ENHANCED FLOTATION OF PLATINUM MINERAL FINES THROUGH FEED CAVITATION – "BRINGING THE MOUNTAIN TO MOHAMED"

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ABSTRACT

The flotation of fine minerals less than 10 µm in size is an age old challenge spanning both the precious metal and industrial mineral sectors across a range of commodities. This problem has been brought into sharper focus by the emergence of the practice of fine grinding of flotation feed to effect better liberation of the targeted minerals. However, the ability of conventional flotation cells to effectively float the liberated fines remains questionable. In order to overcome this problem, Gold Ore postulates the "Bringing the Mountain to Mohamed" hypothesis which comprises the steps of gas nucleation on particle surfaces, aggregation of particles and levitation of aggregates. Testing of this hypothesis at Mintek, South Africa, showed a ~180% increase in the Kelsall k_{fast} factor coupled with a projected recovery improvement of ~4 % for the Mach Reactor case coupled with a final concentrate grade of ~2 times that of conventional flotation. These fundamentals were then extrapolated to plant scale with Mach Reactors installed on the flotation feed at Platmin's Tailings Scavenger Plant (TSP) with the objective of scavenging the fine minerals lost to tailings by the main plant. This paper details the theory, pilot plant results as well as key aspects of the full scale plant design supplemented by operational plant observations after commissioning. This game changing application is regarded as being pivotal to future flotation plant design whilst providing the technology leverage required for the survival of mineral operations in an economically unfriendly environment.

KEYWORDS

Bringing the Mountain to Mohamed, mineral fines, pico-bubbles, cavitation

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INTRODUCTION - THE CONUNDRUM OF FINE PARTICLE FLOTATION

"If the mountain won't come to Mohamed then Mohamed must go to the mountain" is an age old saying written into the book of proverbs in 1670. Legend has it that Mohamed promised his people that he would summon a mountain to come over to him so that he could offer up his prayers from its summit. After numerous attempts at moving the mountain went in vain, Mohamed, quite unabashed, said "Well if the mountain will not come to Mohamed, then Mohamed will go to the Mountain." In this analogy, Mohamed is a fine particle <10 µm and the mountain is a bubble within a flotation system. The age old challenge is how to bring these two together to achieve attachment?

Classically, the flotation process can be regarded as being made up of three distinct sub-processes: collision, attachment and detachment (Yoon & Luttrell, 1986). A fine particle <10 µm in size typically has low mass and low inertia and is unable to penetrate the streamlines around a bubble for collision and attachment to occur. Hence the probability of contact is often regarded as the rate-determining step in froth flotation for ultrafine particles (Weber & Paddock, 1983; Yoon & Luttrell, 1989).

Rule and Anyimadu (2007) demonstrated that after addressing liberation with Ultra Fine Grinding (UFG), an alarmingly high proportion of <10 µm and particularly <5 µm fully liberated Platinum Group Metals (PGMs) were being lost to tailings. This is consistent with the limitations of conventional flotation at finer size fractions. They commented that this problem was unlikely to be solved by introducing more power into conventional flotation cells and predicted that different flotation technology would solve this problem eventually. This is the pivotal point that we have arrived at today.

A LEFT OF CENTRE SOLUTION – CAVITATION IN FLOTATION

Thinking out of the box, are there other ways of bringing a bubble and a fine particle together apart from collision theory? Consider this, why not "grow" a bubble on a fine particle and so "Bring the mountain to Mohamed"? If this hypothesis can be proven correct, it would change the thinking around flotation mechanics.

One such way that this can be achieved practically is by hydrodynamic cavitation (Sobhy & Tao, 2013). According to Bernoulli's principle, when a liquid flows through a constriction the velocity increases causing the instantaneous pressure to fall. At a certain critical velocity the instantaneous pressure will fall below the vapour pressure of the liquid causing tiny cavities/bubbles to form on impurities in the liquid (Hu, Finch, Zhou & Xu, 1998).

In slurry systems, these impurities can be the hydrophobic mineral particles that we are trying to float. Hydrophobic mineral particles emanating from a milling circuit often have minute quantities of gas trapped on its surface which act as perfect nucleation points for cavitating bubbles. These cavities then violently implode into a multitude of pico-bubbles as soon as the static pressure increases. Cavities can be partially stabilised by diffusion of dissolved gases into the cavities and the addition of a frothing agent.

However, the pico-bubbles cannot provide sufficient buoyancy force to float mineral particles and hence the involvement of flotation size bubbles of 600–2000 µm is still required (Tao, 2005). Therefore it is suggested that the pico-bubbles be introduced into flotation cells to complement rather than replace flotation size bubbles (Nesset, Hernandez-Aguilar, Acuna, Gomez, & Finch, 2006). Haipeng (2014) showed that the aging of both pico-bubbles and flotation sized bubbles was detrimental to bubble/particle attachment and that future flotation aeration devices should emphasize the close proximity of pico-bubble and flotation size bubble generation.

GOLD ORE'S MACH REACTOR

This is achieved in Gold Ore's patented and proprietary Mach Reactor technology which employs a system of multi-staged cavitating venturis with air injection generating both pico-bubbles by cavitation and flotation size bubbles by the shearing of external air, creating the ideal environment for fine particle collection. In the high speed nozzles of the Mach Reactor, instantaneous pressure is reduced to below the vapour pressure of water causing “cold boiling” or cavitation to occur. Speeds of the bubbly mixture within the reactor approach the speed of sound – hence the name “Mach Reactor”. Figure 1 is a schematic of the Mach Reactor internal design.

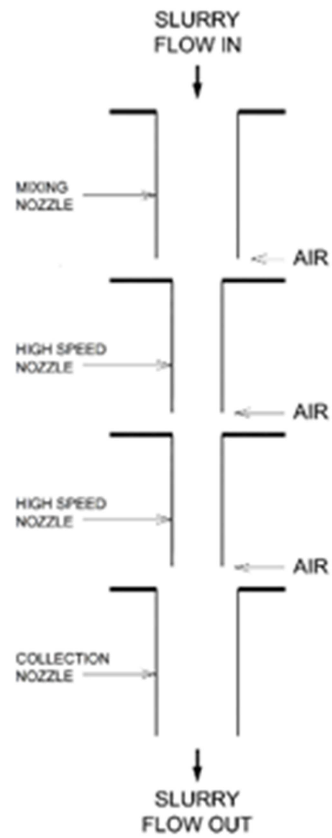

Figure 1 – Schematic of Mach Reactor internal design

The Mach Reactor design features a medium speed mixing nozzle feeding into two high speed cavitating nozzles which jet into a collection nozzle at the exit of the reactor. External air is injected between the nozzles. This design, which provides a range of bubble sizes from pico-bubble to flotation size bubbles, maximises the cavitation effect for fine particle collection in the high speed nozzles while also providing a relatively calmer environment in the collection nozzle to promote aggregation of fine particles via a proposed bubble bridging mechanism. The collection nozzle, which incorporates features of a plunging jet, also generates flotation size bubbles which attaches to particle-bubble aggregates to complete the collection process and provide for a higher rate of flotation in a conventional flotation cell (Zhou, Finch, Hu & Rao, 1997). In principle, fine particle collection takes place in the Mach Reactor while the conventional flotation cell provides the vehicle for the separation of froth from slime through levitation of the particle-bubble aggregates in accordance with the reactor-separator principle (Changgen & Bahr, 1992; Finch, 1995).

CONVENTIONAL FLOTATION IS THE FALL-BACK POSITION

While the reactor-separator system (Mach Reactor-Conventional Flotation) proposed in this paper has some resemblance to pneumatic flotation in concept, it has the significant advantage of being grounded by tried and trusted conventional flotation cells providing for easier industry acceptance. The Mach

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Reactors can be bypassed if required leaving the conventional flotation cells as the fall-back position. Retrofit applications to existing circuits are also easily executed making the concept available to old as well as new circuits.

THE BRINGING THE MOUNTAIN TO MOHAMED HYPOTHESIS

The Bringing the Mountain to Mohamed hypothesis, depicted schematically in Figure 2, can be summarised into three steps, as proposed by Gold Ore:

- Step 1: Nucleation
    - Cavity formation on a hydrophobic particle
    - Cavity stabilisation by gas and frother addition
    - Bubble frosting on the particle surface
- Step 2: Aggregation
    - Particles aggregate through a bubble bridging mechanism
- Step 3: Levitation
    - Presentation of a pseudo larger particle to flotation

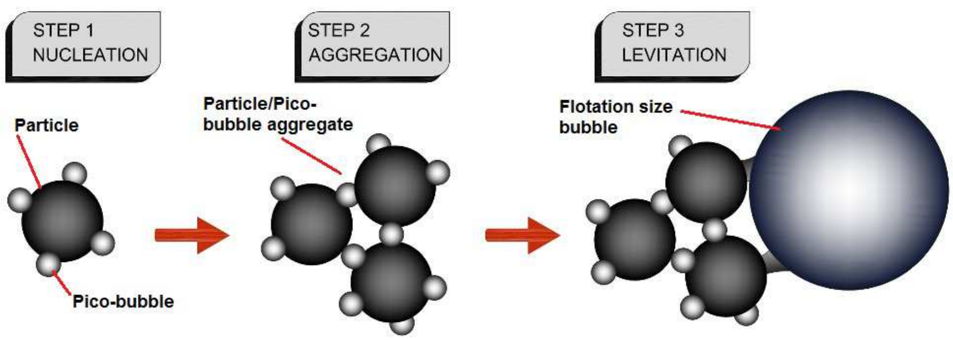

Figure 2 – Schematic of the Bringing the Mountain to Mohamed hypothesis

AND WHAT IF THE MOUNTAIN WILL NOT COME TO MOHAMED?

The Mach Reactor technology is a shear reactor that not only provides the cavitating environment for gas nucleation on hydrophobic particles but also:

- Higher gas flow and higher numbers of smaller bubbles when compared to conventional systems translating into higher S_b values
- Significantly higher shear and energy dissipation rates compared to conventional flotation
- Removal of oxidised layers, slime coatings and misplaced collector
- Emulsification and dispersion of flotation reagents
- Depression/oxidation of gangue minerals.

These parameters have already been shown to be critical for the flotation of fine hydrophobic particles by other researchers (Jameson & Goel, 2012) and provide a convenient fall-back position should the Mountain not come to Mohamed.

PLATMIN PILOT PLANT TESTWORK

Mintek Pilot Studies

In order to test the Bringing the Mountain to Mohamed hypothesis, a pilot scale plant was set up at Mintek allowing for a conventional flotation bank to be run either without reactor technology as a base case, or with Mach Reactor cavitation of the flotation feed. A scaled down Mach Reactor was installed on the feed to the pilot rougher bank. The pilot plant ran at 3 m^3/h using a bank of six 80 L flotation cells. A

4 t sample was used and time allocated to each run. The feed was sent through no reactor (base case) and through the Mach Reactor with a stabilisation time allowed for between each run. During each of the three runs samples were collected and mass and metal balances completed for each scenario. Only the rougher feed was processed via the Mach, but hot bench scale floats were conducted on the rougher concentrates produced in each of the scenarios.

Owing to the significantly higher gas hold-up achieved with the reactor run, residence times were correspondingly much shorter for the reactor run than for the base case run. For this reason it is more prudent to compare Kelsall k_{fast} factors for the base case and the reactor run respectively. Kelsall curve fitting gave a k_{fast} factor of 0.27 for conventional flotation and 0.75 for the Mach assisted flotation (Table 1) which represents a significant improvement of ~178% in flotation rate for the Mach assisted flotation over the base case.

Table 1 – Kelsall k_{fast} factors for conventional flotation and Mach assisted flotation

	Conventional Flotation	Mach Flotation
k_{fast}	0.27	0.75

The grade vs recovery curve (Figure 3) shows that significantly better concentrate grades were obtained with the Mach Reactor technology compared to the base case for the same recovery. Owing to the smelter requirements for concentrate grade, the improved enrichment ratios seen with the Mach were viewed as being pivotal to the success of the full scale plant.

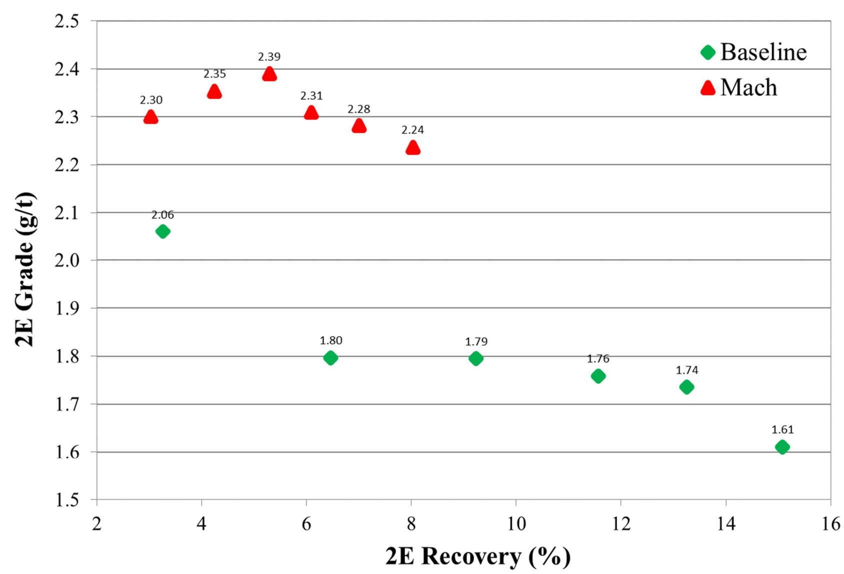

Figure 3 – Grade vs recovery for Mintek pilot plant work

The significant improvement in k_{fast} coupled with the significantly reduced residence time for the Mach run could also explain the improvement in enrichment ratios seen in Figure 3. A projection of recovery for equivalent mass pulls showed a ~4 % improvement in recovery with the Mach assisted flotation compared with the base case. Cleaner results obtained on the hot float bench tests produced from the rougher concentrates showed a significantly higher grade of ~25 g/t for the Mach Reactor compared with ~14 g/t obtained for the base case.

From the above it is clear that the Mach run provided for a faster flotation rate as well as higher enrichment ratios with higher recoveries when compared to the base case. The Mach appeared to have depressed the gangue flotation rate whilst simultaneously enhancing the PGM flotation rate for the same mass pull. On a production plant the mass pull is a variable that can be controlled by the operator, so it was decided to continue with full scale implementation of the Mach Reactors on the TSP plant.

Owing to the low grades of the material treated, a size by size recovery determination was not possible—however if one considers that the vast majority of liberated PGMs in the feed were in the <5 µm fraction it would be reasonable to conclude that the improvements noted with the reactor run may be attributed to the more efficient recovery of PGM fines.

PLATMIN FULL SCALE INSTALLATION

The Mintek pilot plant data (3 m^3/h) was used as a guide to a full scale installation (1,200 m^3/h) at Platmin's TSP. The TSP treats the flotation tails from the main concentrator plant at Platmin and recovers platinum from the material that would otherwise be pumped out to the tailings dam without further recovery. Platmin owns Pilanesberg Platinum Mines (PPM) located in South Africa on the Western Limb of the Bushveld complex which treats a mixture of Merensky and UG2 ore.

Mineralogical analysis of the tails from Platmin's main concentrator in Pilanesberg, South Africa, showed that the majority of PGM losses to the tails was in the <10 µm size fraction. Owing to smelter requirements on grade, the TSP includes cleaning, re-cleaning and re-re-cleaning circuits, with recycling of the cleaner tails, for final concentrate grade control. The objective of the TSP is to produce more PGE ounces for the same mining cost. Financial modelling showed this to be a robust project.

At the time of completion of the testwork, the design for the TSP was already in the advanced stages. The reactors were retrofitted to the design on the conventional flotation plant. Gold Ore Mach reactors were installed on the roughers while alternative shear reactors were installed on the cleaners and re-cleaners. Figure 4 depicts the flowsheet developed for the TSP plant.

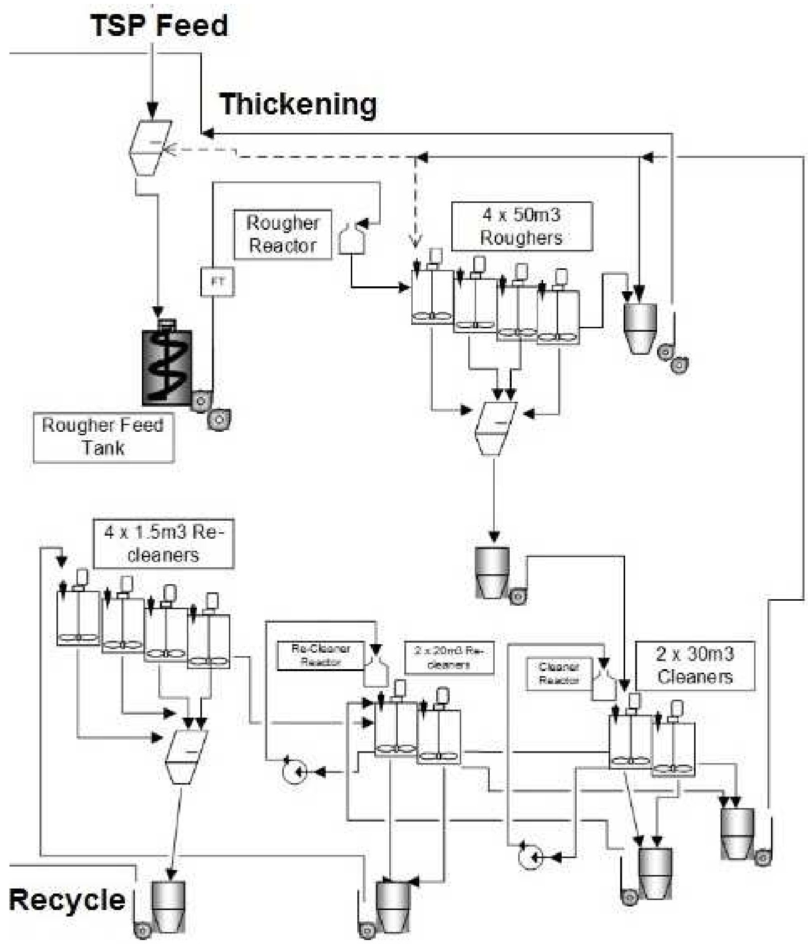

Figure 4 – Pilanesberg TSP flowsheet

Live tailings, at a nominal flowrate of 1,200 m^3/h, from the main concentrator plant is piped to a surge tank over a 4mm screen for trash removal. Xanthate, frother and a small amount of sodium silicate are added to the surge tank as required. The conditioned pulp is then pumped to the first rougher cell via three Mach Reactors. A fourth unit is stored on site should any of the units require change out. Life expectancy of the Mach Reactors is estimated at 5 to 10 years owing to a rugged HDPE shell lined with high quality ceramics. The smallest gap size on these units is ~91 mm, which should minimise blockages on the slurry side while the air ports are self-aspirating which minimises the risk of airline blockages. These attributes were considered in the adjudication process overseen by Platmin. The rougher reactors were viewed as being critical to the success of the project and would need to be capable of the relatively high flow requirements as well as being able to withstand the abrasive conditions created by the high chrome content of the feed material. The reactors on the cleaner and re-cleaner circuits on the other hand serve a supporting role to the rougher reactors and serve the role of enhancing concentrate grade. The feed to the cleaner and re-cleaner reactors would have a significantly lower chrome content and would be of a finer grind than the rougher feed material. Consequently the conditions in this circuit would be far less abrasive. Hence it was decided to run alternative shear technology on the cleaner and re-cleaner circuits. Running/standby units were installed using a fixed volume design.

Figure 5 details the arrangement of the rougher reactors with respect to the first rougher cell and shows the discharge from the reactors directed into the feedbox of rougher cell 1. This layout maximises the effect of the pico-bubbles produced in the reactor through further interaction with flotation size bubbles in the rotor-stator mechanism of the conventional flotation cell.

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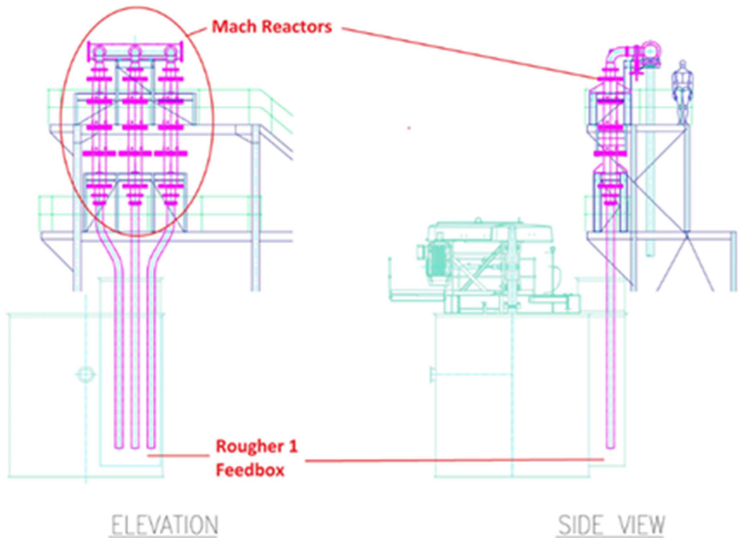

Figure 5 – General arrangement drawing showing the installation of the Mach Reactors on the first rougher cell

Figure 6 shows the general arrangement of all of the planned reactors with respect to the flotation cells. The reactors are installed in a central tower section with the rougher and cleaner cells on either side.

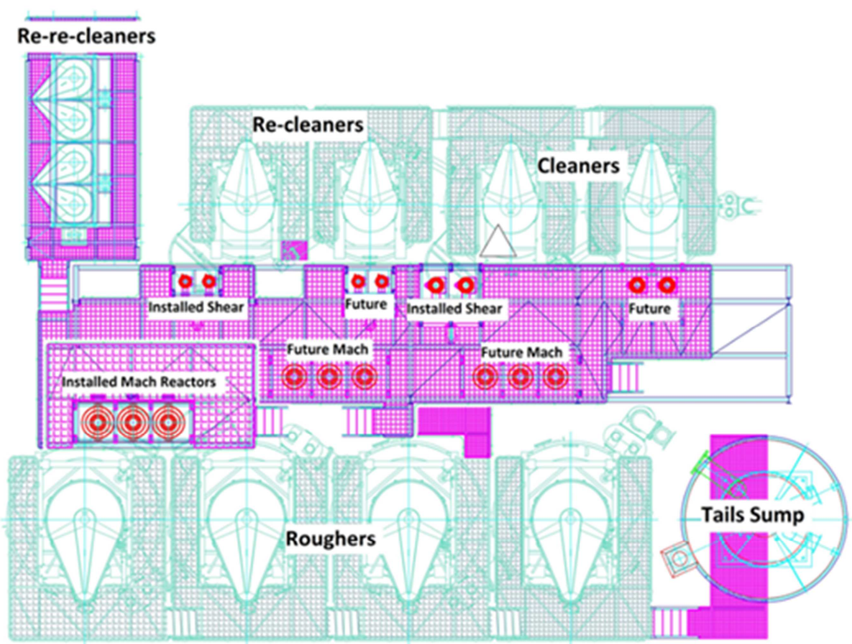

Figure 6 – General arrangement drawing showing the installation of all of the planned reactors with respect to the flotation cells

For the reactor installation on the cleaner circuits, feed to a recirculation pump was taken from a drain valve on the cell and channelled via the reactor back into the feedbox of the cell. This arrangement may also prove to be suitable for retrofit installations with minimal disruption to production.

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Platmin Full Scale Plant Observations

At the time of writing the TSP had been in continuous operation for ~3 months with minimum results available. No serious problems were experienced with the commissioning of the Mach Reactors and inspection of the reactor internals after 3 months of running showed no signs of wear. From visual observation it could be seen that the bubble sizes were significantly finer with the reactors online compared to when they were offline. The effect of the Mach Reactors on the roughers was visible even when the blowers were offline with the first rougher cell floating on the "reactorised" feed alone. Figure 7 shows photographs taken of the first three rougher cell concentrates being produced with the reactors online and with the blowers to the cells offline.

Rougher Cell 1 Rougher Cell 2 Rougher Cell 3

Figure 7 – Photographs of the first three rougher cells with the Mach Reactors online and the blowers offline

The effect of the rougher reactors with the blowers offline was most visible in the first rougher cell and dissipated as one moved down the bank. Bubbles significantly smaller than that obtained on a conventional cell were observed. This alludes to the fact that in addition to the set of reactors feeding the rougher bank, the remaining rougher cells should also have Mach Reactors running on re-circulation for maximum effect. The cleaning circuit was tuned to give a final concentrate grade of 20 to 30 g/t to be blended with high grade concentrate from the main plant before shipment to the smelter. The original process design criteria (PDC) estimated operating plant recoveries ~ 35% with a regrind ahead of the TSP. The client opted to build the TSP without the regrind. Despite the lack of regrind, actual plant recoveries achieved to date are in the order of 30% higher than the PDC estimates. The improved results were realised amidst unsteady plant conditions and fluctuating plant parameters. These early indicators show that the full scale plant installation is more than capable of outperforming pilot plant work and of meeting, if not surpassing, client expectations.

CONCLUSIONS

The following conclusions can be drawn:

- Early indications of the full scale plant observations of the Mach-Conventional Cell solution showed the system to be robust in terms of wear, easy to operate and maintain and forgiving with regards to changes in process parameters.
- The Gold Ore reactor-separator style solution to the flotation of mineral fines can be retrofitted to conventional flotation cells with relative ease.
- Early indications show that the full scale installation is more than capable of meeting the expectations set by the Mintek pilot plant work and is capable of delivering more concentrate ounces for the same mined cost in a sustainable manner.
- With regards to the Mach Reactor enhanced flotation system:
  - Improves the flotation of fine minerals
  - Significantly improves the Kelsall k_{fast} factor
  - Renders better enrichment ratios of the flotation system
  - Improves concentrate grades
  - Improves overall flotation recovery.

RECOMMENDATIONS

The following recommendations are made:

- The Mach Reactor-Conventional Flotation system is recommended for the flotation of mineral fines <10 μm in size at full scale operational plant level. The remaining three rougher cells at Platmin should be installed with reactors on re-circulation to maximise the beneficial effect of the Mach.
- Size by size analysis should be conducted on the production plant to evaluate the capabilities of the reactors to float the <10 μm particles.
- Froth washing should be considered for improved product quality and grade.
- Further tests should also be conducted at Mintek as part of ongoing research to investigate the addition of different gases to the Mach Reactor (e.g. oxygen and CO_2).
- Further research needs to be conducted on the effect of Mach Reactor enhanced flotation on the first order flotation rate constant on different ore types and the ability to enhance both the fine and coarse size fractions normally missed by conventional flotation.

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