Application of IMHOFLOT G-Cell centrifugal flotation technology

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Journal Paper

Synopsis

The Imhoflot G-Cell, a new development in the pneumatic flotation technology (which incorporates centrifugal forces in the separating vessel), is a recent innovation in the mineral processing world. The G-Cell was invented by Dr Rainer Imhof and commercialized by Maelgwyn Mineral Services Ltd. In a short time span a number of plants and units have been successfully commissioned in the mineral processing industry. In addition, a number of industrial G-Cell flotation plants are in the process of construction for the purpose of coal preparation and environmental remediation. In this paper two industrial installations have been highlighted, together with a pilot plant test programme investigating ultra-fine flotation recovery for a base metal operation.

Introduction

The Imhoflot G-Cell was invented by Dr Rainer Imhof of Maelgwyn Mineral Services Ltd (MMS), based in Cardiff, Wales. The G-Cell is a new addition to the family of pneumatic flotation technologies developed and commercialized in the last few decades. The term 'pneumatic flotation' is generally accepted as defining flotation systems where aeration occurs outside the separating vessel. It was originally developed in Germany, where Professor Bahr and his colleagues undertook much research and development in the 1970s and 80s. The first Imhof system, of vertical design—the V-Cell—was developed over 15 years ago. Since that time Dr Imhof has been responsible for the design and installation of over 50 pneumatic flotation plants, covering the full spectrum of minerals and metal applications. Recently the classic Imhoflot V-Cell design has been superseded by the G-Cell, which differs from the original V-Cell in terms of the centrifugal feeding mechanism and residence time.

Technical description of IMHOFLOT G-Cell

The term pneumatic flotation is generally associated with flotation where the aeration of the pulp is conducted outside the flotation cell. This is the main differentiating factor between pneumatic flotation and conventional tank flotation. The energy required by conventional cells to keep particles in suspension and generate bubbles is now focused solely on the production of very fine bubbles in the Imhoflot system, and the suspension of particles is catered for in the surplus energy of the system. The external aeration is usually achieved either by utilizing a simple venturi system in a pipe with downcomers or by using specialized fine bubble generation technology. This fine bubble generation technology is a core feature of the Imhoflot system.

The design objectives for Imhoflot pneumatic flotation are to separate and optimize the independent process steps that make up froth flotation: aeration, bubble-particle contact and froth separation. The aerator is self-aspirating and uses a high shear ceramic multi-jet venturi system operating at around 2.5 bar (250 kPa) back pressure. Bubble sizes generated start with ultra-fine bubbles at around 5 μm–10 μm. Bubbles in the 2 mm to 3 mm size range can also be found owing to the subsequent coalescence of bubbles that takes place. The high shear aerator reactor is designed to maximize the attachment of bubbles to all hydrophobic particles. Therefore the aerator can be seen to tend to the generation of bubbles as well as assisting the bubble-particle contact required for successful flotation. In the original design of the Imhoflot cell, the V-Cell, the aerated pulp was introduced upwards into the cell by means of a ring distributor system and nozzles.

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Residence time in the cell was generally in the order of three to four minutes. Over the last few years MMS has developed the concept of using centrifugal forces to speed up the separation of concentrate and enhance the removal of the froth phase. This is achieved by introducing the aerated feed tangentially into the separating vessel, thus creating specific rotational speeds in the cell. The cell is not designed as a gravity separator, and the rotational speeds are not high enough to strip coarse particles from the froth. However, the centrifugal froth separation has now reduced the residence time in the cell to around 30 seconds, which results in a multi-fold increase in flotation unit capacity.

Figure 2 (a) details the forces acting on the particles in the slurry inside the G-Cell. The downward force (G) is the force exerted by gravity and can be calculated using Newton's second law of motion, which states:

FG = m.a

FG = gravitational force

M = mass

A = Gravitational Acceleration

The acceleration of an object due to gravity is constant and equal to 9.8m/s^2. For the purpose of this example, we can ignore the mass of the object because it will be variable for different size particles entering the separation vessel. We can therefore say that gravitational acceleration (FG) of 9.8m/s^2 in a downward direction will be exerted on all particles entering the separating device. By using the cylindrical shape of the vessel, and injecting the slurry tangentially into it, it is possible to create a centrifugal force acting on the aerated pulp in the separating vessel. The following equation is a derivative of Newton's second law and can be used to determine the centrifugal force experienced by a particle in the rotating pulp:

Figure 1—3D Model of an Imhoflot G-Cell

$F_c = m \cdot v^2/r$

Fc = centrifugal force

V = rotational velocity

r = radius

Therefore at a predetermined speed and radius (and ignoring the mass of the object, as before) it can be calculated that the centrifugal acceleration experienced by the object would be 9.8m/s^2. This force will be exerted in an outward direction. The resultant force is shown in the diagram below.

FR is the resultant force that is experienced by a particle in the pulp. To calculate the resultant force, we use the Pythagoras theorem. For example, when the centrifugal acceleration is 9.8m/s^2, the resultant force experienced by the slurry will be 13.86m/s^2 at an angle of 45°. The resultant force on the particle in the slurry is greater than that of the gravitational force alone, as experienced in other flotation systems. This increased force in the system encourages hydrophilic particles to drop out of the system faster, and thus allows a much shorter residence time in the separating vessel. The additional force added to the particles aids in the reduction of the entrainment of hydrophilic particles into the froth. This results in higher selectivity' and hence produces

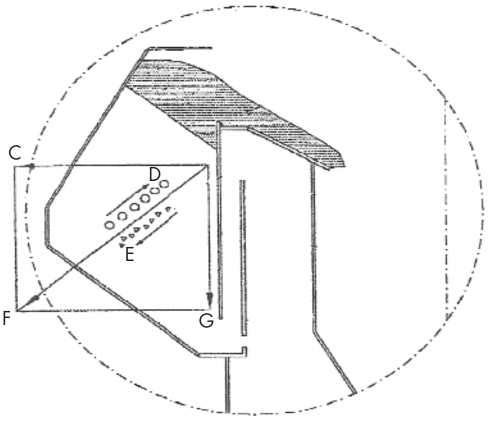

Figure 2(a)—Schematic detailing the forces working on particles floating in the G-Cell

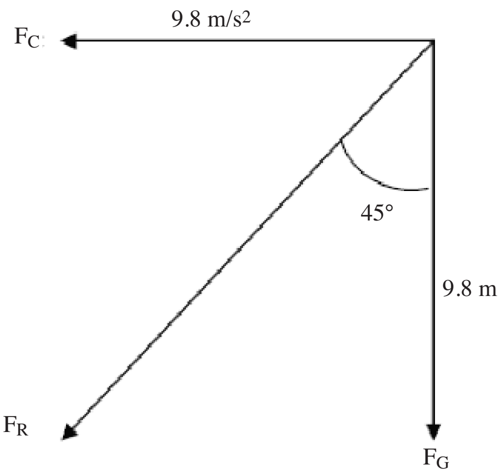

Figure 2(b)—Example of a possible resultant force diagram that a particle is subject to in an Imhoflot G-Cell better grades in the froth. The resultant force on the pulp creates an angled pulp/froth interface. This is beneficial, as it allows the froth to essentially 'flow' over the interface towards the inner channel, thus aiding in the removal of froth from the system. This faster froth removal ensures that valuable particles are removed from the system before they can detach from bubbles and drop back into the pulp, to be lost to the tails. This, in combination with the generation of fine bubbles in the high shear aerator, results in better recoveries of valuable minerals in the finer size fractions. This increased performance in the flotation system enables the separating device to be smaller in size and more cost-effective than standard flotation cells.

Applications of Imhoflot G-Cell

Imhoflot G–Cell has been successfully installed in a number of industrial sites, and can also be used for processing various metals and minerals. Two selected industrial installations are described in this paper.

Dorfner kaolin plant

The industrial practice for separating kaolinite ore is traditionally achieved by dispersing the mined ore and classifying it by means of multi-stage hydrocyclone systems. Kaolin particles are commonly found in the size range of only a few microns, and therefore report to the hydrocyclone overflow. This overflow is then further classified in the next, smaller cyclone, and so on. However, this traditional practice is ineffective because of its inability to produce clean quartz, feldspar and kaolin products individually. This inefficiency leads to the production of a middling stream which is either used in the cement industry or disposed of by returning it to the quarry.

In certain kaolin treatment plants, the beneficiation process of kaolin is undertaken by the use of froth flotation. Amines are used as collectors in a low pH environment exclusively to enable effective flotation to take place. Dorfner has been using pneumatic flotation by means of Bahr-Cells, the earliest development of pneumatic flotation for many years.

Dorfner flotation plant upgrade

Two of the limitations of the flotation plant at Dorfner were its low throughput capacity and the need for a cleaning stage to produce a saleable grade of concentrate. The use of amines to float fine particles results in a very stable froth, but this causes significant problems with froth handling and pumping of the rougher concentrate to the cleaner flotation cells. Dorfner planned to increase the flotation capacity by building a new flotation plant. The company's initial studies indicated that an Imhoflot pneumatic flotation plant would offer considerable capital cost savings over a conventional tank cell plant. In addition it appeared that a pneumatic flotation plant had the potential to produce a high grade concentrate without the need for further cleaning cells, another significant saving. If the middling product could be effectively cleaned in the flotation plant it would produce more than 4 t/h of high-value kaolin. (The simplest way to measure the grade of Kaolin is to measure the mass percentage loss on ignition at 1000°C. Kaolin has a theoretical maximum loss on ignition of 13.9%. This measurement is the one most commonly used in this paper.)

Operational process installation

The middlings from the current kaolin cyclone plant are pumped at a high density to the flotation plant. This material is passed through an MMS designed cascading mixing tank where H_2SO_4 is added to reduce the pH to 2.5. The reagent addition and conditioning (amine and acetic acid) is also performed in the cascade. The final cascade level is controlled with a float valve through which process water is added to reduce the slurry density. The use of process water at this point helps in the conservation of reagents, especially of H_2SO_4 in pH regulation.

Three Imhoflot G-Cells, 1.8 m diameter and with a design capacity of 110m^3/h, are operated in series with the tails of each cell being processed by the next cell. The flotation froth is washed with fresh water to ensure that the required Kaolin grade is achieved in the final combined concentrate. The concentrate produced from the cells is collected and treated with a destabilizer to break down the froth and aid the pumping efficiency of the concentrate, which is thickened in a lamella thickener. The overflow water is collected and used as process water in the flotation plant. The underflow (thickened concentrate) is treated with NaOH to increase the pH to 7, and pumped to a collection tank. The tails from the final flotation cell are pumped to a small set of cyclones. The overflow from the cyclones can either be used as process water, or can be removed from the plant as a tails product. The underflow from the cyclone station is then filtered using a vacuum drum filter. The filter cake (final tails) is removed by conveyor belt, and the filtrate water is pumped back into the plant to be used as process water. A flow sheet of the process can be seen in Figure 3.

Installation and commissioning

The plant was successfully commissioned in June 2005' and achieved results that far surpassed the clients' specifications. See Figure 4. The three-stage Imhoflot G-Cell plant was able to achieve a kaolin concentrate at a recovery of above 85% and a loss on ignition of greater than 13%. The initial laboratory flotation tests indicated that a cleaning stage might be required; however, the G-Cell operating with the froth washing system was able to achieve the desired kaolin grade without such a cleaner stage. Figure 5 shows a graph of the initial results obtained during commissioning.

Figure 5 depicts the variation of grade with yield measured during the initial commissioning of G–Cells at the Dorfner kaolin processing plant. It can be shown that as the yield increased, the recovery increased at a loss of grade. The loss of grade observed was not very large, and showed that when the yield was increased from approximately 67.2% up to 73.6%, the grade decreased from a loss only on ignition of 13.5% to 13.1%.

After commissioning, concentrate samples from each of the three G-Cells were analysed from a low grade feed specifically put into the plant to test the effect of pneumatic flotation. The results can be seen in Table I, which indicates that all three G-Cells were able to achieve the desired upgrading of kaolin. Although the concentrate produced was less than that achieved on the commissioning runs, the feed

Applications of IMHOFLOT G-Cell centrifugal flotation technology

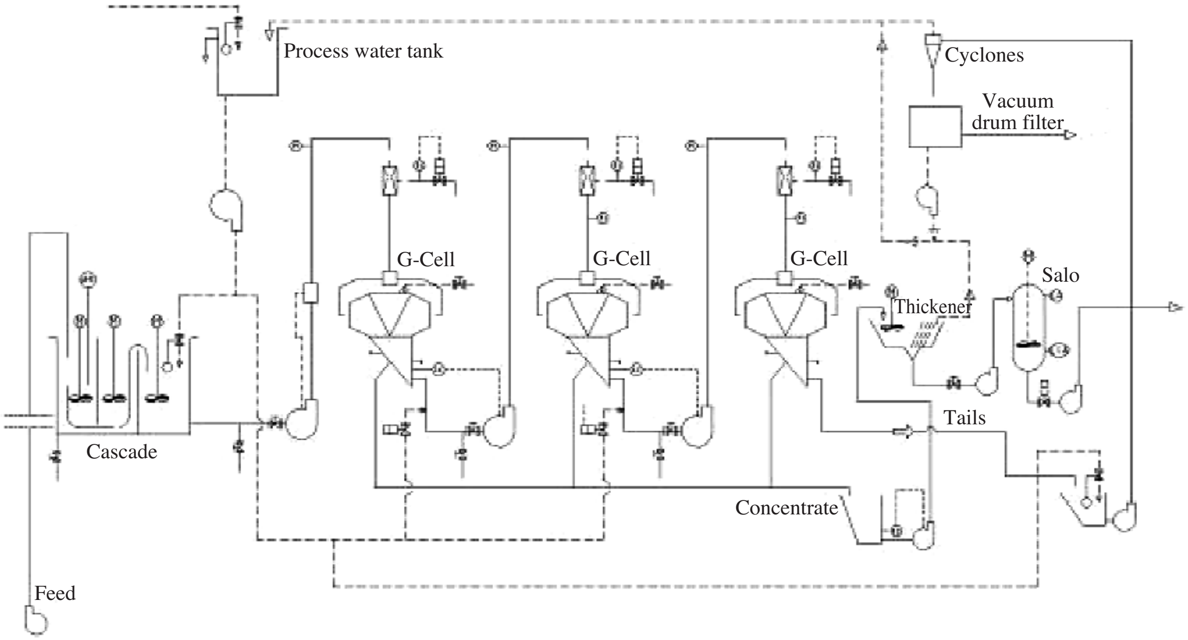

Figure 3—Dorfner kaolin flotation plant flow sheet

Figure 4—Dorfner flotation plant showing the 3 G-Cells in series

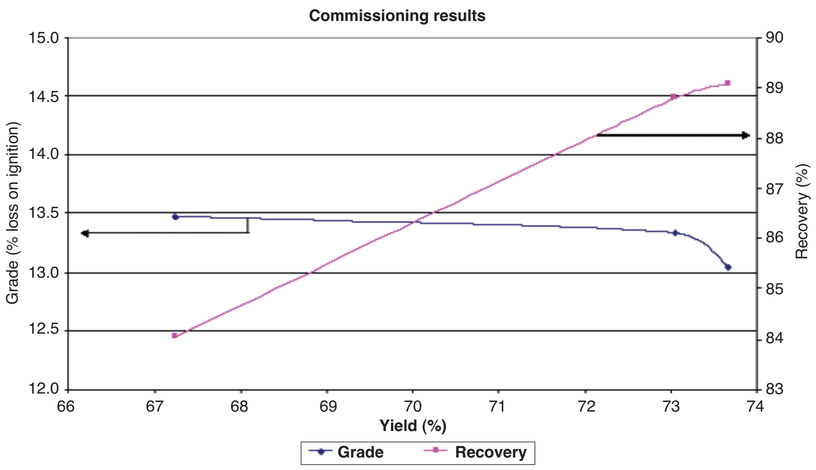

Figure 5—Results obtained during initial commissioning

Table I

Grades obtained from individual G-Cells

	Feed	G-Cell 1	G-Cell 2	G-Cell 3	Final Tails
% Loss on ignition	8.18	12.71	12.93	12.01	2.37

Table II

Detailed composition of flotation components

Element	Mass %		
	Feed	Concentrate	Tails
SiO_2	53.80	48.50	72.90
Al_2O_3	32.50	37.10	16.50
Fe_2O_3	0.18	0.20	0.12
TiO_2	0.74	0.19	2.16
K_2O	1.35	0.46	3.52
Na_2O	0.10	0.04	0.13
PbO	< 0,008	0.01	< 0,008
BaO	0.01	0.03	0.01
Loss on Ignition @ 1000°C	10.97	13.34	4.55

grade was significantly lower at 8.18%. Other tests during the commissioning had a feed grade of approximately 10.5% loss on ignition and, indicated the ability of G-Cells to handle variations in feed grade easily.

A detailed analysis of the concentrate produced during the commissioning runs is presented in Table II.

Summary of the results of using G-Cells at Dorfner

The Imhoflot G-Cell plant was delivered, installed and commissioned within three months of the order being received from Dorfner. No major commissioning problems were encountered. See Figures 6 and 7. The plant was fully operational in July 2005. With the use of froth washing, the three-stage plant produced an acceptable concentrate without the need for further cleaning, resulting in substantial cost savings. The residence time of the complete G-Cell installation is less than 120 seconds. This can be compared for this application to eight minutes of conventional roughing time, and a further six minutes in a required cleaner section.

Transvaal Gold Mining Estates—South Africa

The Transvaal Gold Mining Estates (TGME) gold mine represents a portfolio of 10 mines, active or dormant, and a metallurgical plant owned by Simmer & Jack Mines Ltd. It is located in the Pilgrim's Rest area of Mpumalanga Province, home to one of the richest goldfields in South Africa. TGME is South Africa's oldest gold mining company still in production. Constituted in May 1985, it was mined continuously until 1971, when inadequate underground infrastructure, combined with a fixed gold price, led to a hiatus in operations. In 2004 Simmer and Jack instigated a capital funding programme for a development and expansion programme at TGME mines. However, disappointing gold recoveries of less than 45% were achieved in the expanded mine, due to the higher than expected amount of refractory ore being extracted.

TGME flow sheet

TGME developed an innovative flow sheet that depicts the processes required to overcome the metallurgical problems associated with:

- Fine-grained refractory gold trapped in sulphides
- Entrained preg-robbing carbon in the concentrate
- High flotation plant mass pull and low concentrate grade and recovery.

The processes contained in the TGME flow sheet consist of crushing and milling, followed by Dense Media Separation (DMS) to reduce tonnages to be treated in the milling section by 68%. This is done by separating othe gangue from the ore-bearing reef material, which results in an improvement of the head grade from around 5g/t Au to approximately 15g/t Au., while at the same time removing pregnant solution robbers of gold, such as various carbons.

MMS assisted Simmer and Jack in considerably increasing the overall recovery of the TGME plant by the installation of the proprietary Leachox refractory gold process. As part of this process a single Imhoflot G12 G-Cell was incorporated in the flow sheet to increase the gold grade going to the Leachox process.

Figure 6—Kaolin flotation at Dorfner

Figure 7—Froth washing of the concentrate to produce the required grade

Applications of IMHOFLOT G-Cell centrifugal flotation technology

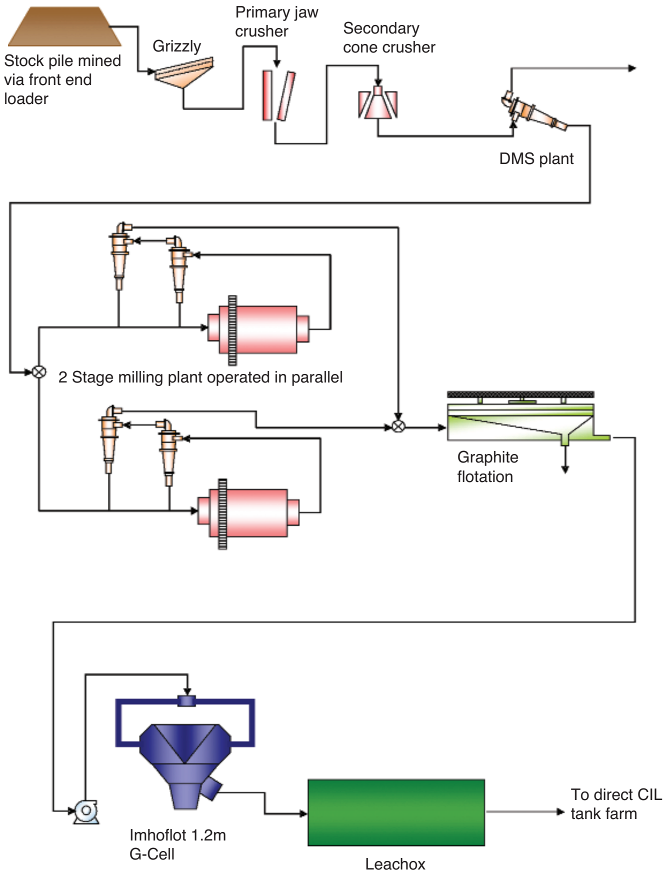

Figure 8—TGME flow sheet

The advantage of using a Imhoflot G-Cell plant

The self-aspirating Imhoflot G-Cells offered the benefits of a low-cost installation that was easy to retrofit in the circuit. One 1.2 m diameter G-Cell, with a capacity to handle 45m^3/h, was installed at TGME. A static screen was fitted on the feed to the G-Cells to remove any oversize trash that might cause blockages in the aerators.

The G-Cell is operated in open circuit, with the tails also reporting to the leach. The objective of the G-Cell application at TGME was to concentrate as much as possible of the gold in as small a mass as possible to allow for a reduction in size and cost of the downstream Leachox™ circuit. The G-Cell achieves a roughly 2.5times upgrade of the feed grade, and concentrates about 74% of the gold into roughly 30% of the mass. The DMS circuit upstream of the G-Cell rejects much of the gangue ahead of the G-Cell, resulting in the lower than normal upgrade ratio in this instance. See Figures 9, 10 and 11.

The G-Cell equipment was delivered, installed and commissioned within four weeks.

Summary of the results of using G-Cell at TGME

The small footprint of the G-Cell allowed for a compact installation to be retrofitted in the existing mill space at TGME to enable a large proportion of the gold to be concentrated into a small enough mass to allow for economic treatment of the refractory ore through the LeachoxTM circuit.

Ultra-fine particle Imhoflot flotation

Background

Due to the combination of the very fine bubbles generated and the high energy in the collection zone, the Imhoflot G-Cell is particularly applicable to the flotation recovery of very fine particles. MMS has recently undertaken pilot plant testwork at a mine that has a particularly difficult fine-grained polymetallic orebody. As part of the mine's separation process the zinc plant produces a bulk lead/zinc

Figure 9—G-Cell and feed box arrangement

concentrate, which is sold to various smelters. The ore deposit is one of the largest polymetallic sources in the world, but also one of the most difficult to process. Owing to the very finely disseminated nature of the ore. A size reduction to below seven microns is required to liberate the valuable material and reduce the silica entrainment to the concentrate. Penalties on the final concentrate are predominantly based on silica (SiO_2) content. The target value for silica in the final concentrate is set at below 3.7%, which is not however always achievable. To liberate the ore, the rougher concentrate is finely ground in ultra-fine grinding mills. The flow sheet for the current plant configuration is shown below in Figure 12.

The final tails of the plant are made up of the rougher tails and cleaner tails from cleaners 1, 2, 3 and 4. The plant's overall recovery varies from 60% to 75%, but seems to average about 65%. The final Zn grade is above 40% and the average SiO2 value is between 3.5 and 4%.

Figure 10—G-Cell Bowl

Figure 11—Flotation froth produced at the TGME Gold Mine

Imhoflot G-Cell pilot plant testwork

A self-contained G-Cell pilot plant was used for the testwork. This unit was used to complete the trials undertaken at the mine. The pilot plant consisted of two IMF-G-10 G-Cell units which operated in series with the tailings of G-Cell 1 feeding G-Cell 2. The unit was able to treat approximately $23m^3/hr$, with tonnages varying depending on percentage solids in the feed. For this operation the percentage of solids was very low: the unit was treating approximately 1t/hr during the trials. See Figure 13.

One of the major points of interest was to determine whether any of the cleaner tailings streams could be re-treated in the G-Cell to produce a final grade concentrate. This would then be used to blend back into the plant's final concentrate and increase saleable tonnage.

Testwork was completed on the cleaner tails streams produced from Cleaners 4, 5 and 6. Cleaner tailings from 5 and 6 were tested to see if it would be possible to open-circuit one stream and so reduce the recycling load building up in the flotation system. The majority of the trials were completed on the Cleaner 4 tails, as this stream was a Zinc-rich tailings stream and was discarded.

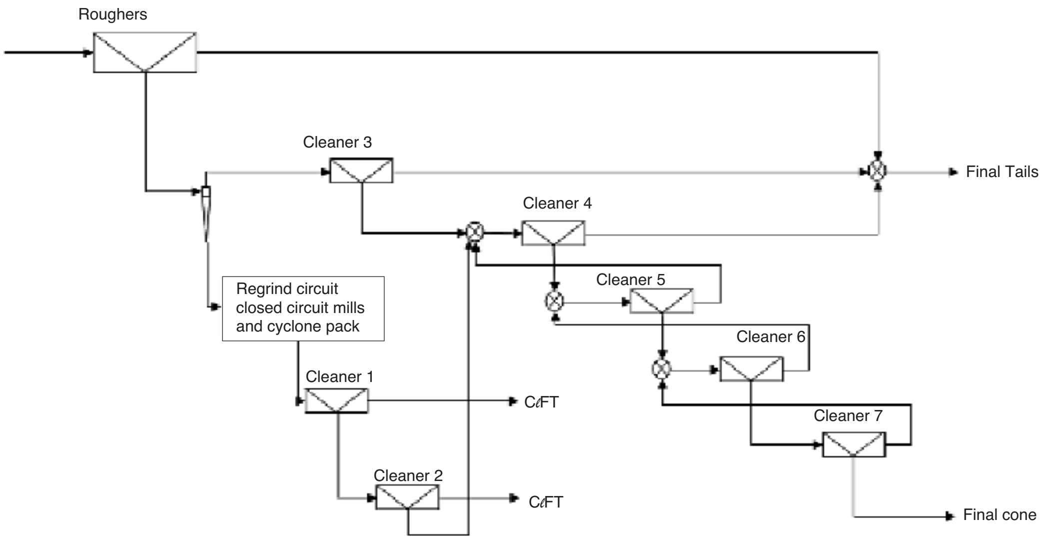

Figure 12—Current concentrator flow sheet

Selected results from the pilot plant trials

Table III below shows the most optimistic results achieved from the trials of Cleaner 4 tailings. Two scenarios were tested, one with a lower mass pull to produce the highest grade possible, and the other an attempt to achieve a higher recovery without reducing the concentrate grade too significantly.

As can be seen, the recovery varied from 9.2% to 20.2%, with the associated grades ranging from 37.9% to 35.6% zinc. As was expected, when additional air was added, there was an increase in SiO_2 grade in the concentrate due to increased entrainment. The upgrade ratio for Zinc was significant at 3.6 for both samples taken, showing that the G-Cell was able to increase recovery without loss of concentrate grade. It should be noted that the silica grade was slightly higher than the target wanted for a final concentrate, but if the project were to be followed up, the mass that a G-Cell plant would produce is sufficiently low for it to blend into the final product without increasing the overall silica grade.

Figure 13—G-10 Pilot plant on the mobile rig for easy transport and operation

Table IV shows the grades and recoveries achieved for the individual G-Cells. It is very encouraging to see that both G-Cells were able to produce high upgrade ratios. Sample 1 showed a change from 38.1% to 37.6%, and sample 2 showed a change of 1.9% zinc from 36.3% to 34.2%. This shows that it would be very likely that a third G-Cell could be added to the series. This could result in increased recovery without impacting the grade. A third G-Cell would also mean that the mass pull across the three cells could be better balanced to optimize the grade/recovery relationship.

Economic evaluation

Although the recoveries may appear low, at only 9.2% and 20.2%, they represent a very valuable economic improvement for the plant as it yields material that could not be recovered by the current conventional flotation plant despite excess flotation capacity. Tables V and VI show the economic calculations for both the low recovery and high recovery options.

Based on the last plant survey that was completed on the plant, the cleaner 4 tailings stream contained 760kg/hr of zinc material. Recovery between 9% and 20% of this stream as a final concentrate would increase final product tonnage by between 70 and 150kg/hr, representing an economic value of approximately 1.8 to 4 Million US$/year (based on the Zinc price in October 2006. The latest zinc price from LME is 3,675 US$/ton).

At the time that the trials were completed, the average cleaner 4 tailings zinc content was double that recorded in the previous survey, reporting at 1.5tph of Zinc. Based on this figure the economic improvement would be a minimum yearly gross revenue increase of 3.7 million US$.

The payback time for the installation of a 3-stage Imhoflot G-28 G-Cell plant has been calculated at between 4 and 9 months, based on the low and high recovery scenarios. The installation of any new equipment at this mine is dependent on the expansion of the limited on-site power generation capacity. Once this issue has been addressed, the advisibility of installing a G-Cell plant will be considered at the end of 2007.

Table III

Selected results from Cleaner 4 tailings

	Zinc feed (%)	Zinc recovery (%)	Zinc grade conc (%)	SiO_2 feed (%)	SiO_2 grade conc (%)	Mass pull (%)
Sample 1	5.7	38.1	4.7	3.5	37.6	4.7
Sample 2	13.9	36.3	4.9	6.3	34.2	5.7

Table IV

Individual G-Cell recoveries and results

	Cell 1	Cell 2				
	Zinc recovery (%)	Zinc grade conc (%)	SiO_2 grade conc (%)	Zinc recovery (%)	Zinc grade conc (%)	SiO_2 grade conc (%)
Sample 1	5.7	38.1	4.7	3.5	37.6	4.7
Sample 2	13.9	36.3	4.9	6.3	34.2	5.7

Table V

Low recovery economic scenario

	Last survey	Circuit mass balance 30 Aug–5 Sep		
	Min	Average	Max	
Zn mass in CL4 tail (TPH) G-cell recovery Zince mass in conc (TPH)	0.76 9.2% 0.07	0.81 9.2% 0.07	1.51 9.2% 0.14	2.31 9.2% 0.21
Current zinc price (US$/ton) Net smelter return Sell price to smelter (US$/ton)	$3.916 85% $3.329	$3.916 85% $3.329	$3.916 85% $3.329	$3.916 85% $3.329
Gross revenue (US$/hr) Operating hours/year Gross revenue (US$/yr)	$233 8000 $1.861,886	$247 8000 $1.975,661	$463 8000 $3.700,838	$706 8000 $5.649,394

Table VI

High recovery economic scenario

	Last survey	Circuit mass balance 30 Aug–5 Sep		
	Min	Average	Max	
Zn mass in CL4 tail (TPH) G-cell recovery Zince mass in conc (TPH)	0.76 20.0% 0.15	0.81 20.0% 0.16	1.51 20.0% 0.30	2.31 20.0% 0.46
Current zinc price (US$/ton) Net smelter return Sell price to smelter (US$/ton)	$3.916 85% $3.329	$3.916 85% $3.329	$3.916 85% $3.329	$3.916 85% $3.329
Gross revenue (US$/hr) Operating hours/year Gross revenue (US$/yr)	$506 8000 $4.047,578	$537 8000 $4.294,915	$1.006 8000 $8.045,299	$1.535 8000 $12.281,291

Summary

The Imhoflot G-Cell has been successfully installed and is operating around the world in a number of plants processing metals and minerals. Two industrial installations (for gold and kaolin recovery) and one proposed application for recovering ultra fines are discussed in this paper. A number of new installations for recovering coal and for environmental remediation are in the process of being developed around the world.

The Imhoflot G-Cell is a cost-effective solution for flotation process plants. Key benefits of the Imhoflot G-Cell are the very short residence times (30 seconds) and higher selectivity than other (conventional and column) flotation systems can provide. The Imhoflot G-Cell pneumatic flotation system also offers lower capital and operating costs compared with conventional tank style flotation.

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