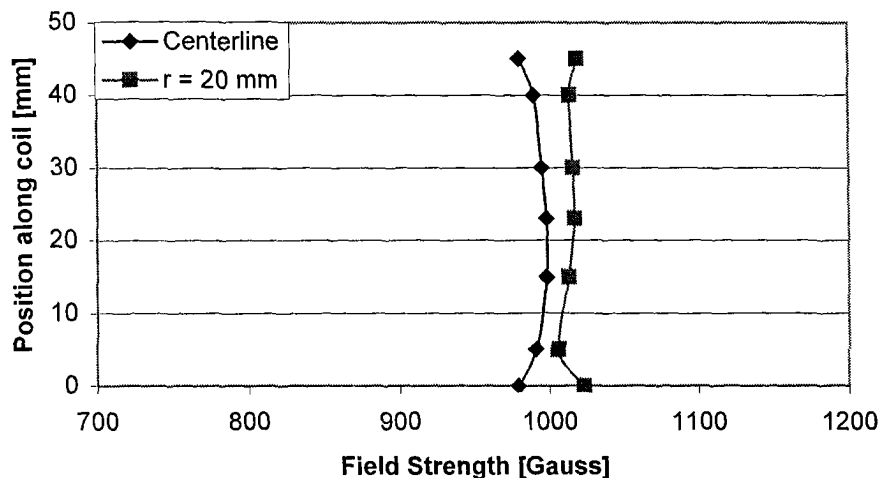


Figure 3-2: Magnetic field strength profile along the centerline and at a radius of 20mm from the centerline of a magnetic field perpendicular to a rising bubble using the experimental set-up as described in figure 3-1.

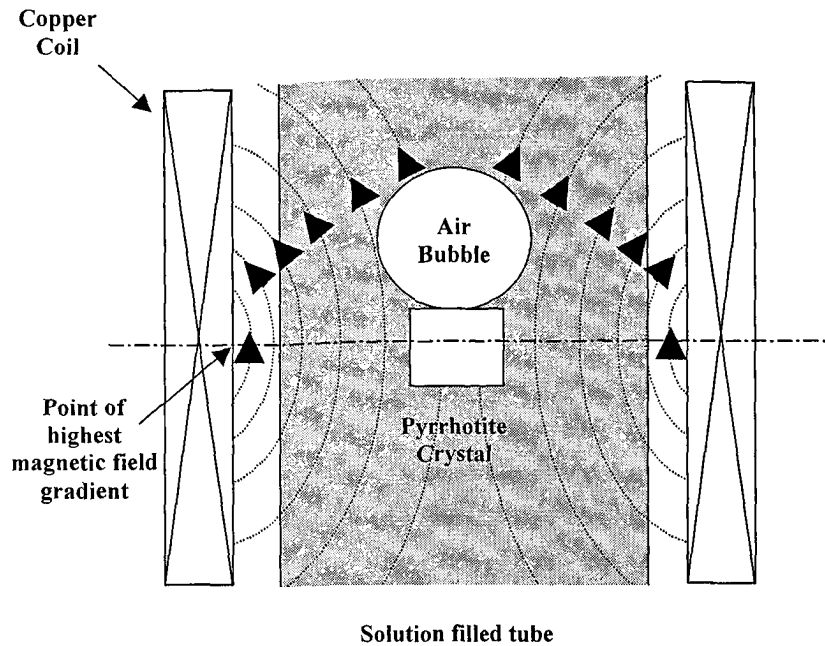


Figure 3-3: Experimental set-up, using copper coils, to generate a magnetic field parallel to the movement of rising bubbles.

The magnetic field parallel to gravity was generated by using copper coils, which were 45mm and 100mm long respectively, with an internal diameter of 55mm and which fitted around the flotation column. The shape of the magnetic field lines and the field gradient in the coil are schematically represented in figure 3-3. Figure 3-4 and figure 3-5 show the magnetic field profile along the length of the magnetic coil at the centerline and at a radius of 20mm from the centerline. For both the 45mm and 100mm long coils, the magnetic field strength was the highest in the middle of the coil. The magnetic field in the middle of the coil was higher at a radius of 20mm than the magnetic field at the centerline for both magnetic coils.

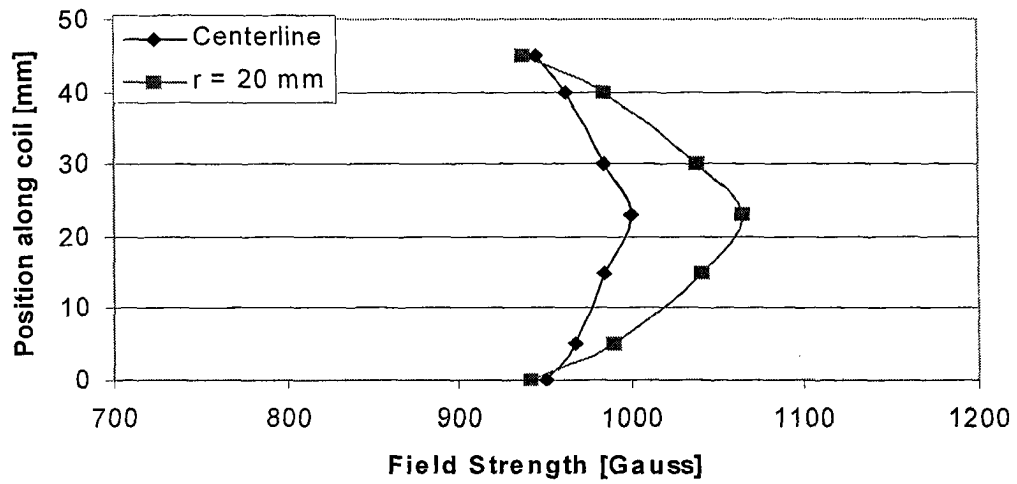


Figure 3-4: Magnetic field strength profile along the centerline and at a radius of 20mm from the centerline of the copper coil 45mm long using the experimental set-up as described in figure 3-3.

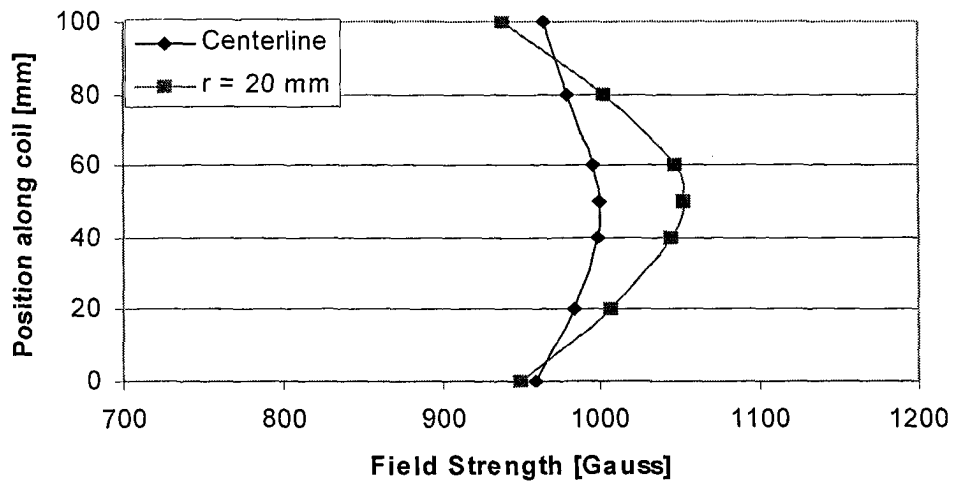


Figure 3-5: Magnetic field strength profiles along the centerline and at a radius of 20mm from the centerline of the copper coil 100mm long using the experimental set-up as described in figure 3-3.

3.2.5 Visual observations of particle movement in an applied magnetic field.

3.2.5.1 Experimental set-up

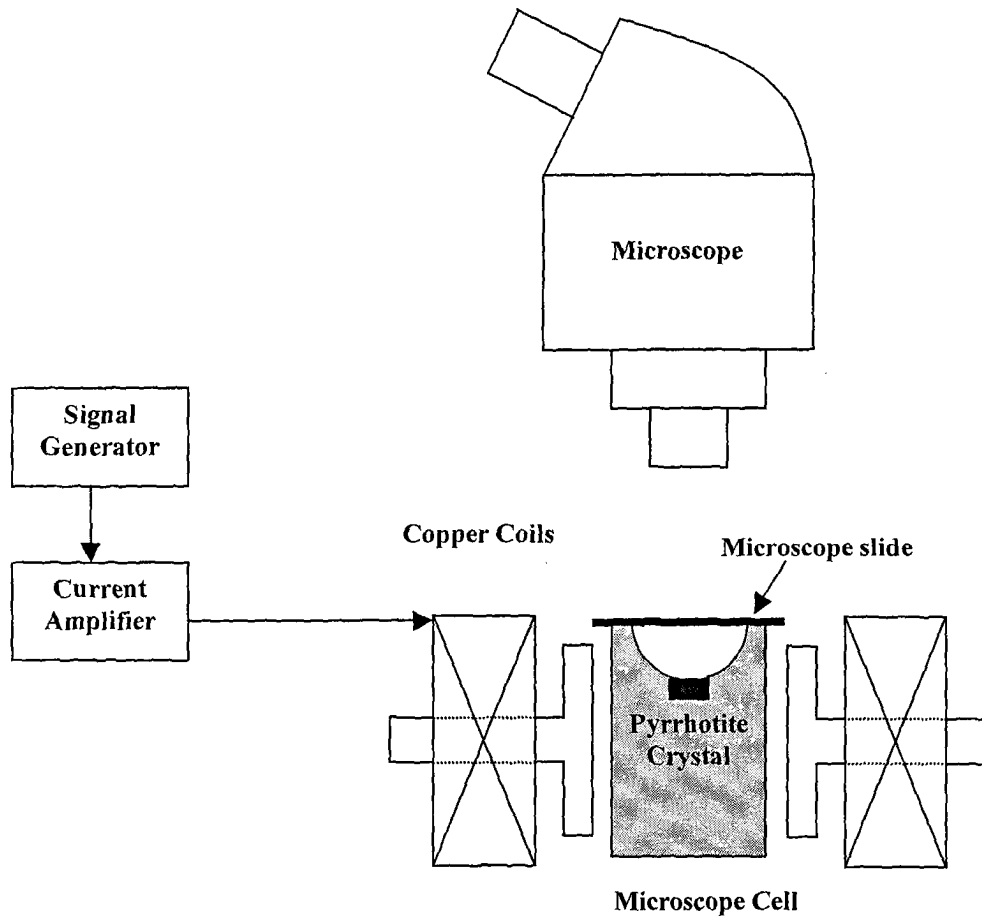


Figure 3-6: Experimental set-up to visually examine the oscillation of a magnetically susceptible crystal in a magnetic field.

The experimental set-up, shown in figure 3-6, was used to visually examine the relationship between frequency, magnetic field strength and oscillation of a magnetically susceptible particle.

3.2.5.2 Experimental procedure

One gram of crushed sample ($-150\mu\text{m} +63\mu\text{m}$) was conditioned in 100ml of a 10mg/l Potassium Amyl Xanthate (PAX) solution for 10 minutes. A measure of the solution and approximately 0.1g of sample was transferred to the microscope

cell shown in figure 3-6. A microscope slide was used to cover the cell. A bubble was injected into the bottom of the cell through a silicon sealed opening, using a hypodermic needle and syringe. The bubble rose through the sample bed and collected the hydrophobic sulphide particles. The loaded bubble then rose to the top of the cell where it adhered to the bottom of the microscope slide. A Nikon SMZ-10 binocular microscope was used to visually observe the behavior of the magnetically susceptible particles in a magnetic field.

3.2.6 *Set-up to investigate retention of magnetically susceptible particles in a magnetic field*

3.2.6.1 Experimental set-up

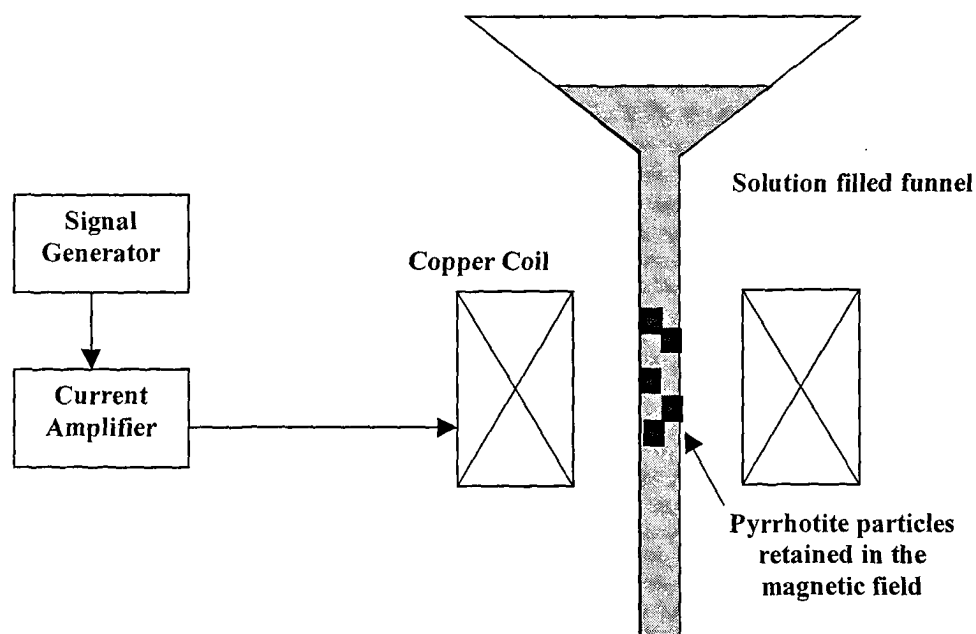


Figure 3-7. *Experimental set-up for the examination of the retention of magnetically susceptible particles in a magnetic field.*

A funnel was placed in the 45mm long copper coil as shown in figure 3-7 and a current was supplied to the coil by the frequency generator and the current amplifier as described before.

3.2.6.2 Experimental procedure

The frequency of the magnetic field was set and the magnetic field was increased to maximum. The funnel was sealed at the bottom and filled with water, after which approximately 0.2 grams of milled sulphide sample (-150 +63 μ m) was added to the top of the funnel. The sample moved through the magnetic field where the magnetic fraction of the sample was retained in the magnetic field. The magnetic field strength was reduced to a point where none of the particles were retained in the magnetic field. At this point the funnel was removed from the magnetic field and the magnetic flux was measured using a Hall probe. Both the magnetic flux and frequency were recorded. The experiments were repeated at several different frequencies.

3.2.7 Hallimond tube flotation procedure

3.2.7.1 Experimental set-up

A glass Hallimond tube as shown in figure 3-8 was used for flotation tests. A magnetic field was applied to the flotation tube by fitting an electromagnet, as described earlier, to the flotation tube. Both the magnetic field strength and frequency were controlled using the set-up described before. Pressurised air was injected into the bottom of the tube and the flowrate was controlled using a rotameter.

3.2.7.2 Experimental procedure

After conditioning, the mineral sample and the xanthate solution were transferred into the Hallimond tube shown in figure 3-8. The mineral sample settled at the bottom of the tube. Air was bubbled from the bottom of the tube at a rate of 0,037l/min for 1 minute. The flotation concentrate was collected in a small tube at the side of the Hallimond tube.

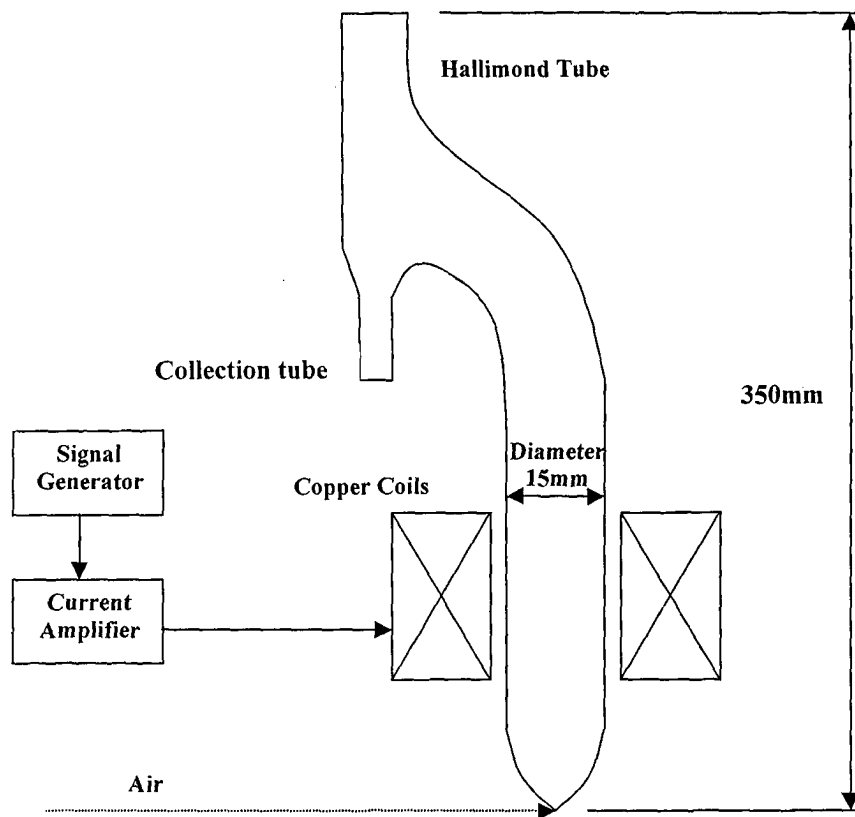


Figure 3-8. Experimental Hallimond flotation set-up with an electro magnet fitted to the tube to apply an oscillating magnetic field to the tube during flotation experiments.

After the test was completed, the flotation concentrate sample in the collection tube and the flotation tail sample that was left in the bottom of the tube were drained into separate beakers before they were filtered, dried and weighed. The flotation recovery was calculated by dividing the mass of the concentrate by the total mass of the sample and expressed as a percentage recovery.

3.2.7.3 Effect of magnetic field strength and frequency on flotation

A magnetic field was applied to the Hallimond tube by fitting a 100mm long copper coil with a 55mm diameter over the bottom of the flotation tube as shown in figure 3-8. A range of frequencies and magnetic field strengths were applied to the tube during the flotation experiments, with a summary of conditions given in table 3-2.

3.2.7.6 Effect of residence time in a magnetic field on flotation of the sulphide sample

To vary the residence time in the magnetic field, two coils with lengths of 45mm and 100mm were alternatively fitted to a Hallimond tube. The residence time in the magnetic field was estimated by measuring the time it took a single bubble to rise through the length of the Hallimond tube. The ratio between the length of the copper coil to the total length of the tube was multiplied by the total rising time to give the retention time in the magnetic field. Conditions for this experiment are given in table 3-2.

3.2.8 Position of magnetic field

3.2.8.1 Experimental set-up

A flotation column shown in figure 3-9 was used to investigate the flotation behaviour of pyrrhotite with magnetic fields applied to different positions of the column. The plastic column was 350mm long with a diameter of 25mm. Air was injected from the bottom of the column through a glass frit to produce air bubbles. The bubbles collected hydrophobic particles which rose to the top of the column where a stable froth formed. The froth overflowed from the top of the column and was collected in a beaker. During the experiments the solution level was kept constant by using a steady head tank.

The 100mm long copper coil with an inside diameter of 55mm, was placed over the column. The magnetic field was controlled by coupling the copper coil to the power and signal generators as described earlier. The magnetic field was respectively applied to the bottom and middle of the column to test the effect of the magnetic field position on the flotation response of pyrrhotite.

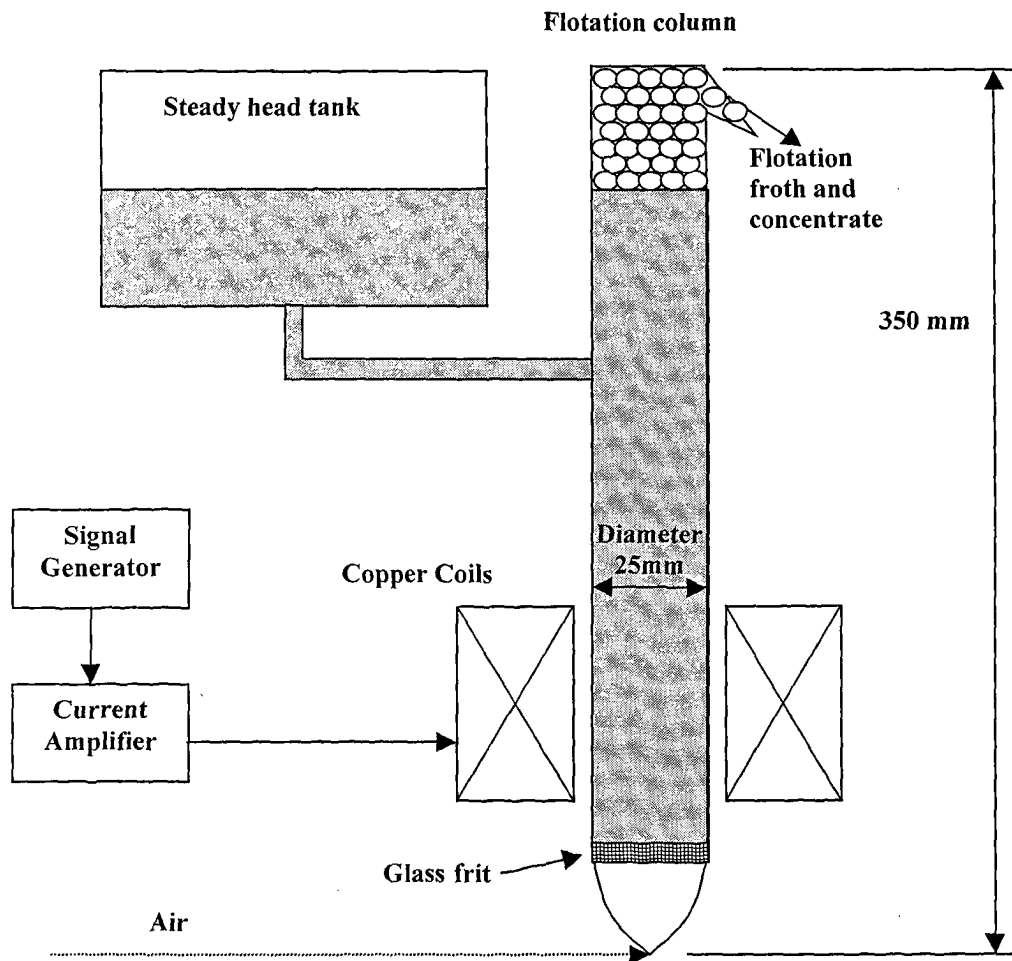


Figure 3-9. Experimental set-up for column flotation tests with an oscillating magnetic field applied to the bottom of the flotation column.

3.2.8.2 Experimental procedure

The sample preparation of the sulphide sample was the same as that described for the Hallimond flotation tests. Two grams of sample was conditioned in a 10 mg/l PAX solution while the temperature was kept constant at 20°C by immersing a 300ml Pyrex beaker in a water bath. The pH was controlled at 7.4 by the addition of a potassium dihydrogen ortho phosphate/ di-sodium hydrogen ortho phosphate pH buffer to the conditioning solution. A stable froth was obtained by adding 20mg/l of Aerofroth 65 frother (Cyanamid) to the conditioning solution.

Table 3-2: Experimental conditions to examine the effect of various parameters on flotation recovery of a sulphide sample (-150 μ m +63 μ m) in a Hallimond tube .

Experiment		Magnetic field strength and frequency	Magnetic field orientation	Collector concentration	Residence time in a magnetic field
Flotation Time	sec	60	60	60	60
Conditioning Time	min	10	10	10	10
Conditioning Temperature	°C	20	20	20	20
pH		7.4	7.4	7.4	7.4
Xanthate Concentration	mg/l	10	10	Variable	8
Magnetic Field Frequency	Hz	Variable	50	50	50
Magnetic Field Strength	Gauss	Variable	Variable	800	800
Magnetic Field Type		Coil	Variable	Coil	Coil

3.2.7.4 Effect of magnetic field orientation on flotation.

A magnetic field perpendicular and parallel to the rising bubble, as described in figure 3-1 and figure 3-3, were respectively applied to the Hallimond flotation tube. A frequency of 50Hz with various magnetic flux densities was used for the experiments. The length of the magnetic coil and the magnetic T-pieces was 45mm.

3.2.7.5 Effect of collector concentration on flotation of pyrrhotite

The collector concentration during conditioning was varied from 0 to 50mg/l PAX and the magnetic field was kept constant at 100Hz and 800 Gauss with the rest of the sample preparation, conditioning and flotation procedures as described before. Table 3-2 shows the conditions for this experiment.

After conditioning for 10 minutes, the mineral sample and the solution was transferred to the flotation column shown in figure 3-9. The column and glass frit were used to fluidise the mineral sample, which formed a static bed in the Hallimond tube. The water level in the column was kept constant during the flotation test, by using a steady head. Air was introduced at the bottom of the column for 30 seconds at a rate of 0.074l/minute through a glass frit.

The froth was collected in a glass vessel at the top of the column. The concentrate and the residue were dried at a temperature of 110°C.

A magnetic field generated, as described earlier, of 800 Gauss at a frequency of 50Hz was respectively applied to the bottom and middle of the flotation tube. Table 3-3 summarises the experimental conditions for this experiment.

Table 3-3: Experimental conditions to examine the effect of magnetic field position during pyrrhotite flotation.

Flotation Device	Flotation Column	
Flotation Time	30	sec
Conditioning Time	10	min
Conditioning Temperature	20	°C
pH	7.4	
Airflow rate	0.074	l/min
Xanthate Concentration	5×10^{-5}	M
Aerofroth 615	20	mg/l
Magnetic Field Frequency	50	Hz
Magnetic Field Strength	800	Gauss
Magnetic Field Type	Coil	

3.3 Results and discussion

3.3.1 Rotation of a magnetically susceptible particle in a magnetic field

The behavior of a ferromagnetic material in a magnetic field can be best described by a simplified hysteresis loop shown in figure 3-10.

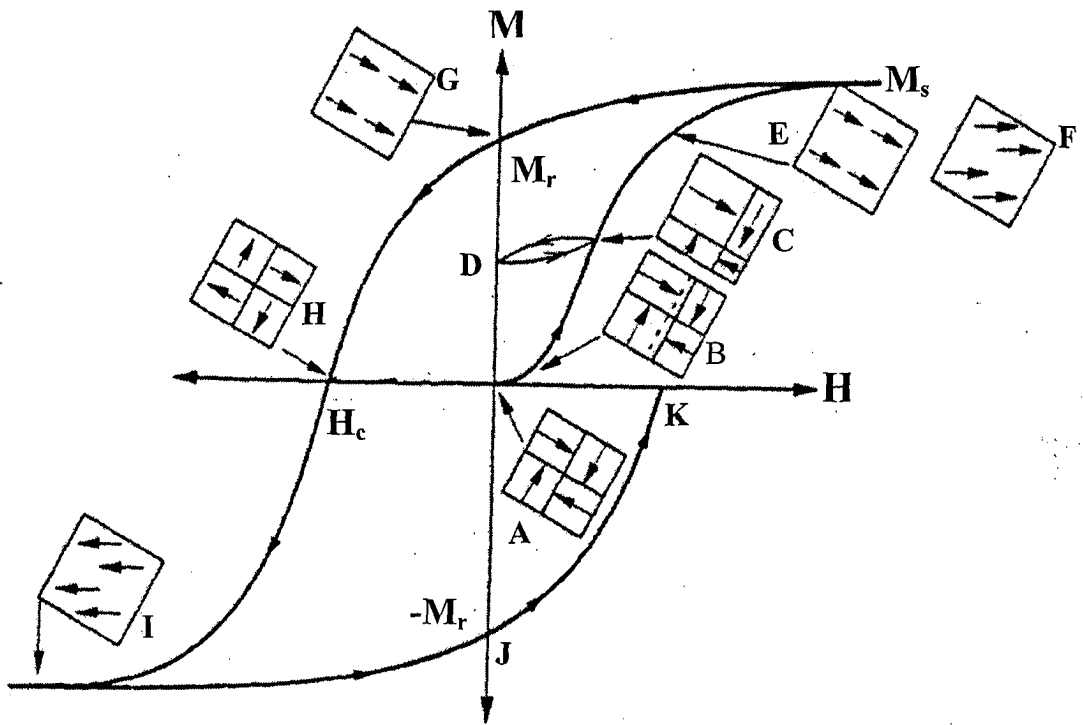


Figure 3-10: Magnetic response curve for a ferromagnetic material subjected to a magnetic field of varying intensity. The behavior of the magnetic domains are indicated by arrows (After Bate and Kryder, 1993)

- With no magnetic field applied to the sample depicted by position A, the internal magnetic domains cancel each other out and the net magnetisation of the sample is zero.
- With a small positive increase in the magnetic field to position B, the domains with orientation closest to the applied field will increase, while the domains opposing the magnetic field will decrease. The domain walls will be displaced

as the domains grow and the displacement of the domain walls is reversible at position B.

- A further increase in the field strength to position C, will result in the growth of the dominant domains. The movement of the domain walls is irreversible at position C.
- If the field is removed, the magnetisation (M) would return to a value at position D.
- Near the knee of the magnetisation curve, position E, all the domain walls will be removed by the applied magnetic field, but the orientation of the induced magnetisation is not parallel to the applied magnetic field.
- At position F, the orientation of the magnetisation is parallel to the external field and no magnetic dipoles exist that can be orientated in the direction of the applied magnetic field and the sample is magnetically saturated (M_s).
- Upon removing the applied magnetic field, the magnetisation of the sample will return to position G. This retained magnetisation is called the remnant magnetisation (M_r).
- To return the sample to its original magnetisation state, a negative external field (H_C) must be applied to the sample at position H. The domains reappear and although the net magnetisation is again zero the domains may be magnetised differently from that of the initial sample.
- By increasing the field strength to position I the process described above will repeat itself.

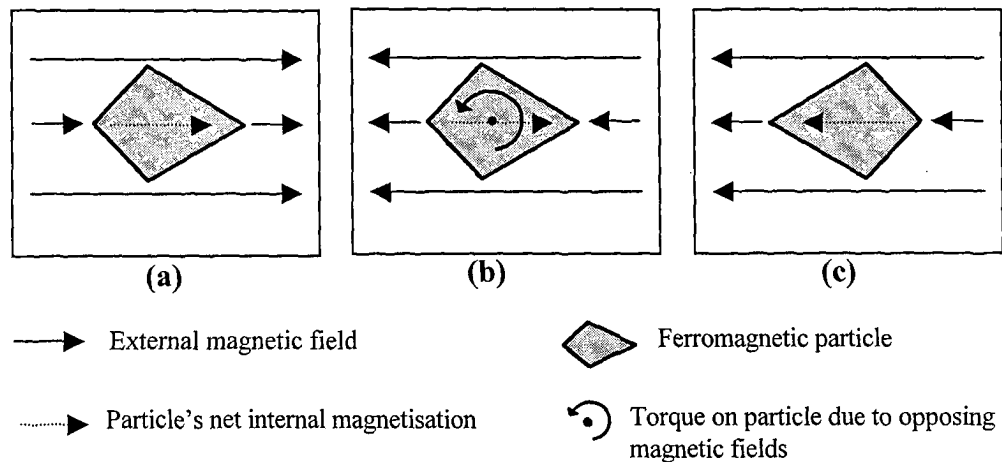


Figure 3-11 :Schematic representation of the behaviour of a free rotating ferromagnetic particle in an oscillating magnetic field. a) Internal and external magnetic fields are aligned. b) Particle's remnant magnetic field opposing the external magnetic field. c) Rotated particle with internal and external magnetic fields aligned with each other.

A ferromagnetic particle, placed in an oscillating magnetic field and allowed to rotate without any physical constraints, is schematically presented in figure 3-11 a-c. The particle is magnetised in the direction of the external field as shown in figure 3-11(a). When the external magnetic field is removed, there would still be remnant magnetisation present in the particle. The effect of reversing the polarity of the external magnetic field is shown in figure 3-11(b). The remnant magnetisation of the particle would now oppose the external magnetic field. A torque is thus produced on the particle to align the particle's internal magnetic field with the external magnetic field. The torque causes the particle to rotate to a position where the internal and external magnetic fields are aligned as shown in figure 3-11(c). By continuously reversing the magnetic field, the process described above will cause the particle to rotate.

Ferrimagnetic materials, like monoclinic pyrrhotite, exhibit the same behavior as ferromagnetic materials, except for the anti-ferromagnetic fraction of the material which aligns itself non-parallel to the external magnetic field.

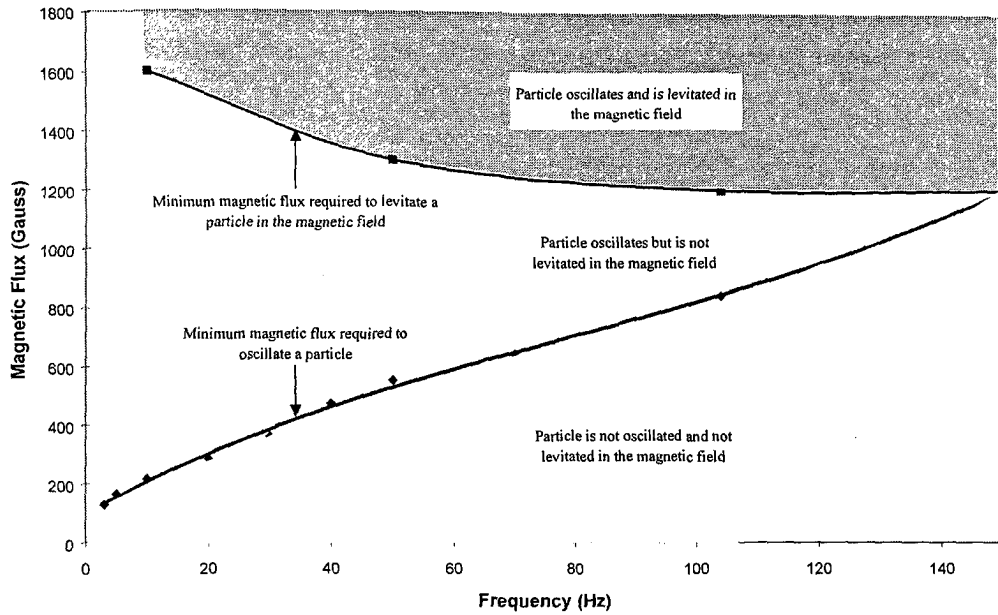


Figure 3-12. Relationship between minimum magnetic flux density and magnetic field frequency required to oscillate and retention of a $75\mu\text{m}$ magnetically susceptible pyrrhotite particle.

With the visual set-up, as described earlier, the relationship between rotation of a magnetically susceptible particle and the external magnetic field was examined. Figure 3-12 shows the relationship between the required magnetic flux density required to rotate a $75\mu\text{m}$ magnetically susceptible particle as a function of the magnetic field's frequency. It was found that the magnetic field strength necessary to oscillate the magnetically susceptible particle, increased with an increase in frequency of the magnetic field.

As the frequency of the magnetic field increased, the inertia and the drag forces on the magnetically susceptible particle played an increasingly important role to limit the oscillation of the particle. An increased magnetic field must therefore be applied at the higher frequencies to oscillate the particle as shown in figure 3-12.

With low frequencies and high magnetic field strengths, the particle will be able to rotate through 180° to align itself with the external magnetic field. At higher frequencies, the particle will be magnetised in the direction of the magnetic field

before it is able to complete the 180° rotation. Under these circumstances it was observed, using the visual set-up described earlier, that the particle still oscillates but the angle through which it oscillated was less than 180°.

3.3.2 Retention of magnetically susceptible particle in a magnetic field

The data in figure 3-12 also shows the dependence of frequency and the magnetic flux density on the retention of magnetically susceptible particles in the magnetic field produced by a coil. The retention line in figure 3-12 indicates the minimum magnetic field strength required to retain any of the sample in the magnetic field at a specific frequency. In all the flotation experiments, the field strength was kept below the retention line to prevent accumulation of magnetically susceptible particles in the magnetic field.

A minimum magnetic field is necessary to retain the particles in the coil. But since the magnetic field strength changed in a sinusoidal fashion, there were periods when the magnetic field was not strong enough to retain the particles in the magnetic field. During these periods the particles moved downwards under the influence of gravity. If a particle moved too far down, the magnetic field was not able to retract the magnetically susceptible particle back into the magnetic field when the magnetic field again increased in strength. The distance covered by the particle during the period where the magnetic field was not strong enough to retain the particle in the magnetic field, was dependent on the frequency of the magnetic field. With frequencies lower than 40Hz, the particle gravitated downwards and the magnetic field necessary to retain the particles, had to be increased as shown in figure 3-12.

3.3.3 Effect of a magnetic field on flotation

The Hallimond tube flotation results for the pyrrhotite sample are shown in figure 3-13 a to d. From the data, it is clear that both the frequency and magnetic flux had an effect on the flotation recovery. The minimum flux needed to oscillate a 75µm magnetically susceptible particle is shown by the broken lines.

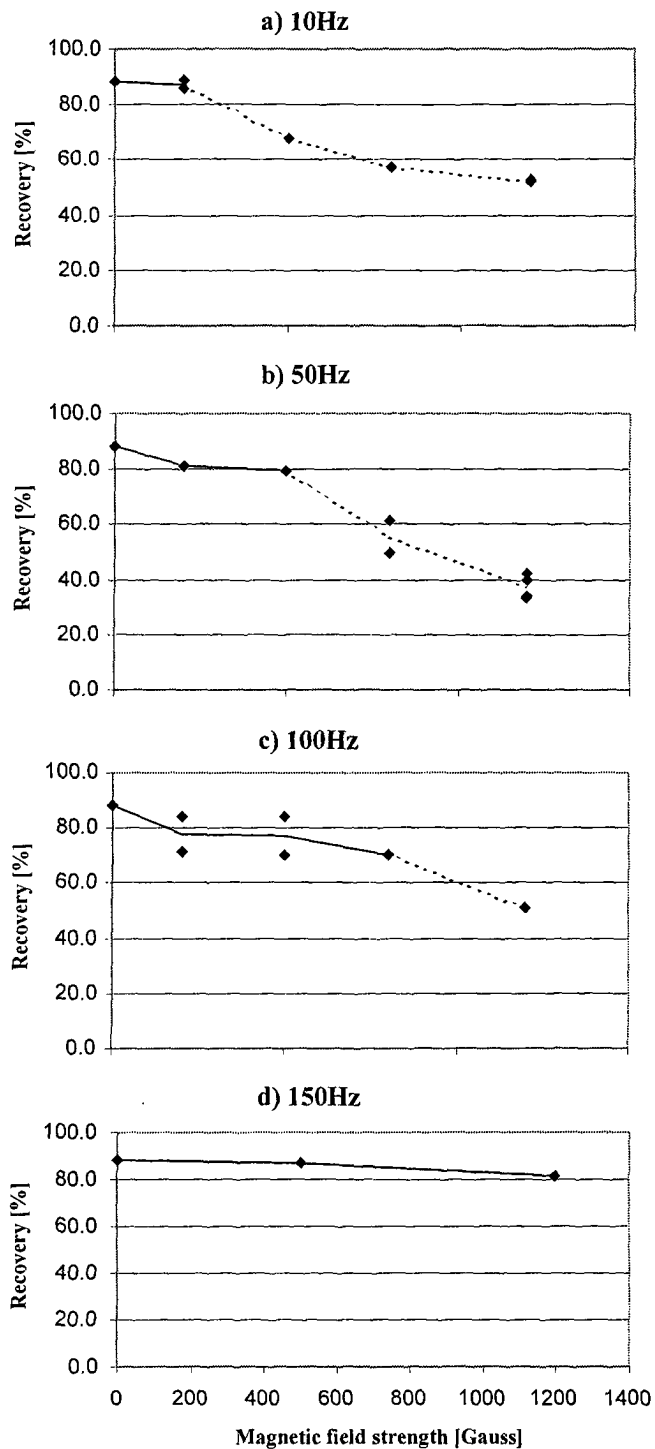


Figure 3-13. Effect of magnetic field strength and oscillation frequency on flotation recovery of the pyrrhotite sample at a) 10Hz, b) 50Hz, c) 100Hz, d) 150Hz.

In general, it was found that flotation recoveries were not reduced when the particles were not oscillated. For example, with a magnetic oscillating frequency of 10Hz, the flotation recovery stayed relatively constant until the magnetically

susceptible particles started to oscillate. The flotation recovery decreased further with increasing magnetic flux density. The increased magnetic flux density increased the torque induced on the magnetically susceptible particle, causing the particle to oscillate more vigorously and to lose contact with the air bubble.

The flotation response of the sample at frequencies of 10, 50, and 100Hz all showed the same trend of decreasing flotation recovery with an increase in magnetic flux, once the particles started to oscillate. The magnetic flux density where a decrease in flotation was observed, increased with frequency and correlated well with the magnetic flux densities necessary to oscillate a 75 μ m particle, as shown in figure 3-12. The flotation recovery of magnetically susceptible particles at 150Hz stayed constant with magnetic flux, since the magnetically susceptible particles were not oscillated.

3.3.4 Effect of magnetic field orientation on flotation

It was noted, from the visual observations described earlier, that the orientation of the magnetic field relative to the magnetically susceptible particle influenced the motional behavior of the particle.

An oscillating magnetic field, perpendicular to the rising bubble shown in figure 3-14(a), magnetised the particle in the direction of the applied magnetic field. When the polarity of the external magnetic field was reversed, the polarity of the particle's remnant magnetisation opposed the external magnetic field as shown in figure 3-14(b). The opposing magnetic fields generated a torque on the particle around an axis perpendicular to the applied magnetic field. With this direction of rotation, the contact between the bubble and the particle was not challenged and the particle rotated without losing contact with the air bubble. Finally, the particle was rotated to align the internal and external magnetic fields as shown in figure 3-14(c).

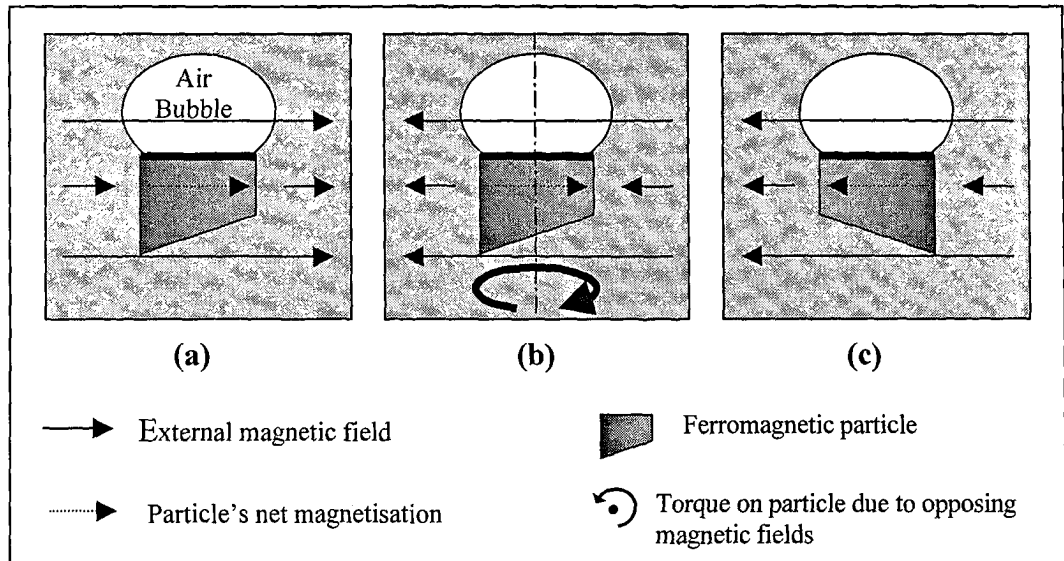


Figure 3-14: Schematic representation of the behaviour of a ferromagnetic particle attached to an air bubble in an oscillating magnetic field perpendicular to the rising bubble. a) Internal magnetic field and external field aligned. b) Particle's remnant magnetic field opposing the external magnetic field. c) Rotated particle with internal and external magnetic fields aligned with each other.

Figure 3-15 describes the behaviour of a ferromagnetic particle, attached to an air bubble, in an oscillating magnetic field parallel to the direction in which the bubble rose. Figure 3-15(a) shows how the external magnetic field magnetises the ferromagnetic particle in the direction of the applied magnetic field. In figure 3-15(b) the direction of the torque on the particle due to the opposing internal and external magnetic fields is shown. It is clear that the contact between the air bubble and particle resists the torque that is applied to the particle. If the particle is not homogeneously hydrophobic, which is typically the case, bubble / particle contact must be broken before the particle can rotate as shown in figure 3-15(c). The implication of this loss of contact between the bubble and the particle during flotation is that the flotation recovery of the particles will decrease.

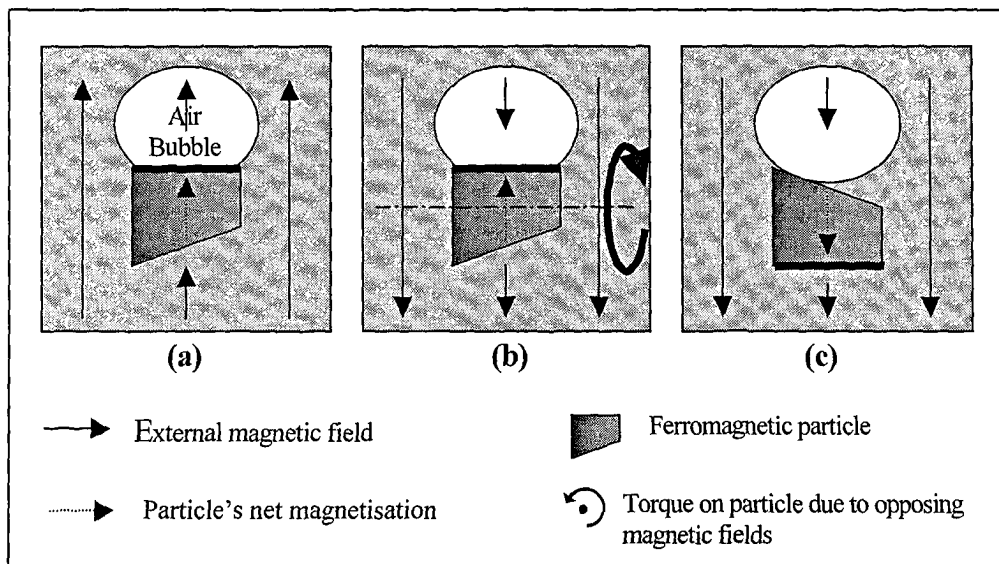


Figure 3-15: Schematic representation of the behaviour of a ferromagnetic particle attached to an air bubble in an oscillating magnetic field parallel to the rising bubble. a) Internal magnetic field and external field aligned. b) Particle's remnant magnetic field opposing the external magnetic field. c) Rotated particle with internal and external magnetic fields aligned with each other.

For magnetic fields alternating parallel to the rising bubble, shown in figure 3-3, it was visually observed that the magnetically susceptible particles attached to the bubble, moved to the side of the bubble, where they oscillated around an axis perpendicular to the applied magnetic field. For a coil, the position with the highest field gradient is shown in figure 3-3. A magnetically susceptible particle, attached to an air bubble, is attracted to the point with the highest field gradient. In this case, the magnetically susceptible particle will move to the side of the air bubble, where it will rotate around an axis perpendicular to the magnetic field lines. However, during flotation the particle will be washed to the bottom of the rising air bubble by the solution.

It was observed using the visual set-up, that the magnetically susceptible particles that did not move to the side of the bubble rotated around an axis perpendicular to the applied field and lost contact with the bubble.

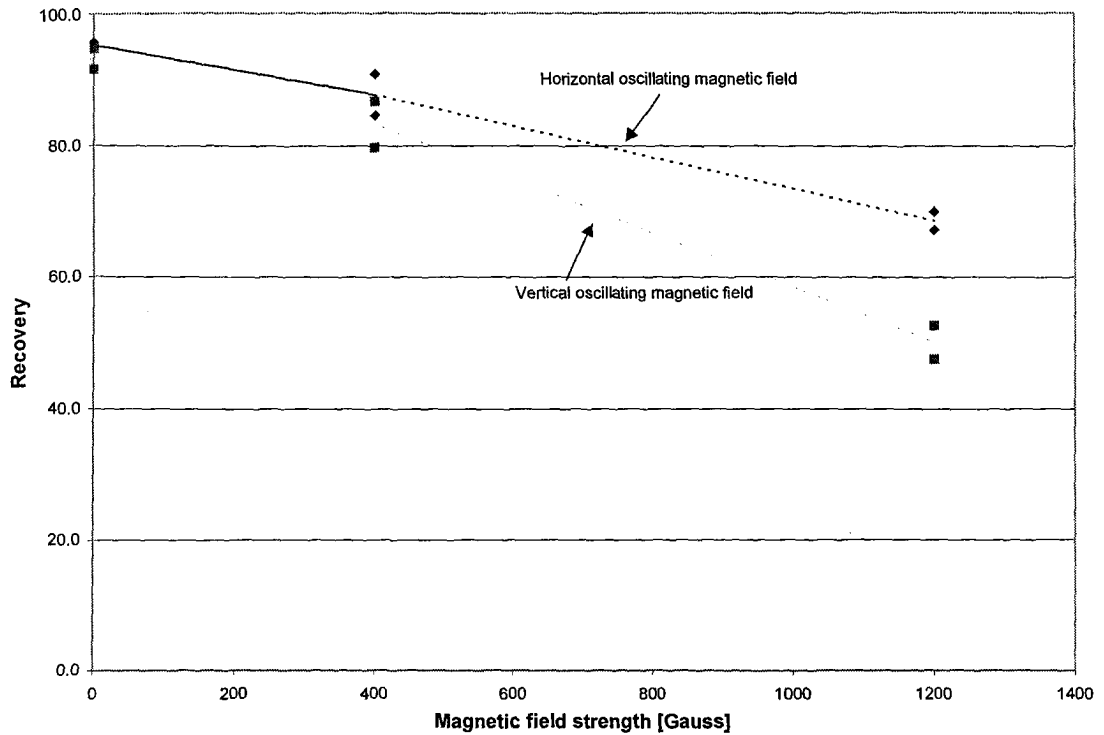


Figure 3-16. Influence of magnetic field orientation on the flotation in a Hallimond tube. Broken lines indicate magnetic flux densities where the magnetically susceptible particle oscillates.

Figure 3-16 shows the effect of the magnetic field orientation on the flotation with increasing magnetic field strength. Note that when magnetic oscillations are induced, shown as broken lines in figure 3-16, the flotation recovery starts to decrease. As would be expected, the magnetic field parallel to the rising bubble has a more pronounced effect on flotation recovery than a magnetic field perpendicular to gravity.

3.3.5 Effect of magnetic field position on flotation

By varying the position of the magnetic field, the effect of a magnetic field on the various stages of flotation was investigated. At the bottom of the flotation column, the air bubbles collected the hydrophobic sulphide. By applying a magnetic field at the bottom of the flotation column, the magnetically susceptible particles were oscillated, increasing the probability that a hydrophobic surface will attach to the rising air bubble. The already attached particles will also oscillate and may lose contact with the air bubble.

By moving the magnetic field to the middle of the flotation column, the collection of the pyrrhotite particles are less likely to be influenced, as only the particles which are already attached, will be subjected to the magnetic field.

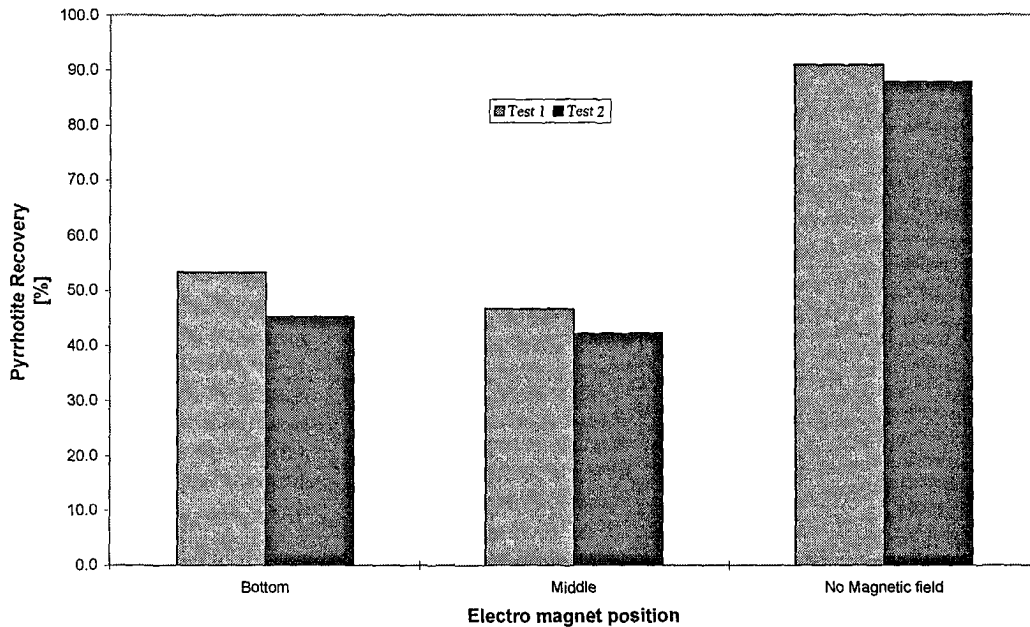


Figure 3-17. Effect of positioning of the magnetic field (50Hz, 800 Gauss) on the flotation of pyrrhotite.

Figure 3-17 shows the flotation recovery of pyrrhotite with a magnetic field positioned at the bottom and middle of the flotation column respectively; also shown is the flotation recovery of pyrrhotite when no magnetic field was present.

It is clear that the magnetic field depressed the flotation of pyrrhotite due to the oscillations induced on the particles by the external oscillating magnetic field. The flotation recovery was not sensitive to the position of the magnetic field, i.e. at either the bottom or the middle of the flotation column. It would thus indicate that the flotation recovery was not enhanced by the oscillation of the magnetically susceptible particles during the collection stage, but rather that the detachment of

the particles, as a result of the oscillation, was more prominent when a magnetic field was applied to the flotation column.

3.3.6 Effect of collector concentration on flotation in a magnetic field

It is obvious that flotation will only occur if the pyrrhotite establishes and maintains contact with the bubble. The presence of a collector will favour bonding between the particle and the bubble, while movement such as that caused by an oscillating magnetic field will tend to challenge this bond. It can be expected that the coverage will increase with increasing collector concentrations, making the bond between pyrrhotite and the bubble less vulnerable.

Figure 3-18 shows that the flotation recovery increased with an increase of collector concentration both in the presence and absence of a magnetic field. The difference between the flotation recovery with and without a magnetic field decreased with increasing collector concentrations. At a concentration of 50mg/l PAX no significant difference in the flotation recovery was notable. The sample showed natural floatability, which explains the 50% pyrrhotite recovery when no collector was present.

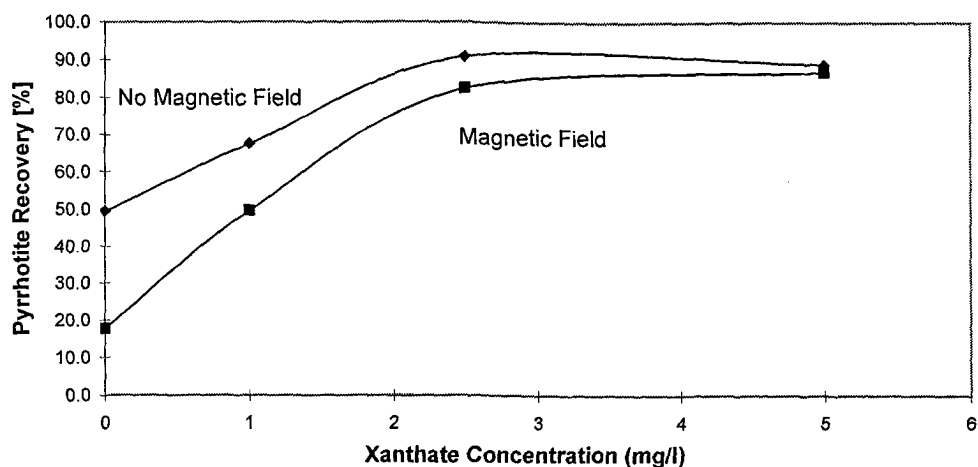


Figure 3-18. Influence of collector concentration on the flotation of pyrrhotite in an oscillating magnetic field (50 Hz, 800 Gauss).

With an increase in collector concentration, the hydrophobicity of the sulphides increased and the flotation recovery increased. The decrease in flotation recovery, when a magnetic field was applied to the flotation process, can be explained in terms of the hydrophobicity of the particles and the magnetically induced oscillations of the particles. With no collector, the hydrophobic fraction of the particle's surface is at a minimum. When a magnetically induced torque is applied to the particle attached to the bottom of a bubble, the hydrophobic bonding force may not be able to counter the magnetically induced torque and the particle would lose contact with the air bubble. From figure 3-18, it can be seen that the maximum effect of a magnetic field on flotation is attained with no collector present.

As the collector concentration increases, the hydrophobic area on the particle's surface and the strength of the hydrophobic bond would probably increase. It would be more difficult for the magnetically induced torque on the pyrrhotite particles to detach the particle from the bubble. The increased contact area between the particle and air bubble or the stronger bond would offer more resistance to the applied torque. The result is that the flotation will be less adversely affected.

3.3.7 Effect of residence time in a magnetic field on flotation.

Increasing the residence time of the magnetically susceptible particles attached to an air bubble in a magnetic field, will enhance the effect of a magnetic field on flotation. The probability that the particle will lose contact with the air bubble increases with the number of oscillations induced on the pyrrhotite particle by the external magnetic field. The number of oscillations is a function of the residence time and frequency of the magnetic field.

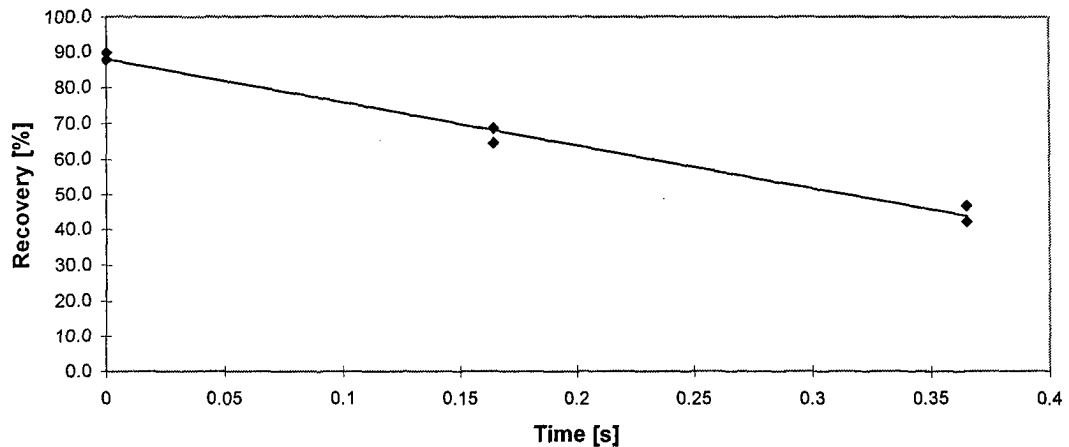


Figure 3-19. Influence of residence time in an oscillating magnetic field (50Hz, 800 Gauss) on the flotation of pyrrhotite

From figure 3-19, it is clear that the increased residence time in the magnetic field had a negative influence on the flotation recovery. At a frequency of 50Hz and a residence time of 0.02 seconds, 1 oscillation was induced on a pyrrhotite particle; similarly 2.25 oscillations were induced on the magnetically susceptible particle if the residence time is increased to 0.045 seconds. Figure 3-19 shows that the flotation recovery decreased with an increase in the number of oscillations induced on the pyrrhotite particle. The increase in the number of oscillations increased the probability that a magnetically susceptible particle will lose contact with the air bubble and thus decreased the probability of flotation.

3.4 Conclusions

The interaction between a magnetic field and a particle is dependent on the magnetic properties of the particle and on the properties of the magnetic field. The magnetic properties of minerals typically present in pulps differ, which implies different responses to a magnetic field. Typical examples are pyrrhotite (ferrimagnetic), pyrite (paramagnetic), and quartz (diamagnetic).

Visual experiments showed that magnetically susceptible particles attached to an air bubble were mechanically oscillated, under certain conditions, when an external magnetic field was applied to a flotation device. The oscillation of these particles was dependent on the frequency and the magnetic flux of the external magnetic field. The magnetic flux required to rotate the magnetically susceptible particles increased with the frequency. Also, the magnetic field strength necessary to retain a magnetically susceptible particle in a magnetic field decreased as the frequency was increased.

The flotation tests showed that there was a definite interaction between the magnetic field and magnetically susceptible particles during the flotation process. The magnetically susceptible particles may oscillate depending on the frequency and magnetic flux density of the magnetic field. Where oscillations were induced on the magnetically susceptible particles, the flotation recovery decreased. This decrease could be ascribed to the relative movement between the particles and the air bubble, which resulted in the loss of contact.

The orientation of the magnetic field determined the direction of oscillation of the magnetically susceptible particles. A field perpendicular to gravity caused the magnetically susceptible particles attached to an air bubble to oscillate freely, whilst a magnetic field parallel to gravity caused the particles to lose contact with the air bubble.

The flotation of magnetically susceptible minerals is depressed by a magnetic field, but there is no significant difference in the depressing effect of the magnetic field when the position of the magnetic field along the length of the tube was changed. Rather, the detachment of the oscillating pyrrhotite particles seems to dominate the flotation behavior of the pyrrhotite in a magnetic field.

Sulphide mineral flotation tests with increased concentrations of PAX collector, in the presence of a magnetic field, showed that the effect of the magnetic field diminished as the collector concentration increased. With an increase in collector concentration, the hydrophobicity of the particles increased with the result that the strength of the bond between the bubble and the particle also increased. The

induced oscillations were thus not able to break the bond between the bubble and the pyrrhotite particles and flotation recovery was not significantly affected by a magnetic field at higher collector concentrations.

The retention time in the magnetic field and the frequency of the oscillation of the magnetic field, determine the number of oscillations induced on a magnetically susceptible particle. With an increase in the number of oscillations on the particles, the probability of the particles losing contact with the bubbles increased and the flotation recovery decreased.

4 INVESTIGATING THE POSSIBLE USES OF MAGNETIC FIELDS DURING FLOTATION

4.1 Introduction

In low-grade nickel deposits, the host minerals often depress the flotation of the nickel sulphide minerals. These host rock minerals include pyrrhotite, quartz, and serpentine minerals. Applying an oscillating magnetic field to a flotation column and utilising the magnetic properties of the ore to selectively increase the flotation performance of the nickel sulphide minerals was investigated.

Pyrrhotite is nearly always associated with pentlandite, the main nickel sulphide mineral (Wang and Heiskanen, 1990). Excessive amounts of pyrrhotite in the flotation concentrate result in high sulphur dioxide emissions when the nickel sulphides are pyrometallurgically treated (Agar, 1991). To reduce the flotation of pyrrhotite, depressants are added to selectively depress the pyrrhotite. Magnetic fields applied to the flotation cells could possibly reduce the pyrrhotite recovery and thus reduce the amount of depressants necessary to attain the desired sulphur grade in the flotation concentrate. The possibility of selectively depressing pyrrhotite flotation was also investigated.

In froth flotation it is both the grade of the concentrate as well as the recovery of the sulphide minerals that are important. Quartz associated with sulphide minerals often reports in the concentrate and lowers the grade of the concentrate. If the concentrate is treated pyrometallurgically, it is critical that the sulphur grade is not too low, since it will cause poor performance in the pyrometallurgical treatment process.

In many low-nickel grade deposits, the original peridotites were altered to serpentines (Edwards et al, 1980). The serpentine minerals generally interfere with the flotation of nickel sulphides. The possibility of improving the flotation of pyrrhotite and pyrite in the presence of chrysotile by magnetic fields were investigated.

4.2 Experimental set-up and procedures

4.2.1 Column flotation experiments

4.2.1.1 Experimental set-up

Conditioning of the pyrrhotite and pyrite was the same as that described before. A column as described in figure 3-9 was used for the flotation experiments; all the procedures as described earlier were followed. The visual set-up was used to observe the behaviour of the minerals attached to the air bubble in the presence of an oscillating magnetic field.

4.2.1.2 Experimental procedure for the flotation of pyrite and pyrrhotite in an oscillating magnetic field

Magnetic pyrrhotite was separated from the milled (-150 μ m +63 μ m) nickel sulphide sample using a permanent magnet. The magnet was dragged through the sample and collected the magnetically susceptible pyrrhotite. The magnetic minerals were removed from the magnet and this procedure was repeated on the magnetic fraction a further 3 times to remove any non-magnetic minerals that was trapped with the magnetic particles. The flotation sample was made up of one gram each of pyrite and pyrrhotite. Experimental conditions are outlined in table 4-1.

Table 4-1: Experimental conditions to examine the effect of magnetic field strength and frequency on the flotation of pyrite and pyrrhotite sample(-150 μ m +63 μ m).

Experiment		Varying magnetic field	Varying magnetic field in presence of chrysothite
Flotation Device		Column	Column
Flotation Time	sec	30	30
Conditioning Time	min	10	10
Conditioning Temperature	°C	20	20
PH		7.4	7.4
Airflow rate	l/min	0.074	0.074
Xanthate Concentration	mg/l	8	8
Aerofroth 615	mg/l	20	20
Magnetic Field Frequency	Hz	50	50
Magnetic Field Strength	Gauss	Variable	800
Magnetic Field Type		Coil	Coil

4.2.1.3 Experimental procedure for the flotation of chrysotile, pyrite and pyrrhotite in an oscillating magnetic field

Approximately 50g of chrysotile obtained from GEFCO was mixed with 100ml of distilled water. The mixture was dispersed with an Ultra Tarrax disperser for 2 minutes to break up the chrysotile fibers. A sieve was used to wash out the

-106 μ m fraction and the undersize fraction was filtered and dried. Before adding the appropriate mass of chrysotile to the conditioning vessel, the chrysotile was mixed with 10ml of distilled water and dispersed for 10 seconds. One to four mass percent of chrysotile was added to 1g each of pyrite and pyrrhotite and conditioned in 200ml of 10mg/l PAX solution. The concentrate and the residue samples were washed in water to remove the chrysotile before the samples were dried and weighed. The flotation conditions and reagents used are shown in table 4-1.

A sample, as prepared for the flotation experiments, was transferred into the cell for the visual observation set-up. The visual set-up, described before, was used to visually observe the effect of the magnetic field on the behaviour of the particles attached to an air bubble in the presence of a magnetic field.

4.2.2 Hallimond flotation of pyrrhotite and quartz in a magnetic field

4.2.2.1 Experimental set-up

The conditioning and flotation set-up for the Hallimond tube were the same as described previously.

4.2.2.2 Experimental procedure

Pure quartz was crushed in an alumina mortar and pestle in the presence of fine (-63 μ m) pyrite. Half a gram of pyrite was added to 100 grams of quartz during grinding. The pyrite smeared onto the quartz surfaces enhanced the hydrophobicity of the quartz. The -106 +63 μ m quartz fraction was then sieved out.

Betacol TA from Beta-chem, an amine collector, was added as an additional collector to enhance the flotation of the quartz particles. The concentration of the xanthate was 20mg/l, while the amine concentration was 3mg/l.

The pyrrhotite was prepared as described before. The flotation time was increased to 60 seconds and the airflow rate was 0.074l/min.

Table 4-2: Experimental conditions used to examine the effect of an oscillating magnetic field on the flotation of pyrrhotite and quartz.

Flotation Device	Hallimond Tube	
Flotation Time	60	sec
Conditioning Time	10	min
Conditioning Temperature	20	°C
pH	7.4	
Airflow rate	0.074	l/min
Xanthate Concentration	20	mg/l
Amine Collector	3	mg/l
Magnetic Field Frequency	50	Hz
Magnetic Field Strength	Variable	Gauss
Magnetic Field Type	Coil	

The effect of a magnetic field on the flotation behavior of the quartz and the pyrrhotite was visually observed by the set-up described in figure 3-6.

4.3 Results and Discussion

4.3.1 *Effect of magnetic fields on flotation of pyrite and pyrrhotite*

Figure 4-1 shows the flotation results for pyrite and pyrrhotite in the presence of an oscillating magnetic field. The flotation of pyrrhotite was not significantly affected by a magnetic field up to 500 Gauss at 50Hz; this was expected since the pyrrhotite particles did not oscillate. However, when the pyrrhotite particles oscillated, shown as the dotted line in figure 4-1, the flotation recovery decreased slightly. Pyrite, which is paramagnetic, was not affected by the magnetic field. These results indicate that pyrrhotite can be depressed by a magnetic field if the

combination of magnetic field strength and frequency induces oscillations on the pyrrhotite particles.

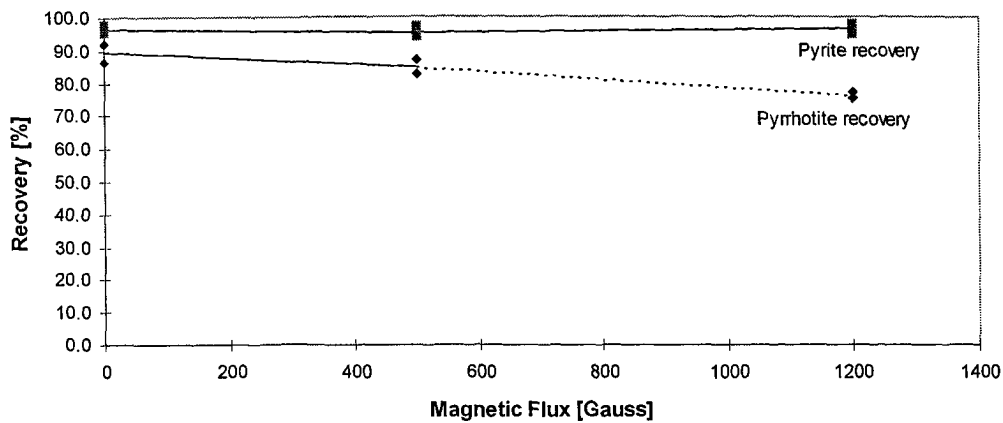


Figure 4-1. Influence of the magnetic field strength of an oscillating magnetic field on the flotation recovery of pyrrhotite and pyrite. The dotted lines indicate magnetic field conditions where rotation of the magnetically susceptible particles was observed.

4.3.2 Effect of chrysotile and magnetic fields on the flotation of pyrrhotite and pyrite

Figure 4-2 shows the influence of the amount of chrysotile in the sample on the recovery of pyrite and pyrrhotite. It is clear that the recovery of both pyrrhotite and pyrite decreased with an increase in the chrysotile concentration. The pyrrhotite recovery was more strongly affected than that of pyrite. Pyrite recovery decreased only slightly from 98% to 85% as the chrysotile concentration was increased to 6%. The magnetic field of 800 Gauss and a frequency of 50Hz did not have any significant influence on the flotation response of the pyrite.

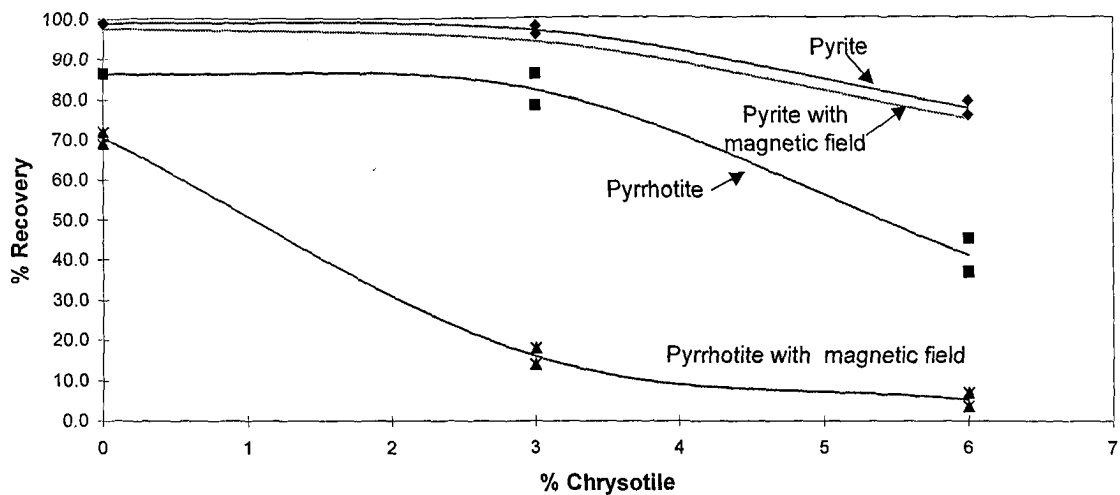


Figure 4-2. Effect of chrysotile and an oscillating magnetic field on the flotation of pyrite and pyrrhotite.

The pyrrhotite recovery decreased significantly from approximately 88% to 50% with an increase to 6 mass percent chrysotile. However, when a magnetic field of 800 Gauss and a frequency of 50Hz was applied to the flotation column, the pyrrhotite recovery decreased dramatically with an increase in the chrysotile concentration.

The experimental set-up as shown in figure 3-6 was used to visually observe the effect of a magnetic field on the flotation of pyrrhotite in the presence of chrysotile. It was seen that a large part of the bubble was covered with chrysotile fibers. When a magnetic field was applied to this bubble, the pyrrhotite particles did not move around the surface of the bubble, but rather detached from the bubble as a result of the magnetically induced torque on the particle. This inhibition of the movement of the particles by the fibrous chrysotile resulted in a dramatic decrease in the flotation recovery of the pyrrhotite.

4.3.3 Effect of magnetic field on the flotation of pyrrhotite and quartz

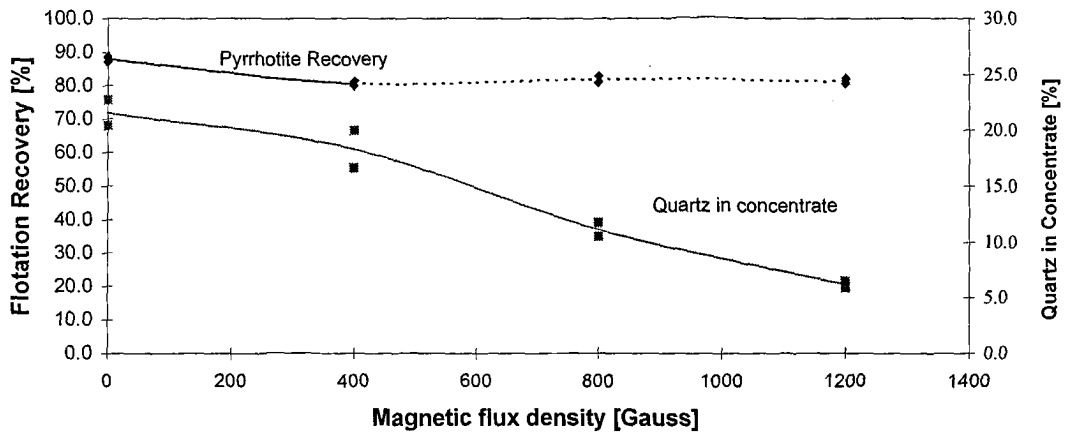


Figure 4-3: Influence of the magnetic strength of an oscillating magnetic field on the flotation recovery and grade of pyrrhotite. Rotation were induced on the pyrrhotite particles at magnetic flux densities greater than 400 Gauss.

Figure 4-3 shows the pyrrhotite recovery and the percentage of quartz in the concentrate obtained from various flotation tests at different magnetic field strengths. As was expected, the pyrrhotite recovery was unaffected by the magnetic field due to the relative high amount of collector used in this experiment. At these high collector concentration levels, the strength of the particle bubble bond is strong enough to prevent the pyrrhotite particles from dislodging from the bubble.

The concentration of quartz in the concentrate stayed fairly constant up to a magnetic flux density of 400 Gauss. The concentration of quartz in the concentrate decreased slightly up to a magnetic flux density of 400 Gauss. However, a more significant decrease in quartz concentration in the concentrate was observed once the pyrrhotite particles started to oscillate at flux densities greater than 400 Gauss.

The quartz was rendered partly hydrophobic by a combination of the pyrite coating, which formed during grinding with the pyrite, and by the addition of an amine collector. Both the quartz and pyrrhotite thus floated and rose into the magnetic field. Using the optical set-up as shown in figure 3-6, it was observed that the oscillating pyrrhotite particles collided with the quartz particles. Quartz is not bonded as strongly as pyrrhotite to the air bubbles and consequently the quartz particles lost contact with the bubble when the oscillating pyrrhotite particle collided with the quartz. This caused the flotation of the quartz to decrease.

4.4 Discussion and conclusions

Pyrrhotite can be selectively depressed to a slight extent by applying a magnetic field whilst pyrite recovery is not influenced by the magnetic field.

The flotation of weakly hydrophobic quartz can be depressed in the presence of pyrrhotite and an external oscillating magnetic field; this improved the grade of the concentrate. The pyrrhotite particles on the bubble oscillated and collided with the quartz particles on the bubble causing the weakly hydrophobic quartz to lose contact with the air bubble.

Chrysotile depressed the flotation of pyrrhotite, but with an applied magnetic field, the recovery of pyrrhotite decreased even further. It was found that the chrysotile fibers attached to the air bubble and inhibited the movement of the pyrrhotite particles to the sides of the air bubble where it is free to oscillate. Consequently, the oscillations of the particle at the bottom of the air bubble tended to break the contact between the bubble and the particle.

5 EFFECT OF MAGNETIC FIELDS ON FLOTATION CHEMISTRY.

5.1 Introduction

The effects of magnetic fields on chemical reactions were, until recently, viewed with skepticism. However, Hayashi (1992) reported on the possible effects of magnetic fields on chemical reactions. It was reported that many chemical reactions, which occur through radical pairs, are influenced by magnetic fields below 2000 Gauss. However, although individual molecules in solution generally exhibit either diamagnetic or paramagnetic behaviour, Hayashi (1992) showed that the reactions of these molecules are not easily influenced by magnetic fields strengths of 2000 Gauss.

Another effect that a magnetic field may have on chemical reactions is by an induced electro-motive force (emf). An oscillating magnetic field induces an emf on any material in the magnetic field. Since the reaction between xanthate ions and pyrite is an electrochemical reaction, it is possible that the induced emf could alter the potential on the pyrite surface, which would in turn influence the chemical reactions supporting the development of hydrophobicity.

The reactions between pyrite and potassium amyl xanthate (PAX) during conditioning in a magnetic field were investigated. This was to establish if a magnetic field has any effect on the type of species that formed during the conditioning and/or the rate at which the species formed. Micro flotation tests were also done to evaluate the effect of conditioning pyrite in a magnetic field.

5.2 Experimental set-up

UV spectrophotometry was used to examine the species formed during conditioning of pyrite and PAX in the presence and absence of a magnetic field. One gram of pyrite, as prepared for the micro flotation tests, was conditioned in 200ml of 10mg/l PAX solution. A water-cooled copper coil similar to the one shown in figure 3-1, was used to produce a magnetic field of 1000 Gauss at 100Hz. The beaker containing the pyrite and xanthate solution was placed in the magnetic field and agitated using a stirrer with a perspex impeller. Five 4ml samples were withdrawn from the beaker and filtered to remove any pyrite, after 2.5, 5, 10, 15 and 20 minutes. The same experiment was done without a magnetic field. The filtered solution was analysed using a UV spectrophotometer, scanning from 200 to 400nm at a rate of 2nm/second.

The pyrite flotation tests were done in a Hallimond tube where all the procedures, as described before, were followed. The flotation tests were done after 2.5, 5, 10, 15 and 20 minutes of conditioning. The flotation test conditions are shown in table 5-1.

Table 5-1: Experimental conditions to examine the effect of conditioning in a magnetic field on the flotation of pyrite

Flotation Device	Hallimond Tube
Flotation Time	60 sec
Conditioning Time	Variable min
Conditioning Temperature	20 °C
pH	7.4
Xanthate Concentration	10 mg/l
Magnetic Field Frequency	100 Hz
Magnetic Field Strength	1000 Gauss
Magnetic Field Type	Coil

5.3 UV-results and discussion

Figure 5-1 shows the various wavelengths where characteristic xanthate species peaks are observed with the relative molar absorptivities indicated. Xanthate ions ($-\text{OCS}_2^-$) exist in solution and decompose by numerous reactions, depending on the pulp potential and pH as shown by Prestidge et al (1993). At a neutral pH, the xanthate ions form attached dixanthogen which dissolved (Ralston, 1991). As the molar UV absorptivities of the different xanthate species differ, it is possible that some of the species with weaker absorptivities were not detected, as the result of the intensity of the xanthate ion and CS_2 peaks.

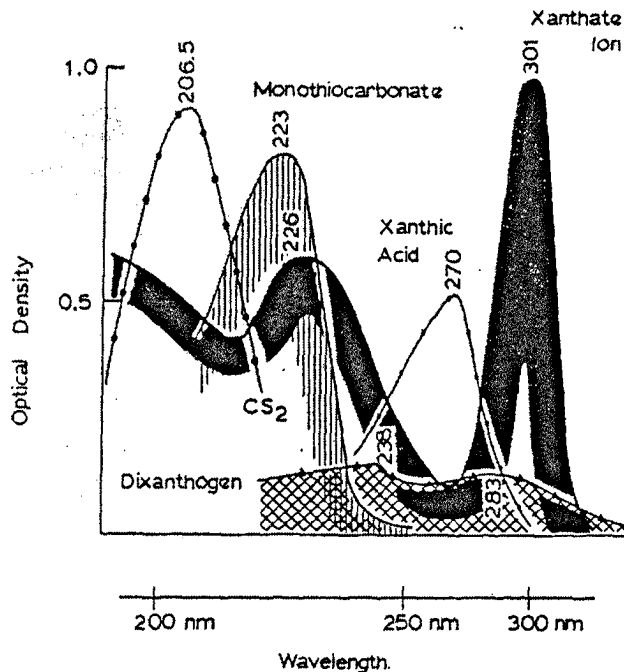


Figure 5-1: UV Spectra of characteristic xanthate species in solution.

Figure 5-2 shows the UV spectra for a xanthate solution and for a xanthate solution in contact with pyrite, both in the presence and absence of a magnetic field after 20 minutes. It is evident from figure 5-2 that an applied magnetic field did not significantly change the spectra. No new peaks appeared on the UV-spectrum, indicating that the xanthate species present during conditioning were not

altered by the magnetic field, at least not in a way that could be discerned on the UV-spectra.

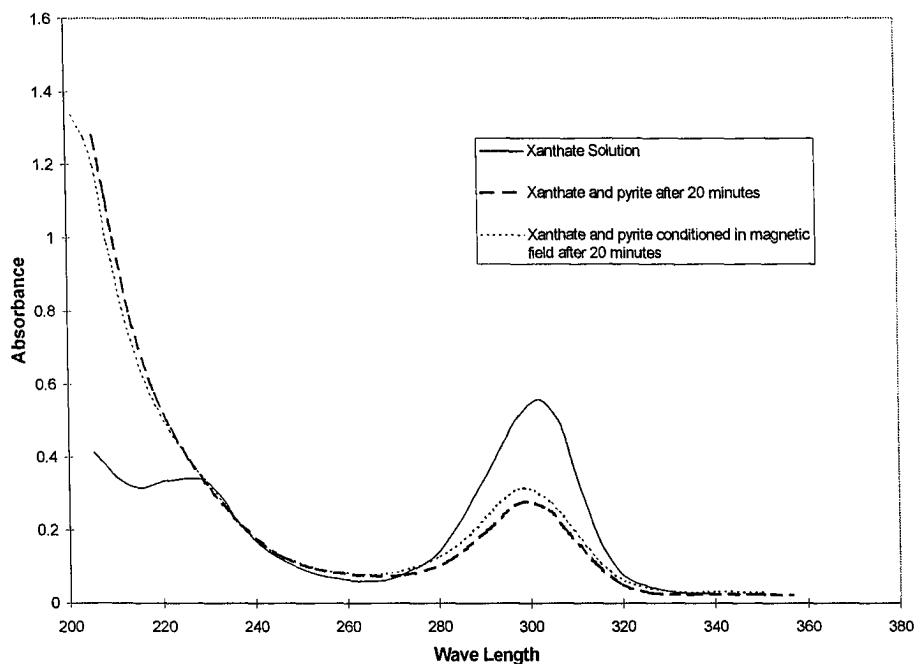


Figure 5-2. UV spectra of 10mg/l xanthate solutions, and xanthate in contact with pyrite at pH 7 after 20 minutes in the presence and absence of a magnetic field.

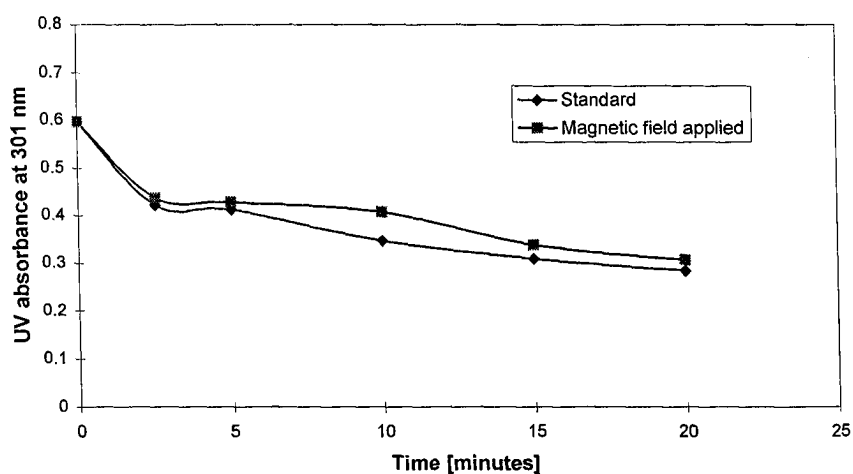


Figure 5-3. Decrease with time of xanthate absorbance at 301nm in the presence of pyrite, with and without an applied magnetic field.

Figure 5-3 shows the concentration of xanthate ions as characterised by the height of the 301nm peak with time, both in the presence and in the absence of a magnetic field. The rate at which xanthate ions react with the pyrite surface is similar in the presence and absence of a magnetic field, although the absorbance obtained in a magnetic field was slightly lower than without the field.

5.4 Flotation test results and discussion

Figure 5-4 shows the effect of conditioning time on the flotation response when pyrite is conditioned in a xanthate solution with an applied magnetic field. The flotation recovery increases with time and then leveled off after 5 minutes of conditioning time, as can be expected for a batch experiment. No significant difference was found between the tests done with and without a magnetic field.

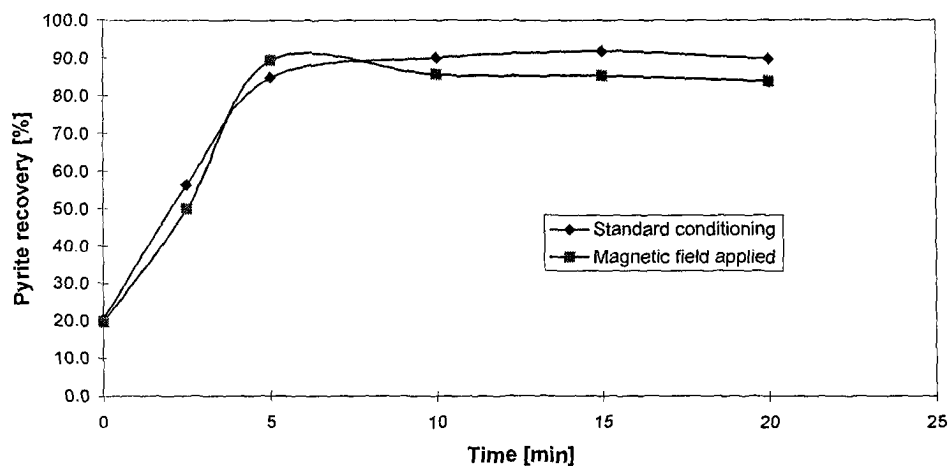


Figure 5-4. The effect of conditioning time and the presence of a magnetic field during conditioning on the flotation of pyrite.

5.5 Conclusions

The presence of a magnetic field did not change the species present during conditioning of pyrite in a xanthate solution. The rate at which xanthate disappeared from solution was also not affected by the magnetic field. Flotation tests also showed that magnetic fields applied during conditioning did not influence the flotation response of pyrite.

6 PILOT COLUMN FLOTATION TESTS TO INVESTIGATE THE EFFECT OF AN OSCILLATING MAGNETIC FIELD ON THE BASE METAL FLOTATION PERFORMANCE

6.1 Introduction

The pilot flotation column was erected at Nkomati Mine, a nickel mine in Mpumalanga, South Africa. A massive sulphide ore body is currently being mined at a rate of 16 000 tons per month with an average head grade of 2.5% nickel, 0.8% copper and 0.3% cobalt. The Nkomati flotation concentrator produces a nickel sulphide concentrate for toll treatment at various refineries in Southern Africa. Nickel is recovered as the primary metal with copper, cobalt platinum, palladium, rhodium and gold as by-products.

Flotation is used to separate pentlandite, chalcopyrite and the cobalt sulphides from pyrrhotite and waste minerals. Two concentrates, a high grade and a bulk concentrate, are produced by the concentrator. The high-grade concentrate is floated from the first cell and a high percentage of platinum group metals is floated into this concentrate. The bulk concentrate is produced by bulk flotation with cleaning and scavenging steps.

In the cleaner application, pentlandite and chalcopyrite are floated away from pyrrhotite. This is an ideal application to apply an oscillating magnetic field to a flotation column. The magnetic fraction of pyrrhotite reporting to the concentrate can be depressed in the flotation column using the oscillating magnetic field. It should thus be possible to increase the grade of the concentrate without sacrificing the recovery of nickel and copper.

A pilot column from Baker Hughes Process was tested in a cleaner application. A magnetic coil was installed around the column and testwork was done to establish the effect of an oscillating magnetic field on the performance of the column in this application.

6.2 Experimental procedure

The 75mm internal diameter column consisted of three 1.5m perspex sections to give a total height of 4.5m. The feed port was situated 2m from the top of the column and the air sparger was located 1m from the bottom. PID controllers controlled the feed and airflow rates. The feed rate into the column was kept constant during the experiment. A variable speed discharge pump, at the bottom of the column, controlled the discharge rate and the pulp level. A pressure sensor, situated at the bottom of the column, was used as input for a PID controller that controlled the variable speed discharge pump. When the pressure was high in the column, i.e. the pulp level in the column was too high, the PID controller increased the pump speed until the set point pressure was reached. Similarly, the pump slowed down when the pressure was too low. Wash water was added at a constant rate of 0.5l/min from the top of the column.

A magnetic field in the column was generated by using a similar set-up as described in figure 3-3. A 200mm long copper coil with 2000 turns was placed 1.2m from the top of the column in the froth zone. A Hall probe was used to measure the magnetic field strength in the middle of the magnetic coil before the experiment was started. The magnetic field strength was set at 1000 Gauss with a frequency of 15Hz. With this flux and frequency the pyrrhotite particles should be rotated but not levitated.

A cleaner feed stream, with a feed analysis of 7.3% nickel and 1.8% copper with pyrrhotite as the main gangue mineral, was used as feed to the flotation column. An agitated tank was filled with the slurry from the main cleaner feed circuit. This tank ensured a constant composition and a stable feed to the flotation column. No extra reagents were added into the feed tank. The feed rate into the column was kept constant at 2l/min with a density of 1.2kg/l. A stabilisation time of at least 3 times the average residence time was allowed before any

samples were taken. Six samples were taken at 5 minute intervals and composited into a single sample for analysis.

Samples of the concentrate and tails were taken for each test and were analysed for nickel, copper and cobalt by the Nkomati laboratory. Recoveries and grades were smoothed using a mass balance package from Kenwalt Systems called Massbal (v1.02). The assay results and the smoothed results are shown in appendix 6.

6.3 Results and discussion

6.3.1 Effect of a magnetic field on mass recovery

The mass recovery into the concentrate was a function of the airflow rate into the column as shown in figure 6-1. It can be seen that the mass recovery was lower when the magnetic field was applied to the column.

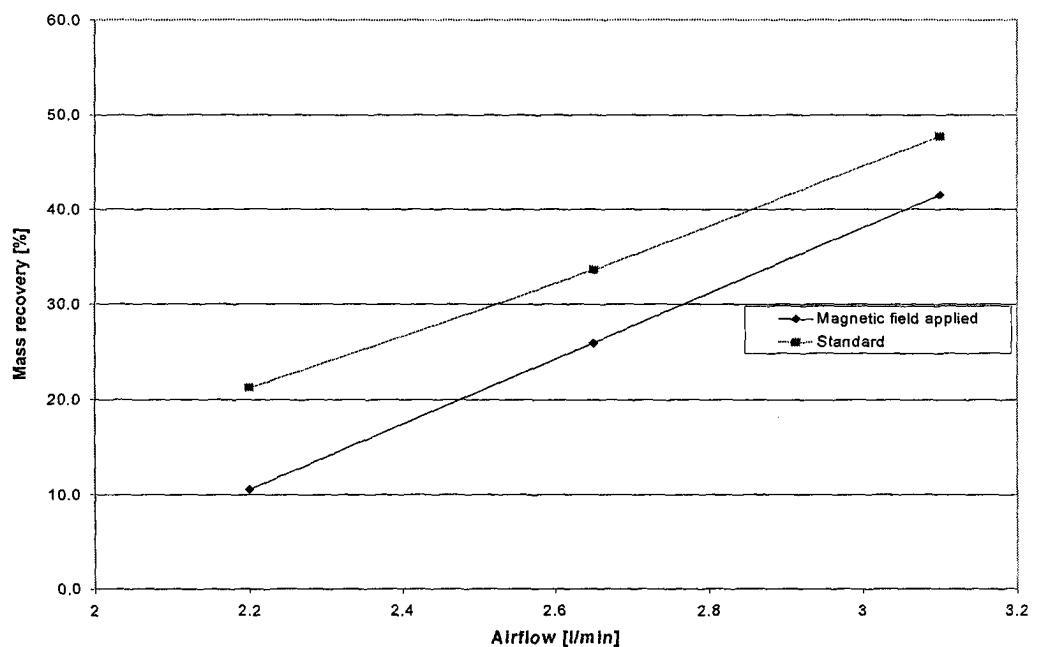


Figure 6-1: Mass recovery of a base metal sulphide feed at various airflow rates for standard column flotation tests and column flotation tests with an externally applied oscillating magnetic field.

At lower airflow rates, the froth flow up the column was slower than at higher flow rates. The retention time of the minerals attached to the air bubbles in the froth zone was higher at lower airflow rates. The magnetic field was applied to the froth zone of the column. Therefore, the time that a pyrrhotite particle, attached to the air bubble, was exposed to the magnetic field increased by decreasing the air flow rate. The probability that the pyrrhotite particle will lose contact with the air bubble is greater at lower airflow rates because of the longer residence time within the magnetic field. It can be seen from figure 6-1 that at low airflow rates there was a greater difference between the mass recoveries for the standard and magnetic tests than for higher airflow rates.

6.3.2 Effect of a magnetic field on copper recoveries and grades

The copper grade and recovery are shown as a function of the airflow rate in figure 6-2.

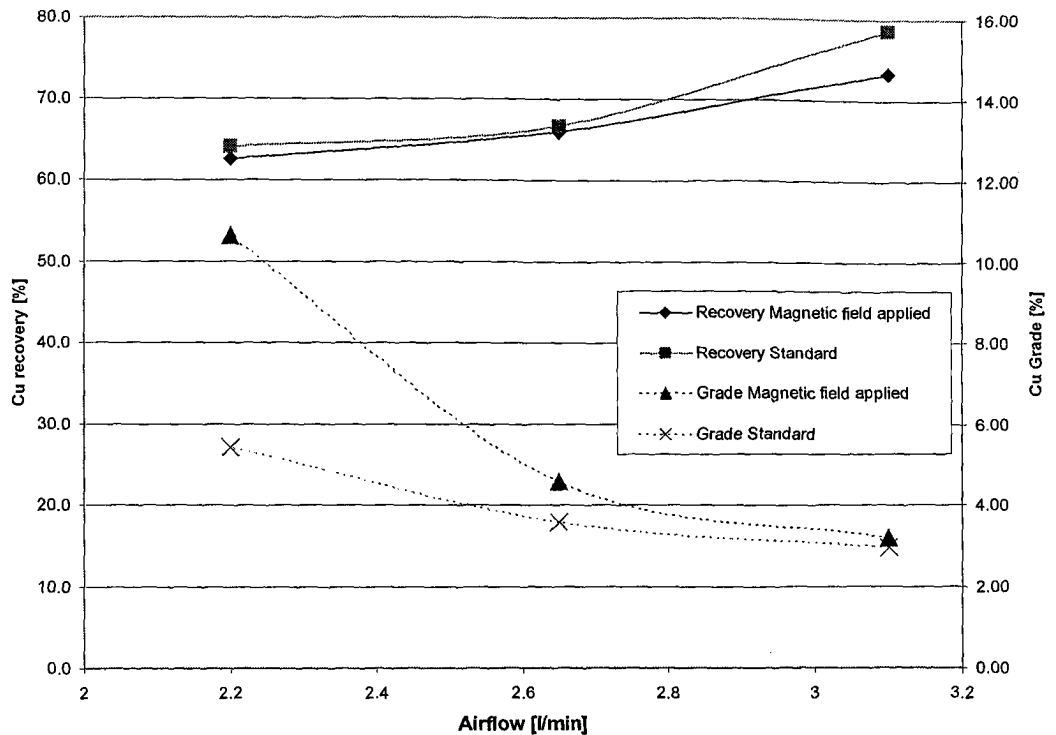


Figure 6-2: Copper recovery and grade at various airflow rates for flotation and for flotation with and without the application of a magnetic field.

As expected, the recovery with and without the application of a magnetic field increased with an increase in airflow rate. Applying an oscillating magnetic field did not significantly affect the recovery of copper. However, the grade at an airflow rate of 2.2l/min in the presence of a magnetic field, was significantly higher than the grade when it was not applied. The higher copper grades can possibly be attributed to depression of pyrrhotite and pentlandite. At higher airflow rates, the difference between copper grades obtained with and without the application of a magnetic field decreased. Using this technique, a copper rich concentrate can be produced albeit at a reduced copper recovery.

6.3.3 Effect of a magnetic field on nickel recoveries and grades

Nickel recoveries and grades for different airflow rates are shown in figure 6-4. Nickel recovery was depressed when a magnetic field was applied to the flotation column. At higher airflow rates, the effect of the magnetic field on nickel recovery diminished. With lower airflow rates, the residence time of a loaded bubble in the magnetic field increased and the possibility of pyrrhotite depression was enhanced. Pentlandite, the nickel bearing sulphide, is closely associated with pyrrhotite. In the cleaner feed stream, used as feed to the pilot column, fine-grained pentlandite is present in pyrrhotite. Therefore, the depression of pyrrhotite will lead to the depression of some of the nickel.

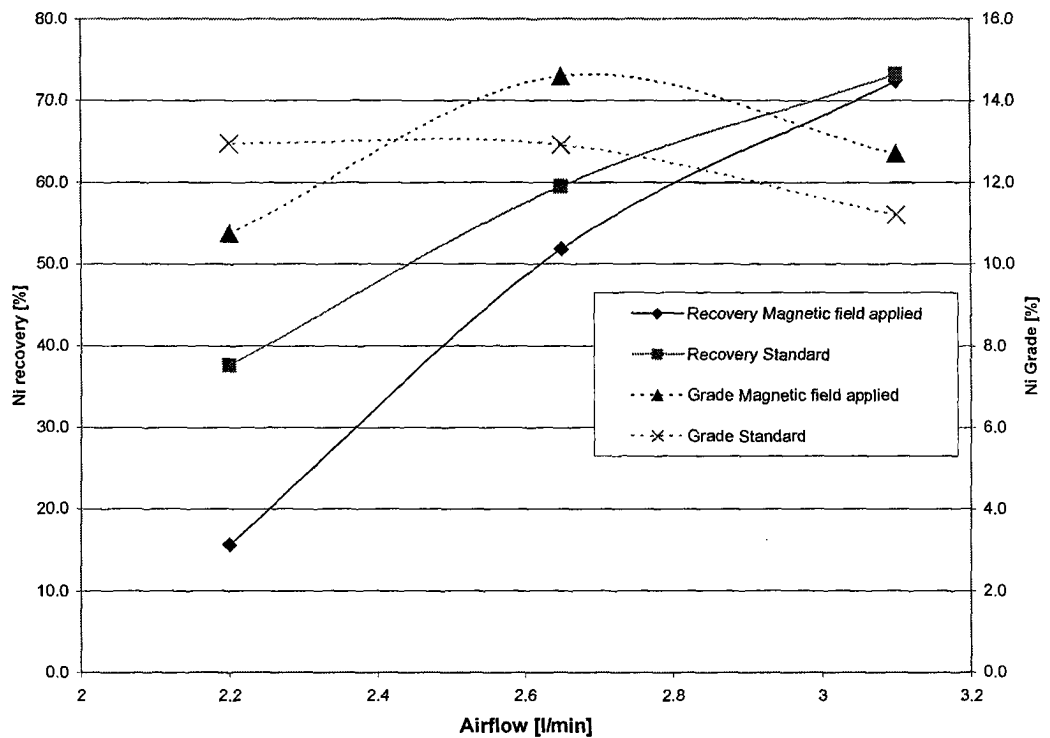


Figure 6-4: Nickel recovery and grade at various airflow rates for standard flotation and for flotation in an oscillating magnetic field.

The low grade of nickel at low airflow rates may be attributed to dilution from copper. Chalcopyrite recoveries were higher than the nickel recoveries, as can be seen by comparing the copper and nickel recoveries from figure 6-3 and figure 6-4. When the magnetic field was applied to the column, the high copper recoveries and the depressed nickel recoveries may be responsible for the low nickel grade at the low airflow rates.

6.3.4 Effect of a magnetic field on the base metal grade recovery curve.

A base metal grade recovery curve, which combines the nickel and copper, is shown in figure 6-5. The base metal grade recovery curve showed the combined nickel and copper recovered at a combined grade. From this curve it is clear that the magnetic field applied to a flotation column produced higher grades for the same recovery. This implies that the flotation recovery and grades can be

improved by applying an oscillating magnetic field to the froth zone of a flotation column.

This base metal grade recovery indicates the pure metallurgical performance and does not take the economic metal values of nickel and copper into account. The economic evaluation of applying a magnetic field to a flotation column must be evaluated for each individual application.

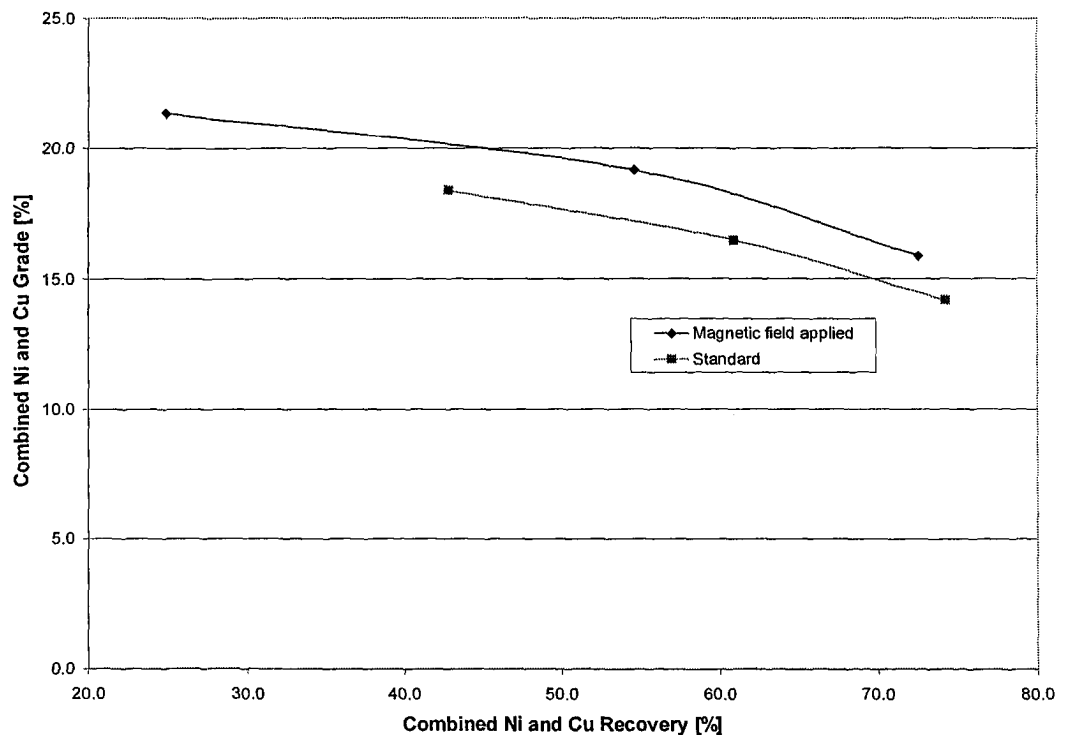


Figure 6-5: Total base metal recovery curves with and without the application of an oscillating magnetic field.

6.4 Conclusions

Copper recoveries were not significantly affected by the presence of an oscillating magnetic field in the froth zone of the flotation column. However, the copper grade obtained in the presence of an oscillating magnetic field and at low airflow rates was higher; possibly due to the depression of pyrrhotite.

The nickel in the cleaner feed stream is closely associated with pyrrhotite and the depression of pyrrhotite will cause some loss in nickel recovery. The combined

base metal grade recovery curve with a magnetic field applied to the flotation column was higher than the standard test grade recovery curve. This implies that the metallurgical separation efficiency with a magnetic field applied to a flotation column is better than for standard flotation conditions, albeit at lower nickel recoveries.

This technique is for applications where magnetic minerals need to be depressed from a flotation concentrate. Due to practical constraints, it would not be possible to apply a uniform magnetizing field of up to 1000 Gauss to a large diameter mechanical flotation cell. Column flotation cells are more suited for this application. Even with column flotation cells, the diameter of the column is limited by magnetic gradient in the column. This technique is best suited for specialized applications with small diameter columns.

7 CONCLUSIONS

In the present work it was found that an oscillating magnetic field, applied to a flotation column, affected the flotation of magnetically susceptible sulphide minerals under specific magnetic field conditions (frequency and magnetic field strength). This technique can be used to *depress* the flotation of magnetically susceptible minerals such as pyrrhotite which occurs naturally with nickel bearing minerals such as pentlandite.

The mechanism by which the magnetic field influenced the flotation of the magnetically susceptible minerals is probably due to the mechanical oscillation of magnetically susceptible minerals. For conditions where the particles oscillated, the flotation recovery of sulphide sample decreased due to loss of contact between the particle and the bubble. Increasing the number of oscillations on the magnetically susceptible particles attached to the air bubble, by increasing the retention time, caused the flotation recovery to decrease. Increasing the amount of collector strengthened the bond between the particle and the bubble. This countered the negative effect of the magnetic field on the flotation recovery of the magnetically susceptible minerals.

The orientation of the magnetic field determined the direction of oscillation of the magnetically susceptible particles. A field perpendicular to a rising air bubble caused particles attached to the bubble to rotate freely, whilst a field oscillating parallel to the rising bubble, challenged the contact bond and caused the particles to lose contact with the air bubble.

The flotation of monoclinic pyrrhotite was depressed by a magnetic field. There was no significant difference in the depressing action of the magnetic field when changing the position of the magnetic field from the collection zone at the bottom of the flotation column to the rising bubble zone in the middle of the flotation column. The detachment of the rotating pyrrhotite particles seemed to dominate the flotation behavior of the pyrrhotite in a magnetic field.

For synthetic samples of pyrite and pyrrhotite it was found that the pyrrhotite could be selectively depressed by oscillating the pyrrhotite particles using a magnetic field.

In the presence of chrysotile, the flotation recovery of pyrrhotite was greatly depressed by a magnetic field as a result of the restriction of the movement of the pyrrhotite by the chrysotile fibers. On the other hand, the flotation recovery of the non-magnetic pyrite was not influenced by the magnetic field. Weakly hydrophobic quartz was dislodged from the air bubble by collisions with the oscillating pyrrhotite particles. This improved the grade of the flotation concentrate.

The chemical reactions between pyrite and xanthate did not appear to be affected by an external magnetic field. A magnetic field with maximum frequency of 140Hz and a field strength of 1200 Gauss did not alter the speciation of the xanthate products in the solution nor did it alter the rate of decomposition of xanthate ions. The flotation response of pyrite did not change by conditioning the pyrite in a magnetic field.

Pilot column testwork, carried out at Nkomati Mine, on a nickel sulphide cleaner stream, showed that copper recoveries were not significantly affected by the magnetic field. The copper grade obtained was higher than that for the standard test

at low airflow rates, possibly due to the depression of pyrrhotite. Nickel in the cleaner feed stream is closely associated with pyrrhotite and depression of pyrrhotite caused some loss in nickel recovery. The combined base metal grade recovery curve, where a magnetic field was applied to the flotation column, was higher than that obtained under standard test conditions. This indicates that improved flotation efficiency can be obtained by applying a magnetic field to a flotation column.

This work has shown that pyrrhotite can be successfully depressed by applying an oscillating magnetic field to a flotation column. Both the grade and recovery of a base metal flotation concentrate can be improved by applying an oscillating magnetic field to a flotation column.

Finally, due to practical constraints of applying a uniform magnetizing field to a large diameter flotation device, this technique is best suited for specialized applications with small diameter columns.

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Appendix 3-1: Magnetic field profile along the length of a 45 mm coil

Coil length [mm]	Magnetic field strength	
	Centreline [Gauss]	radius = 20mm [Gauss]
45	945	938
40	962	985
30	985	1038
23	1000	1064
15	985	1041
5	967	990
0	951	941

Appendix 3-2: Magnetic field profile along the length of a 100 mm coil

Coil length [mm]	Magnetic field strength	
	Centreline [Gauss]	radius = 20mm [Gauss]
100	964	938
80	979	1002
60	995	1048
50	1000	1053
40	998	1045
20	983	1007
0	959	949

Appendix 3-3: Magnetic field profile along the length of 2 parallel magnetic plates

Coil length [mm]	Magnetic field strength	
	Centreline [Gauss]	radius = 20mm [Gauss]
45	980	1019
40	990	1014
30	995	1016
23	998	1017
15	998	1013
5	991	1006
0	979	1023

Appendix 3-4: Magnetic Retention and Rotation as function of frequency and magnetic field strength

Frequency [Hz]	Rotation observed at Magnetic flux (Gauss) [Gauss]	Retention at Magnetic flux (Gauss) [Gauss]
3	130	
5	165	
10	217	1600
20	286	
30	360	
40	470	
50	551	1300
70	641	
104	840	1200
150	1200	1200

Appendix 3-5: Effect of magnetic field strength and frequency on Pyrrhotite Flotation**Experimental Conditions**

Flotation Device	Hallimond Tube
Flotation Time	60 sec
Conditioning Time	10 min
Conditioning Temperature	20 °C
pH	
Xanthate Concentration	10 ppm
Magnetic Field Frequency	50 Hz
Magnetic Field Strength	Gauss
Magnetic Field Type	

Test Results

Test Nr	Type	Magnetic Field		Xanthate Concentration [ppm]	Mass Conc [g]	Mass Tail [g]	Recovery [%]
		Frequency [Hz]	Strength [Gauss]				
1	Coil	10	0	10	0.76	0.1	88.4
2	Coil	10	200	10	0.78	0.1	88.6
3	Coil	10	200	10	0.78	0.13	85.7
4	Coil	10	500	10	0.7	0.33	68.0
5	Coil	10	800	10	0.5	0.37	57.5
6	Coil	10	1200	10	0.44	0.41	51.8
7	Coil	10	1200	10	0.48	0.43	52.7
8	Coil	50	0	10	0.76	0.1	88.4
9	Coil	50	200	10	0.75	0.17	81.5
10	Coil	50	500	10	0.69	0.18	79.3
11	Coil	50	800	10	0.53	0.33	61.6
12	Coil	50	800	10	0.44	0.44	50.0
13	Coil	50	1200	10	0.3	0.58	34.1
14	Coil	50	1200	10	0.38	0.52	42.2
15	Coil	50	1200	10	0.34	0.52	39.5
16	Coil	50	1200	10	0.34	0.68	33.3
17	Coil	100	0	10	0.76	0.1	88.4
18	Coil	100	200	10	0.64	0.12	84.2
19	Coil	100	200	10	0.64	0.26	71.1
20	Coil	100	500	10	0.61	0.26	70.1
21	Coil	100	500	10	0.64	0.12	84.2
22	Coil	100	800	10	0.7	0.3	70.0
23	Coil	100	1200	10	0.48	0.46	51.1
24	Coil	0	0	10	0.76	0.1	88.4
25	Coil	140	500	10	0.79	0.12	86.8
26	Coil	140	1200		0.71	0.16	81.6

Appendix 3-6: Effect Of Magnetic field orientation on Pyrrhotite Flotation**Experimental Conditions**

Flotation Device	Hallimond Tube
Flotation Time	30 sec
Conditioning Time	10 min
Conditioning Temperature	20 °C
pH	7.4
Xanthate Concentration	10 ppm
Magnetic Field Frequency	50 Hz
Magnetic Field Strength	Variable Gauss
Magnetic Field Type	Variable

Test Results

Test Nr	Magnetic Field Type	Magnetic Field		Xanthate Concentration [ppm]	Mass Conc [g]	Mass Tail [g]	Recovery [%]
		Frequency	Strength				
		[Hz]	[Gauss]				
1	Horizontal	50	0	10	0.93	0.05	94.9
2	Horizontal	50	0	10	0.9	0.04	95.7
3	Horizontal	50	400	10	0.91	0.09	91.0
4	Horizontal	50	400	10	0.83	0.15	84.7
5	Horizontal	50	1200	10	0.72	0.35	67.3
6	Horizontal	50	1200	10	0.75	0.32	70.1
7	Vertical	50	0	10	0.88	0.08	91.7
8	Vertical	50	0	10	0.91	0.05	94.8
9	Vertical	50	400	10	0.86	0.13	86.9
10	Vertical	50	400	10	0.79	0.2	79.8
11	Vertical	50	1200	10	0.48	0.43	52.7
12	Vertical	50	1200	10	0.4	0.44	47.6

Appendix 3-7: Effect of magnetic field positioning on Pyrrhotite Flotation

Experimental Conditions

Flotation Device	Flotation column
Flotation Time	30 sec
Conditioning Time	10 min
Conditioning Temperature	20 °C
pH	7.4
Airflow rate	0.074 l/min
Xanthate Concentration	8 ppm
Aerofroth 615	20 ppm
Magnetic Field Frequency	50 Hz
Magnetic Field Strength	800 Gauss
Magnetic Field Type	Coil

Test Results

Test Nr	Magnetic Field Type	Magnetic Field			Coil Length [mm]	Xanthate Concentration [ppm]	Mass Conc [g]	Mass Tail [g]	Recovery [%]
		Frequency [Hz]	Strength [Gauss]	Position					
		1	None	No Magnetic field					
2	None	No Magnetic field			8	49	43	53.3	
5	Coil	50	800	Middle	100	8	44	60	42.3
6	Coil	50	800	Middle	100	8	44	50	46.8
7	Coil	50	800	Bottom	100	8	79	11	87.8
8	Coil	50	800	Bottom	100	8	80	8	90.9

Appendix 3-8: Effect Of collector concentration and a magnetic field on Pyrrhotite flotation**Experimental Conditions**

Flotation Device	Hallimond tube
Flotation Time	60 sec
Conditioning Time	10 min
Conditioning Temperature	20 °C
pH	7.4
Airflow rate	0.037 l/min
Xanthate Concentration	Variable ppm
Aerofroth 615	0 ppm
Magnetic Field Frequency	50 Hz
Magnetic Field Strength	800 Gauss
Magnetic Field Type	Coil

Test Results

Test Nr	Magnetic Field			Xanthate Concentration [ppm]	Mass Conc [g]	Mass Tail [g]	Recovery [%]	
	Type	Frequency	Strength					
		[Hz]	[Gauss]					
1	None			0	0.82	0.84	49.4	
2	None			1	1.2	0.58	67.4	
3	None			2.5	1.6	0.16	90.9	
4	None			5	1.62	0.2	89.0	
5	Coil	100	800	Middle	0	0.34	1.58	17.7
6	Coil	100	800	Middle	1	1	1.02	49.5
7	Coil	100	800	Middle	2.5	1.6	0.34	82.5
8	Coil	100	800	Middle	5	1.6	0.24	87.0

Appendix 3-9: Effect Of Residence Time in a Magnetic field on Pyrrhotite Flotation

Experimental Conditions

Flotation Device	Hallimond tube
Flotation Time	30 sec
Conditioning Time	10 min
Conditioning Temperature	20 °C
pH	7.4
Airflow rate	0.037 l/min
Xanthate Concentration	8 ppm
Aerofroth 615	0 ppm
Magnetic Field Frequency	50 Hz
Magnetic Field Strength	800 Gauss
Magnetic Field Type	Coil

Test Results

Test Nr	Magnetic Field			Coil Length [mm]	Length of Hallimond tube [mm]	Bubble rising time [sec]	Time in magnetic field [sec]	Xanthate Concentration [ppm]	Mass Conc [g]	Mass Tail [g]	Recovery [%]	
	Type	Frequency [Hz]	Strength [Gauss]									
1	None				230	0.84	0	8	79	11	87.8	
2	None				230	0.84	0	8	88	10	89.8	
3	Coil	50	800	Middle	45	230	0.84	0.16	8	68	31	68.7
4	Coil	50	800	Middle	45	230	0.84	0.16	8	60	33	64.5
5	Coil	50	800	Middle	100	230	0.84	0.37	8	44	60	42.3
6	Coil	50	800	Middle	100	230	0.84	0.37	8	44	50	46.8

Appendix 4-1: Effect of a Magnetic field on Pyrrhotite and pyrite flotation**Experimental Conditions**

Flotation Device	Flotation Column
Flotation Time	30 sec
Conditioning Time	10 min
Conditioning Temperature	20 °C
pH	7.4
Airflow rate	0.74 l/min
Xanthate Concentration	10 ppm
Amine Collector	0 ppm
Magnetic Field Frequency	50 Hz
Magnetic Field Strength	Variable Gauss
Magnetic Field Type	Coil

Test Results

Test Nr	Magnetic Field		Conc Mass [g]	Pyrite		Conc Mass [g]	Pyrrhotite	
	Frequency [Hz]	Strength [Gauss]		Tail Mass [g]	Recovery [%]		Tail Mass [g]	Recovery [%]
1		0	0.90	0.04	95.7	0.84	0.13	86.6
2		0	0.83	0.02	97.6	0.92	0.08	92.0
3	50	500	0.89	0.06	93.7	0.79	0.17	82.3
4	50	500	0.93	0.03	96.9	0.86	0.13	86.9
5	50	1200	0.94	0.02	97.9	0.89	0.30	74.8
6	50	1200	0.92	0.05	94.8	0.89	0.27	76.7

Appendix 4-2: Effect of a Magnetic field on Pyrrhotite and Quartz flotation**Experimental Conditions**

Flotation Device	Hallimond Tube
Flotation Time	60 sec
Conditioning Time	10 min
Conditioning Temperature	20 °C
pH	7.4
Airflow rate	0.032 l/min
Xanthate Concentration	20 ppm
Amine Collector	3 ppm
Magnetic Field Frequency	50 Hz
Magnetic Field Strength	Variable Gauss
Magnetic Field Type	Coil

Test Results

Test Nr	Magnetic Field		Quartz Content [g]	Conc Mass [g]	Quartz		Grade [% quartz]	Conc Mass [g]	Pyrrhotite	
	Frequency [Hz]	Strength [Gauss]			Tail Mass [g]	Recovery [%]			Tail Mass [g]	Recovery [%]
1		0	0.5	0.1	0.3	25.0	22.7	0.34	0.05	87.2
2		0	0.5	0.1	0.38	20.8	20.4	0.39	0.05	88.6
3	50	400	0.5	0.07	0.37	15.9	20.0	0.28	0.07	80.0
4	50	400	0.5	0.07	0.32	17.9	16.7	0.35	0.08	81.4
5	50	800	0.5	0.04	0.4	9.1	11.8	0.3	0.07	81.1
6	50	800	0.5	0.04	0.48	7.7	10.5	0.34	0.07	82.9
7	50	1200	0.5	0.02	0.39	4.9	6.5	0.29	0.07	80.6
8	50	1200	0.5	0.02	0.5	3.8	5.9	0.32	0.07	82.1

Appendix 4-3: Effect of chrysotile and a Magnetic field on Pyrrhotite and pyrite flotation**Experimental Conditions**

Flotation Device	Flotation column
Flotation Time	30 sec
Conditioning Time	10 min
Conditioning Temperature	20 °C
pH	7.4
Airflow rate	0.074 l/min
Xanthate Concentration	8 ppm
Aerofroth 615	20 ppm
Magnetic Field Frequency	50 Hz
Magnetic Field Strength	800 Gauss
Magnetic Field Type	Coil

Test Results

Test Nr	Magnetic Field		Chrysotile Content [%]	Pyrite			Pyrrhotite		
	Frequency [Hz]	Strength [Gauss]		Conc Mass [g]	Tail Mass [g]	Recovery [%]	Conc Mass [g]	Tail Mass [g]	Recovery [%]
1			0	0.98	0.01	99.0	0.89	0.14	86.4
2			3	0.93	0.04	95.9	0.72	0.2	78.3
3			3	0.96	0.02	98.0	0.74	0.12	86.0
4			6	0.85	0.27	75.9	0.38	0.46	45.2
5			6	0.77	0.20	79.4	0.31	0.53	36.9
6	50	800	0	1.01	0.02	98.1	0.59	0.23	72.0
7	50	800	0	1.00	0.03	97.1	0.6	0.27	69.0
8	50	800	3	0.84	0.08	91.3	0.17	0.78	17.9
9	50	800	3	0.90	0.03	96.8	0.13	0.8	14.0
10	50	800	6	0.90	0.33	73.2	0.06	0.81	6.9
11	50	800	6	0.92	0.28	76.7	0.03	0.8	3.6

Appendix 5-1: UV Spectra for Xanthate conditioning solutions.

Xanthate Solution		Standard Conditioning Solution		Magnetic Conditioning Solution	
Wavelength	Absorbance	Wavelength	Absorbance	Wavelength	Absorbance
[nm]		[nm]		[nm]	
202.6846	0.433817	202.6846	1.375	200	1.348144
204.4743	0.426702	203.5794	1.367898	200	1.348144
204.9217	0.418165	204.9217	1.328838	200.4474	1.341042
205.3691	0.412473	205.8166	1.275574	200.8949	1.341042
205.8166	0.409627	206.7114	1.250718	201.3423	1.33394
205.8166	0.403935	206.7114	1.236514	201.7897	1.33394
206.264	0.401089	206.7114	1.229413	202.2371	1.326838
206.7114	0.39682	206.7114	1.222311	202.2371	1.319736
206.7114	0.392551	206.7114	1.215209	202.6846	1.312634
207.1588	0.389705	206.7114	1.204556	203.132	1.305533
207.1588	0.385436	206.7114	1.193903	203.132	1.29488
207.6063	0.38259	207.1588	1.183251	203.5794	1.287778
208.0537	0.376898	207.1588	1.176149	203.5794	1.280676
208.0537	0.374052	207.1588	1.165496	203.5794	1.277125
208.5011	0.369783	207.6063	1.147742	204.0268	1.266473
208.5011	0.366937	207.6063	1.129987	204.0268	1.259371
208.9485	0.362668	208.0537	1.119334	204.4743	1.248718
208.9485	0.3584	208.5011	1.090927	204.4743	1.245167
209.396	0.352708	208.9485	1.06607	204.9217	1.234514
209.396	0.351285	208.9485	1.041214	204.9217	1.227413
209.8434	0.345593	208.9485	1.034112	205.3691	1.206107
210.2908	0.342747	209.396	1.02346	205.3691	1.206107
210.7383	0.339901	209.396	1.012807	205.8166	1.199005
210.7383	0.337055	210.2908	0.9843995	205.8166	1.191903
211.1857	0.334209	210.2908	0.9737467	205.8166	1.1777
211.6331	0.32994	210.2908	0.963094	206.264	1.167047
212.0805	0.325671	210.2908	0.9559922	206.264	1.163496
212.0805	0.322825	210.2908	0.9488903	206.7114	1.152843
212.528	0.319979	210.7383	0.9382376	206.7114	1.135089
212.528	0.317133	210.7383	0.9275848	206.7114	1.127987
213.4228	0.314287	211.1857	0.9133812	206.7114	1.124436
213.8702	0.312864	211.1857	0.9062794	206.7114	1.106681
214.7651	0.311441	211.6331	0.8991776	207.1588	1.110232
215.2125	0.311441	211.6331	0.8885248	207.1588	1.103131
216.1074	0.311441	211.6331	0.8743212	207.1588	1.09958
216.5548	0.312864	212.0805	0.8601175	207.1588	1.092478
217.4497	0.314287	212.0805	0.8459138	207.1588	1.085376
217.4497	0.31571	212.0805	0.838812	207.1588	1.078274
218.3445	0.319979	212.0805	0.8281593	207.6063	1.049867
219.2394	0.324248	212.9754	0.8068538	207.6063	1.042765
219.2394	0.325671	212.9754	0.7962011	207.6063	1.085376
220.1342	0.331363	213.4228	0.7819974	207.6063	1.06407
221.4765	0.335632	213.4228	0.7713447	207.6063	1.053418
221.9239	0.339901	213.4228	0.7642428	208.0537	1.035663
222.8188	0.347016	213.4228	0.757141	208.0537	1.02501
223.7136	0.348439	213.8702	0.7500392	208.0537	1.014358
224.6085	0.348439	214.3177	0.7393864	208.0537	1.007256
225.5034	0.349862	214.3177	0.7287337	208.5011	1.003705
226.3982	0.348439	214.7651	0.7216318	208.5011	0.9966031
226.8456	0.348439	215.66	0.6861227	208.5011	0.9788486
227.7405	0.345593	215.66	0.6790209	208.5011	0.9681959
228.1879	0.342747	215.66	0.6683682	208.5011	1.000154
228.6353	0.338478	216.1074	0.6577154	208.5011	0.9930522
229.5302	0.331363	216.1074	0.6506135	208.5011	0.9895013
229.5302	0.328517	216.1074	0.6435117	208.5011	0.9823995
229.9776	0.325671	216.5548	0.632859	208.5011	0.9717467
230.425	0.322825	216.5548	0.6257572	208.9485	0.9681959
230.8725	0.317133	217.0022	0.6186553	208.9485	0.961094
231.3199	0.311441	217.4497	0.6080026	208.9485	0.9575431
231.3199	0.308595	217.8971	0.5795953	208.9485	0.9504413
231.3199	0.305749	218.3445	0.5760444	209.396	0.9468904
231.7673	0.302903	218.7919	0.5618407	209.396	0.9397885
232.2148	0.297212	218.7919	0.5547389	209.8434	0.9291358
232.2148	0.294366	219.2394	0.547637	209.8434	0.918483
232.6622	0.290097	219.2394	0.5334334	209.8434	0.9113812
232.6622	0.287251	219.6868	0.5263316	209.8434	0.9007285
232.6622	0.282982	220.1342	0.5192298	210.2908	0.8900757
233.1096	0.278713	220.5816	0.508577	210.2908	0.8723212
233.5571	0.275867	220.5816	0.5014752	210.7383	0.8616684
234.0045	0.270175	221.0291	0.4837206	210.7383	0.8545666
234.0045	0.265906	221.4765	0.4766188	210.7383	0.840363
234.0045	0.26306	221.9239	0.469517	211.1857	0.8332611
234.4519	0.260214	222.3714	0.4588642	211.1857	0.8297102
234.4519	0.257368	222.8188	0.4517624	211.1857	0.8190575
234.4519	0.253099	223.2662	0.4411097	211.6331	0.8155065
234.8993	0.24883	223.7136	0.4340078	211.6331	0.8119556
235.3468	0.237447	224.1611	0.4162532	211.6331	0.8048538
235.3468	0.234601	224.6085	0.4056005	211.6331	0.797752
235.7942	0.231755	225.0559	0.4020496	212.0805	0.7906501
235.7942	0.226063	225.5034	0.3913969	212.0805	0.7799974
236.2416	0.216102	225.5034	0.3913969	212.528	0.7622429
237.1365	0.208987	225.9508	0.3807441	212.528	0.755141
237.1365	0.206141	226.8456	0.3665405	212.528	0.7373865
237.5839	0.199028	227.2931	0.3558877	213.4228	0.7373865
237.5839	0.19618	228.1879	0.345235	213.4228	0.7231828

Appendix 5-1: UV Spectra for Xanthate conditioning solutions.

Xanthate Solution		Standard Conditioning Solution		Magnetic Conditioning Solution	
Wavelength [nm]	Absorbance	Wavelength [nm]	Absorbance	Wavelength [nm]	Absorbance
238.0313	0.189065	228.6353	0.3381332	213.4228	0.7231828
238.4787	0.184796	228.6353	0.3310313	213.4228	0.716081
238.9262	0.179104	229.0828	0.3274804	213.8702	0.7089791
241.6107	0.14353	229.5302	0.3203786	213.8702	0.7018773
243.4005	0.1293	229.9776	0.3097258	213.8702	0.6983264
244.2953	0.125031	230.425	0.3061749	214.3177	0.6876736
244.2953	0.122185	230.8725	0.302624	214.3177	0.6770209
245.1902	0.116494	230.8725	0.2955222	214.7651	0.6699191
246.085	0.113648	231.7673	0.2848694	215.2125	0.6592664
246.5324	0.109379	231.7673	0.2848694	215.2125	0.6488136
247.8747	0.100841	232.2148	0.2777676	215.66	0.63441
249.217	0.096572	232.6622	0.2742167	216.1074	0.6166553
250.1118	9.23E-02	233.1096	0.263564	216.1074	0.6095535
250.5593	8.95E-02	233.5571	0.260013	216.1074	0.6060026
251.4541	8.66E-02	234.0045	0.2529112	216.5548	0.5989008
252.349	8.38E-02	234.4519	0.2458094	217.0022	0.5846971
252.7964	7.95E-02	234.8993	0.2387076	217.0022	0.5882481
253.6913	7.95E-02	235.7942	0.2245039	217.0022	0.5953499
254.5861	7.52E-02	237.5839	0.2103003	217.0022	0.5882481
255.9284	7.10E-02	238.4787	0.2031984	217.4497	0.5811462
256.8233	6.95E-02	238.4787	0.2031984	217.4497	0.5704935
257.7181	6.67E-02	238.4787	0.1960966	217.8971	0.5633917
259.0604	6.38E-02	239.3736	0.1889948	218.7919	0.5385352
259.5078	6.10E-02	239.821	0.1854438	218.7919	0.5349844
260.4027	5.96E-02	240.2684	0.1747911	219.6868	0.5172298
261.2975	5.96E-02	240.7159	0.1676893	219.6868	0.510128
262.1924	5.96E-02	241.1633	0.1605874	219.6868	0.506577
263.5347	5.82E-02	242.0582	0.1570365	220.5816	0.4959243
264.4295	5.82E-02	242.5056	0.1499347	220.5816	0.4888225
265.3244	5.82E-02	243.8479	0.139282	221.0291	0.4817206
266.2192	5.82E-02	243.8479	0.1357311	221.4765	0.4746188
267.1141	5.82E-02	244.7427	0.1321801	221.9239	0.467517
268.4564	5.96E-02	245.1902	0.1286292	222.3714	0.4533133
269.7986	6.24E-02	246.5324	0.1215274	222.3714	0.4497624
271.1409	6.81E-02	246.9799	0.1144256	222.8188	0.4426606
272.0358	0.072381	247.4273	0.1144256	223.2662	0.4320078
273.8255	0.078073	248.3221	0.1108747	223.7136	0.424906
274.7204	8.52E-02	248.7696	0.1108747	223.7136	0.4142533
275.1678	8.95E-02	249.6644	0.1073237	224.6085	0.4071515
276.5101	9.80E-02	250.1118	0.1002219	225.0559	0.3964987
276.9575	0.10511	251.0067	0.1002219	225.5034	0.3964987
277.8524	0.113648	251.4541	0.096671	225.9508	0.385846
278.2998	0.117916	252.349	9.31E-02	226.3982	0.3751932
278.7472	0.122185	253.6913	9.31E-02	226.8456	0.3716423
279.1946	0.133569	254.1387	8.96E-02	227.2931	0.3645405
280.0895	0.139261	255.0336	8.96E-02	228.1879	0.3538877
280.0895	0.14353	255.9284	8.60E-02	228.1879	0.3503368
280.5369	0.152068	256.8233	8.60E-02	229.0828	0.343235
280.9843	0.156337	257.7181	8.25E-02	229.0828	0.3396841
281.4318	0.160606	258.613	8.25E-02	229.5302	0.3290313
281.8792	0.166298	259.5078	8.25E-02	229.9776	0.3219295
281.8792	0.176259	260.4027	8.25E-02	230.425	0.3148277
282.774	0.183373	261.745	7.89E-02	230.8725	0.3112768
282.774	0.189065	262.6398	7.89E-02	231.3199	0.300624
283.6689	0.197603	263.9821	7.54E-02	231.7673	0.2899713
283.6689	0.203295	264.4295	0.0718146	232.2148	0.2935222
284.1163	0.207564	265.3244	6.83E-02	232.2148	0.2864204
284.1163	0.211833	266.2192	6.83E-02	232.6622	0.2793185
284.1163	0.214679	267.5615	6.47E-02	233.1096	0.2722167
284.5638	0.218948	268.9038	6.83E-02	233.5571	0.2651149
285.0112	0.226063	270.2461	0.0718146	234.0045	0.2580131
285.0112	0.230332	271.1409	7.54E-02	234.4519	0.2509112
285.4586	0.236024	273.3781	8.25E-02	234.4519	0.2438094
285.4586	0.240292	274.7204	8.25E-02	234.8993	0.2402585
285.906	0.244561	276.0626	8.25E-02	234.8993	0.2367076
286.3535	0.24883	277.4049	8.25E-02	235.3468	0.2296057
286.8009	0.260214	278.2998	8.60E-02	236.2416	0.2225039
286.8009	0.264483	279.1946	8.96E-02	236.689	0.2154021
286.8009	0.268752	280.0895	0.096671	237.1365	0.2083003
287.2483	0.275867	280.5369	0.1002219	237.1365	0.2011984
287.2483	0.282982	281.4318	0.1073237	237.5839	0.2011984
287.2483	0.284405	282.3266	0.1144256	238.0313	0.1940966
288.1432	0.292943	283.2215	0.1250783	238.9262	0.1869948
288.5906	0.298635	283.6689	0.1321801	238.9262	0.1905457
288.5906	0.308595	284.5638	0.1357311	238.9262	0.179893
289.038	0.317133	285.4586	0.1428329	239.3736	0.176342
289.4854	0.322825	286.3535	0.1499347	239.821	0.1692402
289.9329	0.331363	287.2483	0.1570365	240.7159	0.1585875
290.8277	0.345593	288.1432	0.1676893	241.1633	0.1585875
290.8277	0.352708	289.4854	0.1818929	243.8479	0.137282
291.2752	0.372629	290.3803	0.1925457	244.7427	0.1301802
291.7226	0.378321	291.2752	0.2031984	245.6376	0.1266292
292.6174	0.389705	291.7226	0.2103003	246.9799	0.1195274
292.6174	0.398243	292.6174	0.2245039	247.8747	0.1159765
293.0649	0.409627	293.0649	0.2351566	248.3221	0.1124256

Appendix 5-1: UV Spectra for Xanthate conditioning solutions.

Xanthate Solution		Standard Conditioning Solution		Magnetic Conditioning Solution	
Wavelength	Absorbance	Wavelength	Absorbance	Wavelength	Absorbance
[nm]		[nm]		[nm]	
293.5123	0.41105	294.4072	0.2493603	248.7696	0.1088747
293.5123	0.415319	295.302	0.2564621	249.6644	0.1017729
293.5123	0.425279	295.7495	0.260013	252.7964	9.47E-02
293.5123	0.430971	296.1969	0.2671149	253.6913	9.47E-02
294.4072	0.443778	297.0917	0.2742167	255.481	9.11E-02
294.4072	0.440932	297.9866	0.2777676	255.9284	0.0875692
294.4072	0.445201	298.8814	0.2813185	256.8233	8.40E-02
295.302	0.452316	299.3289	0.2813185	257.7181	8.40E-02
295.302	0.460854	300.2237	0.2848694	258.613	8.05E-02
295.302	0.470815	300.6711	0.2848694	259.9553	8.05E-02
295.7495	0.47793	302.0134	0.2706658	260.4027	8.40E-02
296.1969	0.486467	302.9083	0.2706658	260.4027	8.05E-02
296.6443	0.496428	302.9083	0.2706658	261.2975	8.05E-02
297.0917	0.500697	303.3557	0.263564	262.1924	8.05E-02
297.5392	0.503543	303.8031	0.260013	263.0872	8.05E-02
297.5392	0.509235	304.2505	0.2529112	263.9821	7.69E-02
297.9866	0.514927	304.698	0.2458094	264.877	7.34E-02
298.434	0.526311	305.5928	0.2280548	265.7718	7.69E-02
298.8814	0.533426	305.5928	0.2387076	266.2192	7.34E-02
299.3289	0.537695	306.0403	0.2316057	267.1141	7.34E-02
300.2237	0.549078	306.4877	0.2138512	268.4564	8.05E-02
300.2237	0.556193	306.4877	0.2245039	269.3512	8.40E-02
300.6711	0.560462	306.9351	0.2138512	270.6935	8.40E-02
301.566	0.564731	307.3825	0.1996475	271.5883	0.0875692
302.0134	0.569	307.3825	0.1960966	272.4832	0.0875692
303.3557	0.569	307.83	0.1925457	272.9306	9.11E-02
303.3557	0.563308	308.7248	0.1854438	274.7204	9.47E-02
304.2505	0.556193	309.1722	0.1712402	275.6152	9.47E-02
304.2505	0.551924	310.0671	0.1605874	276.0626	9.82E-02
304.698	0.549078	310.5145	0.1534856	276.5101	0.1053238
304.698	0.546232	311.4094	0.1428329	277.4049	0.1088747
304.698	0.540541	312.3043	0.1321801	277.8524	0.1195274
305.5828	0.524888	312.7517	0.1286292	279.1946	0.1266292
306.4877	0.50212	313.6465	0.1179765	280.0895	0.1301802
306.4877	0.489313	314.5414	0.1037728	280.5369	0.137282
306.9351	0.479353	315.4362	9.31E-02	281.4318	0.1443838
306.9351	0.476507	315.8837	8.60E-02	282.3266	0.1514857
307.3825	0.469392	316.7785	7.89E-02	283.2215	0.1550366
307.3825	0.466546	317.226	0.0718146	283.6689	0.1621384
307.3825	0.460854	317.6734	6.83E-02	284.1163	0.1656893
307.3825	0.458008	318.1208	6.12E-02	284.5638	0.176342
307.83	0.450893	318.5682	5.76E-02	285.906	0.1834439
308.2774	0.442355	319.4631	5.05E-02	286.8009	0.1869948
308.2774	0.43524	320.3579	4.34E-02	287.6957	0.2011984
308.2774	0.432394	321.2528	4.34E-02	287.6957	0.2047494
308.2774	0.428125	321.7002	3.28E-02	288.5906	0.2154021
308.2774	0.41105	322.5951	3.63E-02	289.038	0.2296057
308.7248	0.42101	323.0425	3.63E-02	289.4854	0.2331567
308.7248	0.416742	323.9373	3.63E-02	290.3803	0.2544622
308.7248	0.402512	323.9373	3.63E-02	290.8277	0.2580131
308.7248	0.393974	324.8322	2.92E-02	291.7228	0.2651149
309.1722	0.401089	325.2796	2.92E-02	292.17	0.2757676
309.1722	0.391128	326.1745	2.92E-02	293.0649	0.2864204
309.1722	0.388282	326.1745	2.57E-02	293.9597	0.2935222
309.1722	0.385436	326.6219	2.21E-02	294.4072	0.304175
309.1722	0.381167	327.0693	2.57E-02	295.302	0.3112768
309.6197	0.378321	328.859	2.21E-02	295.7495	0.3219295
309.6197	0.372629	329.7539	2.57E-02	296.6443	0.3254804
309.6197	0.361245	331.0962	2.21E-02	297.0917	0.3290313
310.0671	0.351285	331.9911	2.21E-02	297.5392	0.3325823
310.0671	0.34417	332.8859	2.21E-02	297.9866	0.3361332
310.0671	0.339901	333.3333	2.21E-02	298.434	0.3361332
310.0671	0.335632	334.6756	2.21E-02	299.3289	0.3325823
310.962	0.328517	336.0179	2.21E-02	299.7763	0.3325823
310.962	0.318556	337.8076	2.21E-02	300.2237	0.3290313
310.962	0.311441	339.5973	2.21E-02	300.6711	0.3254804
311.4094	0.304326	340.4922	2.21E-02	301.1186	0.3183786
311.4094	0.297212	342.2819	2.21E-02	302.0134	0.3183786
311.8568	0.292943	343.1767	2.21E-02	302.4608	0.3148277
311.8568	0.284405	344.0716	2.21E-02	302.9083	0.3077258
311.8568	0.280136	345.8613	2.57E-02	303.8031	0.300624
311.8568	0.271598	348.5459	2.21E-02	304.698	0.2899713
312.3043	0.261637	349.4407	2.21E-02	305.1454	0.2828695
312.7517	0.254522	350.3356	2.21E-02	305.5928	0.2722167
312.7517	0.247407	351.6779	2.57E-02	306.0403	0.2651149
312.7517	0.241715	353.0201	2.21E-02	306.4877	0.2580131
313.1991	0.234601	354.8098	2.21E-02	306.9351	0.2473603
313.1991	0.227486	358.3893	2.21E-02	307.83	0.2331567

Appendix 5-2: Absorbance at 301 nm with time for standard and solutions in the presence of a magnetic field.

Time [minutes]	Standard conditioning solution Absorbance	Conditioning solution in a magnetic field Absorbance
0	0.596	0.596
2.5	0.421	0.437
5	0.412	0.428
10	0.347	0.407
15	0.309	0.338
20	0.284	0.306

Appendix 5-3: Effect Of Conditioning in a magnetic field on pyrite Flotation**Experimental Conditions**

Flotation Device	Hallimond Tube
Flotation Time	60 sec
Conditioning Time	Variable min
Conditioning Temperature	20 °C
pH	7.4
Xanthate Concentration	10 ppm
Magnetic Field Frequency	100 Hz
Magnetic Field Strength	1000 Gauss
Magnetic Field Type	Coil

Test Results

Test Nr	Type	Magnetic Field		Xanthate Concentration [ppm]	Conditioning Time [min]	Mass Conc [g]	Mass Tail [g]	Recovery [%]
		Frequency [Hz]	Strength [Gauss]					
1				10	0	0.19	0.74	20.4
2				10	2.5	0.53	0.41	56.4
3				10	5	0.78	0.14	84.8
4				10	10	0.81	0.09	90.0
5				10	15	0.89	0.08	91.8
6				10	20	0.87	0.1	89.7
7	Coil	100	1000	10	0	0.18	0.74	19.6
8	Coil	100	1000	10	2.5	0.48	0.48	50.0
9	Coil	100	1000	10	5	0.84	0.1	89.4
10	Coil	100	1000	10	10	0.83	0.14	85.6
11	Coil	100	1000	10	15	0.81	0.14	85.3
12	Coil	100	1000	10	20	0.77	0.15	83.7

Appendix 6-1: Nickel and Copper recoveries and grades for standard column flotation and flotation in a magnetic field.

Test Number	Airflow [l/min]	Magnetic field		Feed		Concentrate		Tail		Recovery		
		Strength [Gauss]	Frequency [Hz]	Ni [%]	Cu [%]	Ni [%]	Cu [%]	Ni [%]	Cu [%]	Ni [%]	Cu [%]	Mass [%]
Test 1	3.1	1000	15	7.29	1.80	12.7	3.19	3.44	0.823	72.3	73.3	41.5
Test 2	2.65	1000	15	7.30	1.80	14.6	4.58	4.75	0.828	51.8	65.9	25.9
Test 3	2.2	1000	15	7.30	1.80	10.8	10.62	6.89	0.755	15.6	62.5	10.6
Test 4	3.1			7.32	1.80	11.2	2.96	3.75	0.737	73.2	78.6	47.7
Test 5	2.65			7.29	1.80	12.9	3.57	4.45	0.905	59.5	66.6	33.6
Test 6	2.2			7.31	1.80	13.0	5.43	5.79	0.822	37.6	64.0	21.2

Combined Nickel and Copper Recoveries and grades

Test Number	Airflow [l/min]	Magnetic field		Feed	Concentrate	Tails	Recovery	Mass [%]
		Strength [Gauss]	Frequency [Hz]	Ni + Cu [%]	Ni + Cu [%]	Ni + Cu [%]	Ni + Cu [%]	
Test 1	3.1	1000	15	9.09	15.9	4.27	72.5	41.5
Test 2	2.65	1000	15	9.10	19.2	5.57	54.6	25.9
Test 3	2.2	1000	15	9.10	21.4	7.64	24.9	10.6
Test 4	3.1			9.11	14.2	4.49	74.2	47.7
Test 5	2.65			9.10	16.5	5.35	60.9	33.6
Test 6	2.2			9.11	18.4	6.61	42.8	21.2

Appendix 6-2: Results from test with magnetic field applied and an airflow rate of 3.1

" SysCAD/MB v1.2 "
 " (c) Kenwalt Systems, 1994 "
 " 339 Rivonia Boulevard "
 " Johannesburg, South Africa "

" Time of run 21:21:12 "
 " Date of run 1999/10/12 "

" Magnetic field with high airflow "

" Converged in 2 iterations "
 " Maximum iterations : 50 "
 " Tolerance required : 0.001000 "
 " Tolerance obtained : 0.000619 "

" FLOWS "
 " ===== "

		Adjustment "					
		No. of	Smoothed	Measured "			
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev.	"
1	" Feed	1	1	0	0	100	0.01
2	" Concen	0	0.415	0	0	41.49	0
3	" Tails	0	0.585	0	0	58.51	0

" ASSAYS "
 " ===== "

" Assay Number 1 Ni "

		Adjustment "					
		No. of	Smoothed	Measured "			
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev.	"
1	" Feed	7.3	7.2863	0.1883	0.1883	100	0.073
2	" Concen	12.3	12.7041	0.657	3.285	72.35	0.615
3	" Tails	3.4	3.4437	0.2568	1.2839	27.65	0.17

" Assay Number 2 Cu "

		Adjustment "					
		No. of	Smoothed	Measured "			
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev.	"
1	" Feed	1.8	1.8033	0.1822	0.1822	100	0.018
2	" Concen	3.3	3.1858	0.692	3.4601	73.31	0.165
3	" Tails	0.833	0.8227	0.247	1.2349	26.69	0.0417

" Assay Residuals per stream "

		Average "	
Stream	Average S.S.	No. Std.	Devs "
1	" Feed	0.0001	0.1852
2	" Concen	0.0881	0.6745
3	" Tails	0.001	0.2519

" Assay Residuals per assay "

		Average "	
Assay	Average S.S.	No. Std.	Devs "
1	" Ni	0.0551	0.3673
2	" Cu	0.0044	0.3737

" Overall S.S. of standard analysis residuals for assays 0.1785 "

" Overall sum of Std. Devs. of analysis residuals for assays 2.2233 "

Appendix 6-3: Results from test with magnetic field applied and an airflow rate of 2.6

" SysCAD/MB v1.2 "
 " (c) Kenwalt Systems, 1994 "
 " 339 Rivonia Boulevard "
 " Johannesburg, South Africa "

" Time of run 20:29:25 "
 " Date of run 1999/10/12 "

" Magnetic field with Med airflow "

" Converged in 2 iterations "
 " Maximum iterations : 50 "
 " Tolerance required : 0.001000 "
 " Tolerance obtained : 0.000030 "

" FLOWS "
 " ===== "

		Adjustment "					
		No. of	Smoothed	Measured "			
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev.	"
1	" Feed	1	1	0	0	100	0.01
2	" Concen	0	0.259	0	0	25.93	0
3	" Tails	0	0.741	0	0	74.07	0

" ASSAYS "
 " ===== "

" Assay Number 1 Ni "

		Adjustment "					
		No. of	Smoothed	Measured "			
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev.	"
1	" Feed	7.3	7.2967	0.0446	0.0446	100	0.073
2	" Concen	14.5	14.5834	0.115	0.5749	51.83	0.725
3	" Tails	4.72	4.7452	0.1069	0.5345	48.17	0.236

" Assay Number 2 Cu "

		Adjustment "					
		No. of	Smoothed	Measured "			
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev.	"
1	" Feed	1.8	1.8005	0.0289	0.0289	100	0.018
2	" Concen	4.6	4.578	0.0957	0.4786	65.94	0.23
3	" Tails	0.83	0.828	0.0493	0.2466	34.06	0.0415

" Assay Residuals per stream "

		Average "	
Stream	Average S.S.	Average No.	Std. Devs "
1	" Feed	0	0.0368
2	" Concen	0.0037	0.1054
3	" Tails	0.0003	0.0781

" Assay Residuals per assay "

		Average "	
Assay	Average S.S.	Average No.	Std. Devs "
1	" Ni	0.0025	0.0888
2	" Cu	0.0002	0.058

" Overall S.S. of standard analysis residuals for assays 0.0081 "

" Overall sum of Std. Devs. of analysis residuals for assays 0.4405 "

Appendix 6-4: Results from test with magnetic field applied and an airflow rate of 2.2 l/min

" SysCAD/MB v1.2 "
 " (c) Kenwalt Systems, 1994 "
 " 339 Rivonia Boulevard "
 " Johannesburg, South Africa "

" Time of run 20:03:25 "
 " Date of run 1999/10/12 "

" Magnetic field with Low airflow "

" Converged in 2 iterations "
 " Maximum iterations : 50 "
 " Tolerance required : 0.001000 "
 " Tolerance obtained : 0.000052 "

" FLOWS "
 " ===== "

		Adjustment "					
		No. of		Smoothed		Measured "	
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev. "	
1	" Feed	1	1	0	0	100	0.01
2	" Concen	0	0.106	0	0	10.6	0
3	" Tails	0	0.894	0	0	89.4	0

" ASSAYS "
 " ===== "

" Assay Number 1 Ni "

		Adjustment "					
		No. of		Smoothed		Measured "	
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev. "	
1	" Feed	7.3	7.2961	0.0538	0.0538	100	0.073
2	" Concen	10.73	10.7525	0.0419	0.2095	15.62	0.5365
3	" Tails	6.81	6.8864	0.2245	1.1223	84.38	0.3405

" Assay Number 2 Cu "

		Adjustment "					
		No. of		Smoothed		Measured "	
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev. "	
1	" Feed	1.8	1.8001	0.0052	0.0052	100	0.018
2	" Concen	10.63	10.6214	0.0163	0.0813	62.52	0.5315
3	" Tails	0.755	0.7546	0.0098	0.0488	37.48	0.0378

" Assay Residuals per stream "

		Average "	
		Average	Average
Stream		S.S.	No. Std. Devs "
1	" Feed	0	0.0295
2	" Concen	0.0003	0.0291
3	" Tails	0.0029	0.1171

" Assay Residuals per assay "

		Average "	
		Average	Average
Assay		S.S.	No. Std. Devs "
1	" Ni	0.0021	0.1067
2	" Cu	0	0.0104

" Overall S.S. of standard analysis residuals for assays 0.0064 "
 " Overall sum of Std. Devs. of analysis residuals for assays 0.3514 "

Appendix 6-5: Results from standard test and an airflow rate of 3.1 l/min

" SysCAD/MB v1.2 "
 " (c) Kenwalt Systems, 1994 "
 " 339 Rivonia Boulevard "
 " Johannesburg, South Africa "

" Time of run 20:05:29 "
 " Date of run 1999/10/12 "

" Standard test with high airflow "

" Converged in 3 iterations "
 " Maximum iterations : 50 "
 " Tolerance required : 0.001000 "
 " Tolerance obtained : 0.000047 "

" FLOWS "
 " ===== "

		Adjustment "					
		No. of	Smoothed	Measured "			
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev.	"
1	" Feed	1	1	0	0	100	0.01
2	" Concnent	0	0.477	0	0	47.73	0
3	" Tails	0	0.523	0	0	52.27	0

" ASSAYS "
 " ===== "

" Assay Number 1 Ni "

		Adjustment "					
		No. of	Smoothed	Measured "			
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev.	"
1	" Feed	7.3	7.3158	0.2163	0.2163	100	0.073
2	" Concen	11.7	11.2159	0.8274	4.1372	73.18	0.585
3	" Tails	3.81	3.7538	0.2951	1.4754	26.82	0.1905

" Assay Number 2 Cu "

		Adjustment "					
		No. of	Smoothed	Measured "			
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev.	"
1	" Feed	1.8	1.7968	0.1793	0.1793	100	0.018
2	" Concen	2.86	2.9572	0.6799	3.3993	78.56	0.143
3	" Tails	0.73	0.7369	0.19	0.9502	21.44	0.0365

" Assay Residuals per stream "

		Average	Average "
Stream	S.S.	No.	Std. Devs "
1	" Feed	0.0001	0.1978
2	" Concen	0.1219	0.7537
3	" Tails	0.0016	0.2426

" Assay Residuals per assay "

		Average	Average "
Assay	S.S.	No.	Std. Devs "
1	" Ni	0.0792	0.4463
2	" Cu	0.0032	0.3497

" Overall S.S. of standard analysis residuals for assays 0.2472 "

" Overall sum of Std. Devs. of analysis residuals for assays 2.3881 "

Appendix 6-6: Results from standard test and an airflow rate of 2.65 l/min

" SysCAD/MB v1.2 "
 " (c) Kenwalt Systems, 1994 "
 " 339 Rivonia Boulevard "
 " Johannesburg, South Africa "

 " Time of run 20:07:06 "
 " Date of run 1999/10/12 "

 " Standard test with med airflow "

 " Converged in 2 iterations "
 " Maximum iterations : 50 "
 " Tolerance required : 0.001000 "
 " Tolerance obtained : 0.000118 "

" FLOWS "
 " ===== "

		Adjustment "					
		No. of	Smoothed	Measured "			
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev. "	
1	" Feed	1	1	0	0	100	0.01
2	" Concn	0	0.336	0	0	33.62	0
3	" Tails	0	0.664	0	0	66.38	0

" ASSAYS "
 " ===== "

" Assay Number 1 Ni "

		Adjustment "					
		No. of	Smoothed	Measured "			
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev. "	
1	" Feed	7.3	7.2939	0.0829	0.0829	100	0.073
2	" Concn	12.76	12.9154	0.2436	1.2182	59.53	0.638
3	" Tails	4.41	4.4467	0.1663	0.8316	40.47	0.2205

" Assay Number 2 Cu "

		Adjustment "					
		No. of	Smoothed	Measured "			
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev. "	
1	" Feed	1.8	1.8012	0.065	0.065	100	0.018
2	" Concn	3.61	3.5704	0.2191	1.0957	66.65	0.1805
3	" Tails	0.91	0.905	0.1091	0.5455	33.35	0.0455

" Assay Residuals per stream "

		Average	Average "
		S.S.	No. Std. Devs "
1	" Feed	0	0.074
2	" Concn	0.0129	0.2314
3	" Tails	0.0007	0.1377

" Assay Residuals per assay "

		Average	Average "
		S.S.	No. Std. Devs "
1	" Ni	0.0085	0.1643
2	" Cu	0.0005	0.1311

" Overall S.S. of standard analysis residuals for assays 0.0271 "

" Overall sum of Std. Devs. of analysis residuals for assays 0.8861 "

Appendix 6-7: Results from standard test and an airflow rate of 2.2 l/min

" SysCAD/MB v1.2 "
 " (c) Kenwalt Systems, 1994 "
 " 339 Rivonia Boulevard "
 " Johannesburg, South Africa "

" Time of run 20:08:28 "
 " Date of run 1999/10/12 "

" Standard test with low airflow "

" Converged in 2 iterations "
 " Maximum iterations : 50 "
 " Tolerance required : 0.001000 "
 " Tolerance obtained : 0.000155 "

" FLOWS "
 " ===== "

		Adjustment "					
		No. of	Smoothed	Measured "			
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev.	"
1	" Feed	1	1	0	0	100	0.01
2	" Concenter	0	0.212	0	0	21.22	0
3	" Tails	0	0.788	0	0	78.78	0

" ASSAYS "
 " ===== "

" Assay Number 1 Ni "

		Adjustment "					
		No. of	Smoothed	Measured "			
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev.	"
1	" Feed	7.3	7.3059	0.0806	0.0806	100	0.073
2	" Concenter	13.05	12.9502	0.1529	0.7644	37.62	0.6525
3	" Tails	5.86	5.7853	0.255	1.275	62.38	0.293

" Assay Number 2 Cu "

		Adjustment "					
		No. of	Smoothed	Measured "			
Stream	Meas.	Smooth.	Std.Dev.	% of Meas	Rec.(%)	Std.Dev.	"
1	" Feed	1.8	1.7994	0.031	0.031	100	0.018
2	" Concenter	5.4	5.4266	0.0985	0.4927	64	0.27
3	" Tails	0.82	0.8223	0.0556	0.2779	36	0.041

" Assay Residuals per stream "

		Average	Average "
Stream		S.S.	No. Std. Devs "
1	" Feed	0	0.0558
2	" Concenter	0.0053	0.1257
3	" Tails	0.0028	0.1553

" Assay Residuals per assay "

		Average	Average "
Assay		S.S.	No. Std. Devs "
1	" Ni	0.0052	0.1628
2	" Cu	0.0002	0.0617

" Overall S.S. of standard analysis residuals for assays 0.0163 "

" Overall sum of Std. Devs. of analysis residuals for assays 0.6736 "