The Advantages of the Imhoflot G-Cell Pneumatic Flotation Process with Centrifugal Froth Removal – Two Case Studies

Michael Battersby [1], Michael Fletcher[1], Rainer Imhof [1], Adrian Singh [2] and Franz Puder [3]

1. Maelgwyn Mineral Services Ltd, The Maltings, East Tyndall Street, Cardiff Bay, CF24 5EA, UK. email: mms@maelgwyn.com
2. Greenhills Mining & Industrial Services (Pty) Ltd, 1332 Club House Street, Maraisburg, 1709, South Africa.
3. Gebr. Dorfner GmbH & Co, Kaolin-und Kristallquarzsand-Werke KG, Scharhof 1, D-92242 Hirschau, Germany

ABSTRACT

Pneumatic flotation, as developed by Dr. Rainer Imhof, has been successfully deployed in the minerals and environmental industry for over fifteen years. A recent innovation – the use of centrifugal forces in the separating vessel for rapid froth from tailings separation and removal – has added a new dimension to the technology. The Imhoflot G-Cell has dramatically reduced the size of the flotation plant needed with the consequential reduction in capital required for its construction. This paper will detail the principles and development of the G-Cell and its first commercial installations at the Barbrook Gold Mine in South Africa and the Dorfner Kaolin Plant in Germany.

KEYWORDS

Pneumatic Flotation, Froth Flotation, Gold Flotation, Kaolin Flotation, Imhoflot G-Cell

INTRODUCTION

Although all froth flotation is pneumatic i.e. with air, the term pneumatic flotation is generally accepted to apply to froth flotation where aeration of the pulp takes place outside of the separating vessel and thus differentiates it from conventional tank cell flotation. The external aeration is usually achieved by either utilising a simple venturi system in a pipe with downcomers or using specialised fine bubble generation technology. Imhoflot pneumatic flotation as developed by Dr Rainer Imhof and Maelgwyn Mineral Services (MMS) utilises this last system.

Pneumatic flotation does not follow the rules generally accepted for tank cell flotation. The concept for Imhoflot pneumatic flotation is simple. Take a liberated, correctly prepared, activated and conditioned mineral particle which is hydrophobic. To this particle attach a correctly sized bubble. The air bubble will rise with the hydrophobic particle attached and thus separate from hydrophilic particles which sink. Repeat this process many thousands of times per second. Collect the air bubbles and you have 100% recovery of your hydrophobic mineral. Sounds easy in theory but there are obviously limitations in practice! However this perfect example shows that in pneumatic flotation the term "flotation time", as used in tank type flotation is irrelevant. Also, assuming the mineral is correctly prepared, there can be no such thing as "slow floating" or "fast floating" minerals.

Imhoflot pneumatic flotation tries to reach perfection by generating a range of bubble sizes in the aerator. The aerator is self-aspirating using a high shear ceramic multi-jet venturi system operating at around 2.5 bar pressure. Bubble sizes generated start with ultra fine bubbles at around 10µm but also generating bubbles in the 2mm to 3mm range. Subsequently some coalescence of bubbles takes place. The high shear aerator reactor is designed to maximise the attachment of bubbles to all hydrophobic particles. If it does not manage to do this in the aerator then there is little chance of a bubble attaching to a particle in the distributor or the separating vessel. To achieve more recovery the tails of the separating vessel must be introduced again to an aerator in a second, third or subsequent stages until the desired recovery is achieved.

IMHOFLOT G-CELL BACKGROUND

The design objectives for Imhoflot pneumatic flotation is to separate and optimise the independent process steps that make up froth flotation i.e. mineral preparation, reagent dispersion, collection, aeration, bubble-particle contact and froth separation. As indicated above the separation vessel in Imhoflot is designed only to separate and remove the froth from the tailings slurry and not to contact air bubbles with particles.

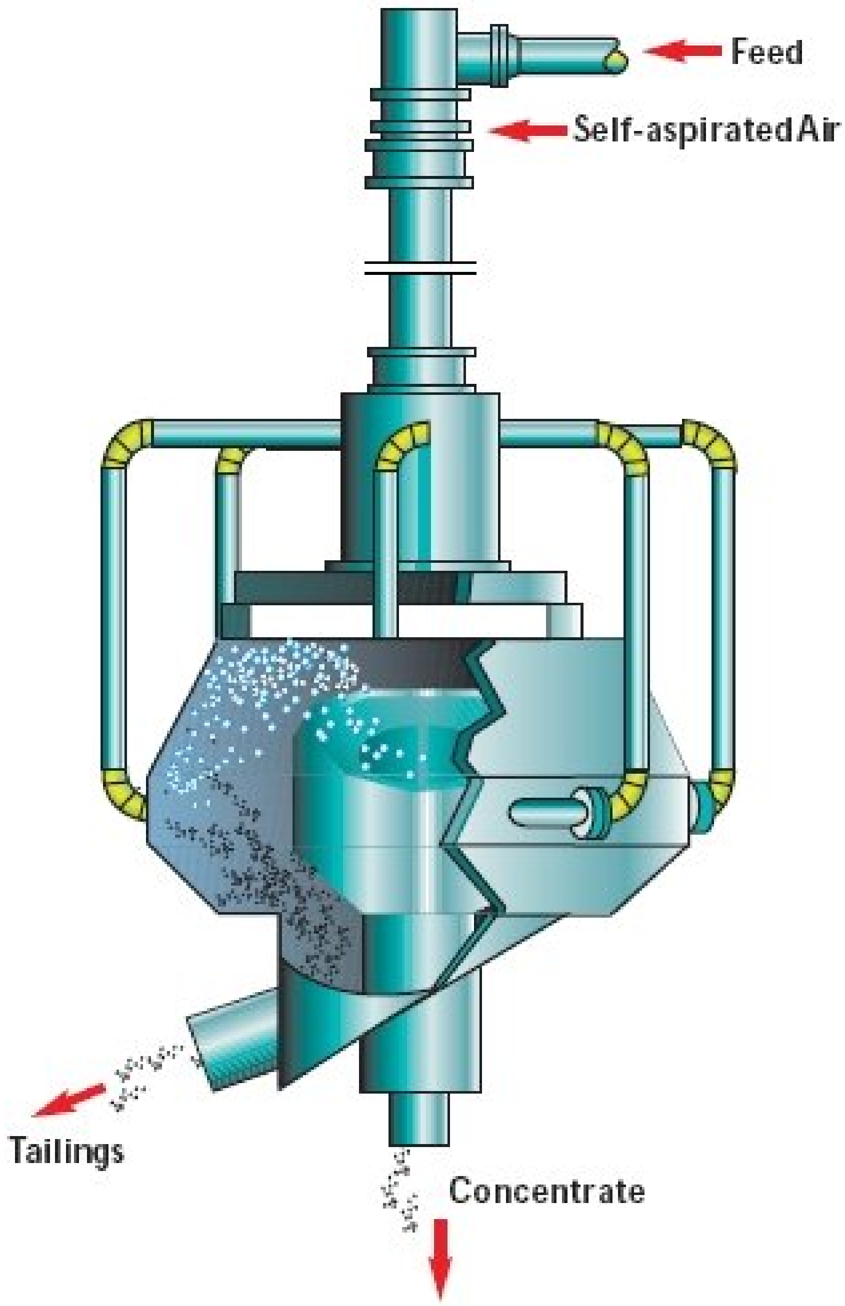

Figure 1: Schematic of Imhoflot G-Cell

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. Residence time in the cell was generally in the order of three to four minutes. MMS over the last few years have developed the concept of using centrifugal forces to speed up the separation and 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 type of 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

CASE STUDY – BARBROOK GOLD MINE

History of Barbrook Mine

Barbrook Gold Mine is 100% owned by Caledonia Mining Corporation. The mine is located near the historic gold mining town of Barberton in the Mpumalanga province of the Republic of South Africa, approximately 375km west of Pretoria and Johannesburg. Barberton has a history of gold mining dating back more than 100 years. The Barbrook gold deposits occur in the Barberton greenstone belt, the host for the other gold deposits in the area. The belt is of Archean age and includes some of the oldest volcanic and sedimentary rocks in South Africa. The gold mineralization at Barbrook is complex – the gold is generally extremely fine grained, associated with refractory minerals such as pyrite and arsenopyrite and contains significant concentrations of "preg-robbing" organic carbon.

The property represents a consolidation of approximately 20 previously worked small gold mines. In the 1980's Rand Mines Ltd unsuccessfully tried to develop a 25,000 ton per month operation which consisted of a flotation plant and roaster to treat the refractory ore. Caledonia took over the mothballed operations and is currently mining at Barbrook using an open-stope, sub-level benching method at around 6000 tons of ore per month at a grade of around 6-8g/t Au. Barbrook dispensed with the roaster but utilises other parts of the original plant.

Innovative Flow Sheet at Barbrook

Barbrook has developed an innovative flow sheet to overcome the metallurgical problems associated with:

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

The Barbrook flow sheet consists of crushing and milling, followed by conventional roughing and scavenging tank flotation cells. Cleaning and recleaning of the rougher concentrate is by Imhoflot G-Cells. The flotation concentrate is then reground before the removal of carbon by gravity/cycloning. The carbon-free, reground concentrate, is then subjected to a two stage Aachen Aerator Reactor oxidation step (also supplied by MMS) before being cyanide leached in a novel resin-in-leach circuit.

G-Cell Cleaner Plant

Before the installation of the Imhoflot G-Cell cleaner circuit, the concentrate grade was only around 10g/t Au with a very high mass recovery of around 30%. The Barbrook resin-in-leach circuit depicts the peculiar phenomenon of a "static" tail which does not increase with increasing head grade. So, as far as the leach circuit is concerned, higher head grades (concentrate grades) yield higher gold recoveries. Laboratory test work showed that the concentrate could be cleaned to a grade of around 40g/t Au. In the original flotation plant that Barbrook was utilising, the cleaning section was hopelessly oversized for the current duty. Also, the high operating cost relating to the existing flotation mechanisms, power consumption and blower requirements made the use of the existing flotation plant an unattractive option. Having said that, space for any new flotation equipment in the mill buildings was at a premium. The self-aspirating Imhoflot G-Cells offered the benefits of a low capital cost installation that was easy to retrofit in a relatively confined space. Two, 1.2m diameter G-Cells, each with a capacity to handle

Figure 2: G-cell cleaner plant installation at Barbrook

45m^3/h were installed in series. A static screen was installed on the feed to the G-Cells to remove any oversize trash that might cause blockages in the aerators.

The G-Cells are operated in closed circuit, with the tails from the second G-Cell reporting to the first G-Cell and the tails from the first cell reporting back to the flotation feed. Each G-Cell gives a two times upgrade; rougher concentrate at 10g/t Au is upgraded to 20g/t Au in the first G-Cell and then further to 40g/t Au in the second G-Cell. Overall mass recoveries have dropped from 30% to 20%.

Summary of G-Cells at Barbrook

The small footprint of the G-Cell allowed for a compact cleaner installation to be retrofitted in the existing mill buildings at Barbrook. The installation of the two stage cleaner circuit has resulted in a lot more flexibility to the operation of the flotation plant as the roughers can now be run for recovery and not grade. The plant has increased the grade of concentrate to the maximum determined by testwork whilst reducing the mass sent to the leach circuit. Barbrook has estimated that the higher grades sent to leach from the G-Cell cleaner plant and subsequent increase in leach recovery gave a pay-back on the installation in under 10 weeks.

Figure 3: Flotation froth produced at the Barbrook Gold Mine

CASE STUDY – DORFNER KAOLIN PLANT

Background

The main constituent of kaolin (also known as china clay) is the mineral kaolinite, which is a hydrated aluminium silicate, $Al_2 Si_2 O_5 (OH)_4$. Kaolin is formed by the decomposition of the mineral feldspar by water and heat. Two types of deposits are commonly found:

- Primary; where the clay occurs in situ in the kaolinised rock.
- Secondary; where water has transported clay from a primary deposit and laid it down elsewhere as beds of comparatively pure clay.

Primary kaolin is most commonly found in Europe whilst secondary clays are more commonly found in the Americas. Kaolin is extensively used in Europe in highly filled uncoated mechanical papers where it contributes to gloss and smoothness. Kaolin is also used in coating applications where good coverage of the surface is critical.

The normal industrial separation process of kaolinite production is achieved by the dispersion of the mined ore and classification by means of multi-stage hydrocyclone systems. Kaolinite 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. The hydrocyclone plant is not able to produce clean quartz, clean feldspar and clean kaolinite products individually. This inefficiency leads to the production of a middlings stream which is either used in the cement industry or disposed of back into 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, for effective flotation to take place. Dorfner has exclusively been using pneumatic flotation for many years, utilising Bahr-Cells, the earliest development of pneumatic flotation, and were consequently comfortable with their use.

Dorfner Flotation plant upgrade

Two of the restrictions of the existing flotation plant at Dorfner were its low throughput capacity and the need of a cleaning stage to produce a saleable grade of concentrate. The use of amines to float fine particles results in a very stable froth. 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. Their 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, a considerable cost advantage. If the middlings product could be effectively cleaned in the flotation plant it would produce more than 4t/h of high value kaolinite. 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 most commonly used in this paper.

Laboratory Test Work

Dorfner undertook a laboratory flotation testwork campaign to determine and optimise the flotation process. A three litre Denver type cell was used and the following flotation procedure was followed. The feed material was conditioned at a high pulp density of 500g/l for approximately four minutes with H_2SO_4 to reduce the pH to 2.5 before flotation. Flotation reagents were also added at this point with Amine 3305 from Clariant being was used as a collector in dosages between 400g/l and 600g/l. The rougher concentrate was collected during the four minute bulk float. This was then transferred to another flotation cell, additional water was added and a cleaner float was performed for approximately three minutes.

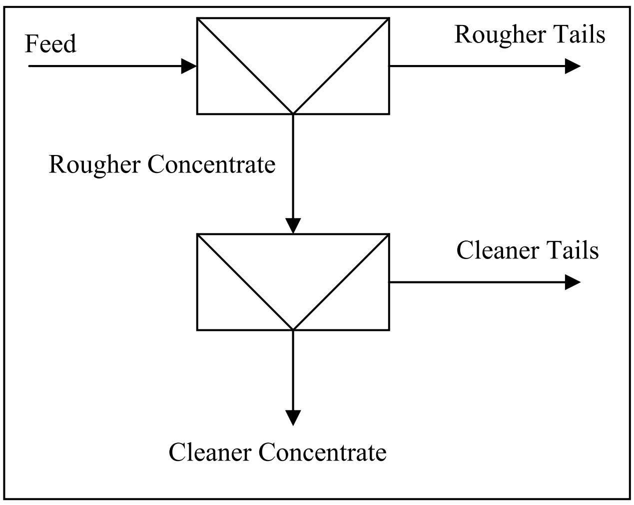

Figure 4 : Laboratory flotation procedure followed

The results from the laboratory flotation test work can be summarised in the following points:

- Maximum kaolin grade achievable was 13.5% loss on ignition (96.8% kaolin grade).
- Kaolin recovery of 85% to 90% was achievable.
- Kaolin mass yield of 65% to 75% was achievable (dependent on kaolin quality).
- Based on the laboratory flotation, conventional flotation would still require a cleaning stage.
- Lower solids density flotation of below 100g/l enabled better concentrate grade to be produced but therefore required more flotation capacity.

Pilot Plant Test Work

In the existing pneumatic flotation plant the solids concentration of the feed was high at around 200g/l. This was due to the small size of the plant and the relatively high amount of feed that had to be processed. From the laboratory tests, it was shown that it would not be possible to obtain rougher concentrates with high enough grades to make cleaning unnecessary at these high feed densities. With the new generation of pneumatic flotation cells, the Imhoflot G-Cell, much higher throughputs are possible at smaller foot-prints.

Dorfner decided that it needed to pilot plant test a G-Cell to demonstrate the throughput and performance benefits and to prove that the required grade of concentrate could be produced without recourse to cleaning. Whilst pneumatic flotation, due to its nature, has historically given higher grades of concentrate, the difficult target required by Dorfner to avoid a cleaning step led MMS to install a froth washing system on the pilot plant. This was easily achievable because the rotational flow of the froth in the cell meant that one simple bar spray arrangement gave full washing coverage of the froth. It was possible to pilot test the full throughput of the middlings stream in a 1.7m diameter G-Cell provided by MMS. This size of cell was easily able to process the entire tonnage even in the low solid concentration of well below 100g/l. Several tests with flow rates of between 70 and 80m^3/h and solid concentrations of around 50g/l proved that concentrates with saleable kaolin grades could be achieved utilising a G-Cell and aided by froth washing without any recourse to further cleaning.

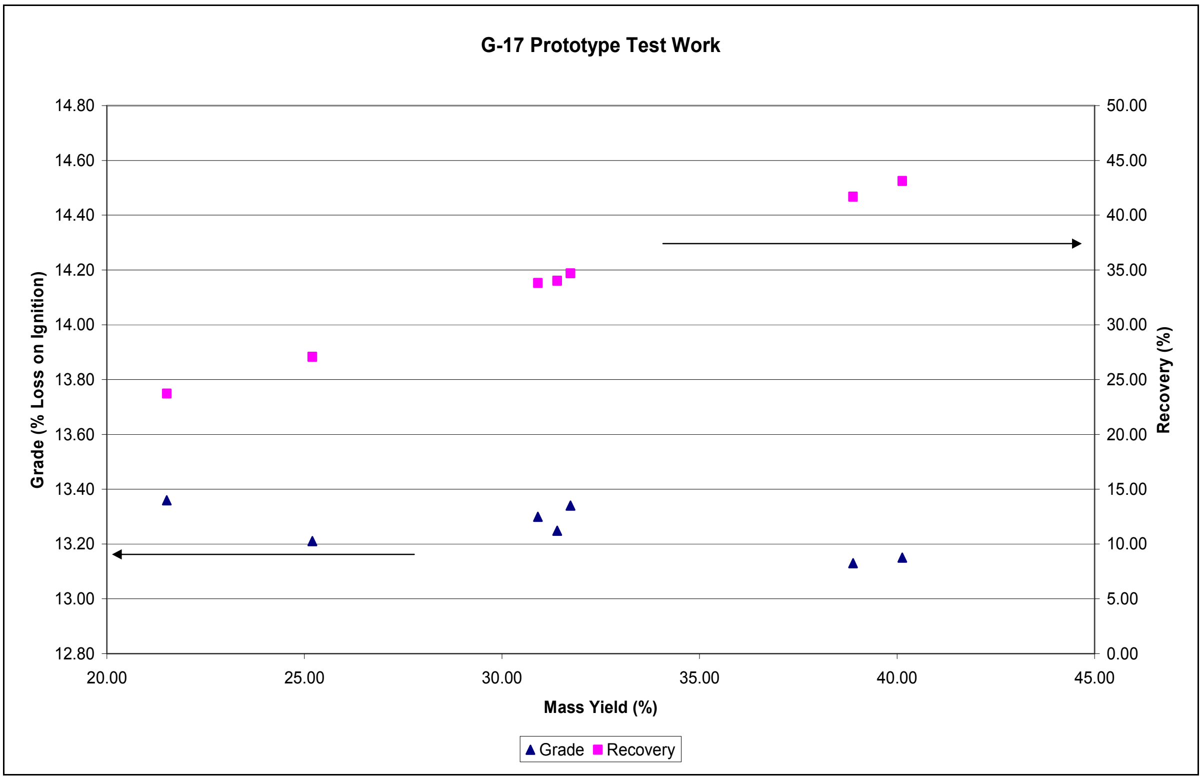

Figure 5: Results obtained from pilot plant test work

To obtain acceptable recoveries it was necessary to maintain a conditioning time for the amines preferably of over four minutes. Anything less than three minutes was not sufficient to obtain acceptable recoveries. Therefore MMS developed a "cascade" type of conditioning system to allow such adequate conditioning time. A single pass through the 1.7m G-Cell resulted in weight recoveries of approximately 31.5% and kaolinite recoveries of nearly 35% at a grade of 13.3% loss on ignition (average of test work). The amine consumption during pilot testing was around 550g/t. The pilot plant results showed that a three stage G-Cell plant in series could achieve economic kaolin recovery of above 85% at the desired grade of kaolin.

Operational 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 where 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, 1.8m diameter, Imhoflot G-Cells with a design capacity of 110m^3/h are operated in series with the tails of each cell being processed by the next cell. In comparison to the G-Cells operated at Barbrook Gold Mine these cells are operated with no recycle with each cell only using a single pass. The flotation froth was washed with fresh water to ensure that the required Kaolin grade was achieved in the final combined concentrate. The concentrate produced from the cells is collected and treated with a destabiliser to break down the froth and aid in pumping efficiency of the concentrate. The concentrate is thickened in a lamella thickener where the overflow water was 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 is 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 6.

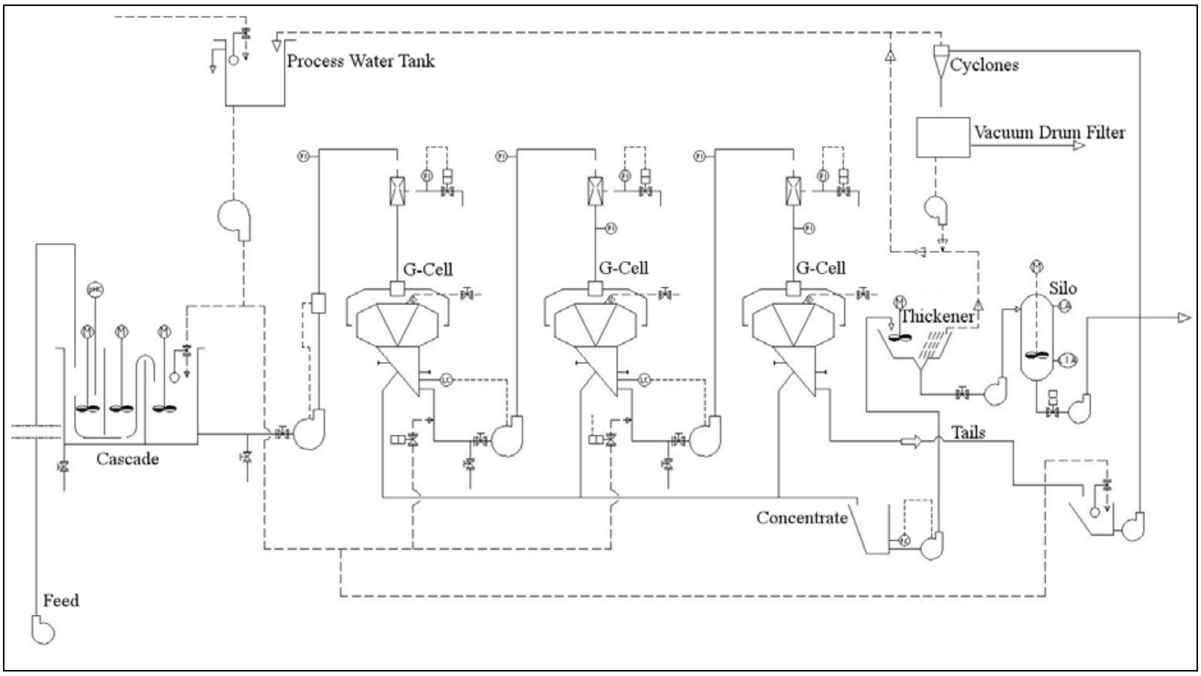

Figure 6: Dorfner kaolin flotation plant flow sheet

Installation and Commissioning

The plant was successfully commissioned in June 2005 and achieved results that far surpassed the clients' specifications. 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 may 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 8 shows a graph of the initial results obtained during commissioning.

Figure 7: Dorfner flotation plant showing the 3 G-Cells in series

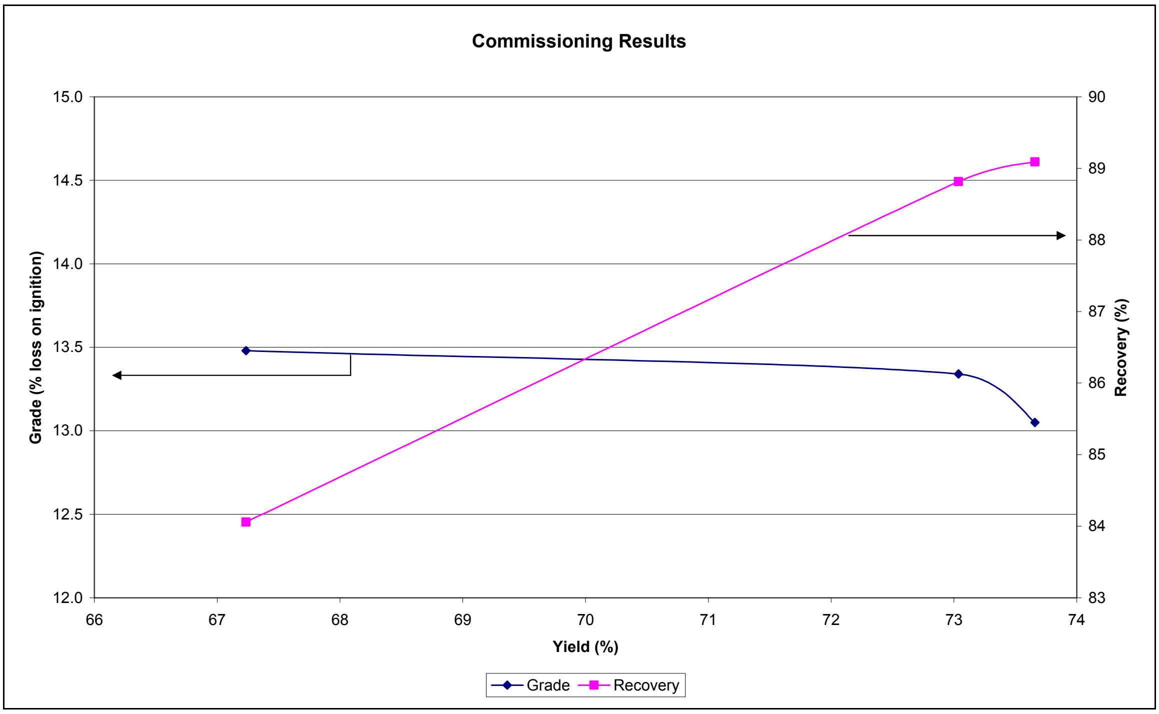

Figure 8: Results obtained during initial commissioning

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 only decreased from a loss on ignition of 13.5% to 13.1%.

After commissioning, concentrate samples from each of the three G-Cells was 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 1.

Table 1: 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 1 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 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 G-Cells ability to easily handle variations in feed grade.

A detailed analysis of the concentrate produced during the commissioning runs is presented in Table 2.

Table 2: Detailed composition of flotation components

	Mass %		
Element	**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

Figure 9: Kaolin flotation at Dorfner

Figure 10: Froth washing of the concentrate to produce the required grade

Summary of G-Cells at Dorfner

The Imhoflot G-Cell plant was delivered, installed and commissioned within three months of the order being received from Dorfner. It was successfully commissioned without any major commissioning problems. 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 considerable cost savings. The residence time of the complete G-Cell installation is less than 120 seconds. This can be compared for this application of eight minutes of conventional roughing time and a further six minutes in a required cleaner section.

CONCLUSION

Dr Imhof supplied his first pneumatic flotation plant in 1987. Since then he has designed and supplied over 110 cells treating a whole range of materials including copper sulphide and oxide ores, gold, coal, iron ore, slags, soil remediation and a range of industrial minerals. The development of centrifugal froth removal providing high performance separation with significantly reduced residence time now offers further reductions in installation costs of flotation plants. The first two successful installations detailed here demonstrate the reliability of a flotation plant based on the G-Cell development.

MMS are currently supplying a 2000m^3/h Imhoflot G-Cell coal flotation plant in Russia utilising 3.6m diameter G-Cells. Current developments include the application of the technology for the recovery of ultrafine platinum group metals which are not recovered by conventional cells. Also the development of Imhoflot cells for the recovery of diamonds up to 2mm in size. For all applications MMS are developing modular mobile flotation plants for the recovery and clean up of tailings ponds and dumps.

ACKNOWLEDGEMENTS
The authors would like to thank Chris Harvey of Caledonia Mining Corporation together with Gebr. Dorfner GmbH & Co for allowing reference to their particular operations.

REFERENCES
Battersby, M.J.G., Imhof, R.M., Brown, J.V., (2003). *The Imhoflot G-Cell – An Advanced Pneumatic Flotation Technology for the Recovery of Coal Slurry from Impoundments*. SME 2003 Annual Meeting 24-26 February 2003, Cincinnati, USA.

Bahr, A., Imhof, R.M., Ludke, H. (1985) *Application and sizing of a pneumatic flotation cell.* Min. Proc. Congress, Cannes, France

Hill, R.D., (2000) *The White Stuff: Fillers and Coating Pigments for the Paper Industry*. Presented at Asia Pulp & Paper, 5 - 6 December 2000, Grand Hyatt, New Delhi, India

Imhof, R.M., Lotzien, R., Sobek, S. (1993). *Pneumatic flotation: a reliable procedure for a correct plant layout*. XVIII International Mineral Processing Congress Sydney, Australia 23-28 May 1993 pp 971-978.

Imhof, R.M., Sanchez, S.P., Fuentes, G.B., Latorre, G.J., Conejeros, V.T., Carcamo, H.G., (1997). *Aplicacion de la flotacion neumatica en Chile*. Mineria Chilena. Vol 16 No. 189, pp97-103

Imhof, R.M., Brown, J.V., (2000). *Imhoflot – Evolution of pneumatic flotation*. Major Trends in Development of Sulfide Ores Up-Grading in the 21st Century Conference Proceedings , 24-28 April 2000, Norilsk, Russia

Imhof, R.M., Battersby, M.J.G., Ciernioch, G. (2002). *Pneumatic flotation – An innovative application in the processing of potash salts*. SME 2002 Annual Meeting, 25-27 February 2002, Phoenix, AZ, USA Preprint 02-162

Imhof, R.M., Battersby, M.J.G., Brown, J.V., Lotzien, R.M., Kleefeld, J., (2003). *Development of Pneumatic Flotation Incorporating Centrifugal Separation*. XXII International Mineral Processing Congress, 28 October-3 September 2003, Cape Town, South Africa

Imhof, R.M., Battersby, M.J.G., Parra, F., Sanchez-Pino, S., (2005). *The Successful Application of Pneumatic Flotation Technology for the Removal of Silica by Reverse Flotation at the Iron Ore Pellet Plant of Compania Minera Huasco, Chile*. Centenary of Flotation Symposium, 5 – 9 June 2005, Brisbane, Australia

Mohanty, M.K., Huang, Z., Gupta, V., Biswal, S.K., (2005). *Perfomance of the Imhoflot G-Cell for Fine Coal Cleaning*. Centenary of Flotation Symposium, 5 – 9 June 2005, Brisbane, Australia

Sanchez-Pino, S., Imhof, R.M., Sanchez-Baquedano, S., Rojos-Tapia, F., Fernandez-Garcia, M., (2003) *Pneumatic Flotation Technology – An Interesting Experience in the Chilean Mining Industry*. CIM 35th Canadian Mineral Processors Operators Conference, 21-23, January 2003. Ottawa, Canada