DEVELOPING SOLUTIONS TO COMPLEX FLOTATION PROBLEMS

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ABSTRACT

Mining of low grade deposits along with the necessity to design and operate flotation plants with high throughput presents unique metallurgical and environmental challenges that need to be addressed to reduce project risks, improve project economics and to sustain the profitability of operations over the life of a mine.

Some of the key challenges include poor recovery of valuables and concentrate quality issues due to complex mineralogy, the need to use poor quality water such as brackish or sea water, reduce environmental impact from the process, integrate flotation with hydrometallurgy to maximize precious metals recovery, escalation of capital and operating costs, use of unproven technology and constant use of larger equipment, high ore variability, worldwide constraints on resource availability and an ever increasing need for reliable metallurgical input to financial models to evaluate economic viability of projects.

The need to develop effective solutions to these problems in a short time frame is becoming a key to the success of any new project and for sustaining the profitability of a mining operation. An integrated multi-disciplinary approach to problem solving is crucial with the need for a more lateral thinking along with strategic partnerships and collaboration involving the right players. This paper presents some of the key findings based on experiences from a large number of challenging projects and operations focused on solving complex flotation problems.

KEYWORDS

Mineral processing, flotation, operations optimization, plant design, innovation

INTRODUCTION

There are various challenges to successful development of mineral resources. Most of the ore bodies being developed worldwide are of lower grades requiring high throughput to be economical. Many of these lower grade ore bodies have significant occurrences of deleterious and penalty elements that could render a deposit unworthy of development unless there are technological solutions to process them economically in a sustainable manner with minimal environment impact. Even in a high metal price scenario, the economics for some of these low grade ore deposits is marginal. From a metallurgical perspective, these ore bodies have complex mineralogy and use of any off-the-shelf technology is not always effective. Development of innovative processes are often required, which is expensive, time consuming and sometimes risky.

This paper will provide a broader perspective on the steps involved in solving flotation problems for operating plants and for greenfield development projects. In addition, some of the key challenges in flotation of complex low grade ore bodies along with the economic benefits in developing solutions to these problems will be presented.

KEY STEPS TO FLOTATION PROBLEM SOLVING

Broadly speaking, there are three key areas where flotation problem solving in plants and development projects could result in significant benefits from a business perspective:

1. **Impact on Revenue**: Concentrate quality issues and losses of valuables to tailings are the key drivers that impact revenue. Optimization of the flotation process is critical and in several plants and projects, this optimization must be carried out in conjunction with comminution and classification efficiency. Majority of the research and development work in the past have focussed on this area, but there are still some major gaps in understanding the complexities involved with difficult ore bodies.

2. **Impact on Operating and Capital costs**: This is critical in situations where flotation problem solving needs to focus on reducing costs for projects to be economical. Not all costs are flotation related, but there are instances when a smarter circuit configuration, proper selection of flotation cells, reagents and comminution equipment, ability to use poor quality water that is available for the process, addition of flash, desliming or gravity circuits and better integration with down-stream unit operations such as leaching, dewatering and tailings treatment could be immensely beneficial in reducing capital and operating costs (Lane et al., 2005; Gorain et al., 2007; Gorain et al., 2008; Gorain, 2011).

3. **Impact on Environmental and Social License to operate**: This aspect is now-a-days critical and in many situations could determine whether an operation or a project can obtain the required permits to operate. Use of a greener flotation chemistry to replace toxic reagents such as cyanide to depress pyrite, sodium hydrosulphide (NaHS) or Nokes reagent along with nitrogen to separate molybdenum from copper minerals, triethylenetetramine (TETA) in nickel flotation to depress pyrrhotite and xanthates due to emission of foul smelling CS_2 gas (Somasundaran, 2012). In addition, the ability to adapt the flotation process to treat sea water or brackish water without the need to exhaust a local fresh water source for community use could be of significant value to a mining operation or project (Arowoshola, 2011).

Based on experience, there are five major steps involved in development of a flotation solution to a complex problem for one or more of the issues discussed in the three categories as discussed above:

Step 1: Problem diagnosis
Step 2: Testing potential solutions
Step 3: Identifying optimum solution

Step 4: Scale-up and large scale validation
Step 5: Plant implementation

It is important to note that each of these steps involve a different set of skill-set requiring the ability to identify the right techniques, tools or technologies and processes to enable proper evaluation and effective management of every step involved. This paper will provide only a brief description of the various aspects involved in the different steps.

Step 1: Problem Diagnosis

There could be several reasons for poor or sub-optimal flotation performance; some of the key reasons are listed below:

1. Poor or excess liberation of valuable and/or gangue minerals
2. Chemistry not optimum to allow effective separation of valuable and gangue minerals
3. Interference of floating non-sulfide gangue minerals such as talc and carbonaceous matter
4. Circuit configuration not optimum
5. Improper design of flotation circuits and associated units such as insufficient residence time, poor plant layout and infrastructure
6. Equipment performance of large flotation cells not optimum
7. Poor control of entrainment and other deportment mechanisms of non-sulfide gangue minerals
8. Cell hydrodynamics not optimum such as gas dispersion behaviour (bubble size, superficial gas velocity, bubble surface area flux) and energy dissipation (suspension of solids)
9. Poor froth flow behaviour and drainage
10. Flotation operating conditions not optimum such as slurry density
11. Flotation control strategy not optimum
12. Problems with using recycled and poor quality water along with solution chemistry issues due to very high soluble species content in certain ores; generation of iron species from grinding and use of sea or brackish water
13. Poor characterization of ore variability.

The first step in problem diagnosis is to narrow down the possibilities that lead to poor flotation performance. Experience is no doubt immensely helpful, but there is a growing need for a holistic approach with transparency in sharing data with various stake-holders involved to collectively agree and make a decision on the best path forward. Procuring the right set of data is an important skill to allow clarity and a deeper understanding of the problem. This data can be obtained through the following sources:

1. Existing plant data: Every operation or a project has a history and it is important to obtain the historical data to get a trend of the metallurgical performance in relation to ore variability, mineralogy, chemistry, grind and design. Geometallurgical characterization of the ore body is an important first step (David, 2010). Understanding the key challenges during the commissioning and ramping-up period provides some background on the limitations and capabilities of the existing circuit design. The impact of any plant modification, addition of equipment, changes in reagent schemes and grind sizes on plant performance help to provide a deeper understanding of the issues in plant design. The collective information of various process and mine personnel along with geologists also provide key data sometimes not available in reports or memos. Compilation of all existing plant data from previous plant surveys, on-site or off-site bench tests, information obtained from plant personnel, consultants reports and in-house memos is an important step to assist in the problem diagnosis process.

2. Plant surveys and measurements: Further plant surveys are sometimes necessary to bridge any gaps in information required to make meaningful diagnosis. This also helps sometimes to confirm previous findings on the present ores being mined and processed. Plant measurements such as densities, flow rates, kinetics and gas dispersion in flotation cells along with metallurgical data are

needed to help with the bench marking and to obtain new insights. Conducting regular plant surveys is well known as an industry best operating practice and should be part of any Key Performance Indicator (KPI) of an operation (Johnson, 2010; Greet, 2010).

3. Sighter bench testing: On-site bench testing helps to confirm existing plant findings and provides additional information on ore characterisation that are not easy to obtain from plant surveys. Also in many situations, making changes in a plant to study the impact of variables is not feasible as this is time consuming and costly especially if capital is involved and also could impact plant productivity. Bench tests, if calibrated correctly, could allow studies of many variables such as impact of grind size, reagent changes and circuit configuration on flotation performance. Some operations have their own specialized flotation cells and procedures to conduct ore floatability studies to allow prediction of future ores to be mined using drill core, chips or grab samples. These bench tests could be rougher kinetics, open cleaner and locked cycle tests.

4. Deeper probe or analysis of flotation products: It is common now-a-days to use sophisticated tools and techniques to carry out mass balancing, precious metal and deleterious metals deportment, liberation, modal, water and surface-chemistry studies to obtain a better understanding of the flotation problems (Buckley, 2010; Grano, 2010, Woods, 2010; Chattopadhyay & Gorain, 2012). These tools could range from Mineral Liberation Analyser (MLA), X-ray diffraction (XRD), Dynamic secondary ion mass spectrometry (D-SIMS), Time-of-flight - secondary ion mass spectrometry (TOF-SIMS), X-ray photoelectron spectroscopy (XPS), Laser ablation microprobe-inductively coupled plasma mass spectrometry (LAM-ICPMS) and many others. These measurements could be expensive and time consuming and therefore it is important to be prudent on representative sample selection with a clear purpose. Improper use of these tools could result in poor diagnosis and wrong interpretation.

Step 2: Testing Potential Solutions

Once the problem diagnosis step is completed, the reasons for poor flotation performance are narrowed down to a select few. In some cases, there could just be one key reason such as improper liberation of valuables in cleaner scavenger concentrate or activation of pyrite in rougher due to residual collector in recycled water. It is important that all conclusions be made through rigorous data analysis along with consultation with experts, colleagues or customers as the case may be.

Once the problem is clearly defined, bench testing is normally utilized to test potential solutions. It is best to assign a champion or form a group to work on problem solving. The best place to start will be to conduct a review of literature and also consult with experts in the field. A list of potential solutions should be prepared and carefully discussed to enable an effective experimental test program. Many operations and projects operate on a tight budget and it is important to develop priorities on test sequence starting with simple and easy to implement solutions. It is preferable to test ideas that, if implemented, will require little or no capital. This is not to suggest that a low-capital based solution is always the best, but could provide a solution to the problem in the interim. A solution involving significant capital and more complexity should be pursued only after the simpler options have been exhausted. As we develop better understanding and confidence with rigorous testing, it will be easier to get support from colleagues and senior management to pursue a more complex route.

1. Bench testing for problem solving could involve the following:
2. Reagent screening: collectors, promoters, frothers, depressants
3. Pre-flotation or de-sliming of ultrafines: non-sulfide gangue; split flotation
4. Optimization of operating conditions: density, air rate, impeller speed, froth depth
5. Inclusion of gravity or flash flotation for precious metals recovery (reducing sliming)
6. Impact of water quality and recyling
7. Optimization of primary grind or regrind for effective liberation
8. Cleaning circuit optimization including reconfiguration

9. Integration with leaching and hydrometallurgy to maximize recovery of valuables.

Statistical Design of experiments (DOE) is commonly used to reduce the number of bench test requirements and also to better understand the interaction effects between different variables (Napier-Munn, 2010). It is always better to obtain training or consult with an expert instead of just using software. There are many excellent references on bench testing protocols, plant practice, reagent selection criteria, flotation chemistry, flotation cell and circuit optimization procedures that are immensely valuable (Johnson and Munro, 2002; Thompson, 2002; Williams et al., 2002; Fuerstenau, 2007; Gorain, 2000 & 2007; Nagaraj and Ravishankar, 2007; Schwartz et al., 2007; Ralston et al., 2007; Tapia, 2008; Harbort and Schwartz, 2010).

A potential solution could also be trialled directly in plants for some cases when bench testing is not effective or when there is urgency to implement a solution. Control of froth pulling rates using froth cameras, changes in plant throughput to maximise flotation capacity utilization, use of a well known reagent such as CMC or guar gum to depress talc or dilution cleaning are some examples. In some situations, the outcomes of bench testing could be misleading due to the use of open circuit primary grinding in bench as the impact of sliming of heavy precious metals due to its high recirculation in plant cyclone underflow is difficult to reproduce in bench. Flash flotation testing in bench is therefore also challenging as the true impact of a plant comminution circuit is difficult to replicate.

Step 3: Identifying Optimum Solution

Once the bench testing to evaluate all potential solutions is completed, the next step is to identify the optimum solution. An optimum solution, however, could vary depending on the perspective of the stake holders involved in the process. In an operating plant or for a development project, an optimum solution could have a different connotation. The following are the different steps involved in identifying optimum solution:

1. Quantifying metallurgical benefits or improvements through statistical data analysis
2. Use of modelling and simulation techniques to investigate “what if” scenarios with a need for extrapolation of the available data to forecast certain situations
3. Impact of this solution to upstream and down-stream processes (value chain): ore variability, comminution, leaching, tailings disposal and concentrate marketing
4. Economics of the solution on Net Smelter Return (NSR), Net Present Value (NPV) and Internal Rate of Return (IRR) requiring smelter terms along with reasonable estimates operating and capital costs.
5. Simplicity and practicality of the solution; Ease of Implementation
6. Impact on environmental, social and permitting issues
7. Risk analysis with an understanding of the risk profiles for every step involved

It is common to see that in many investigations, the optimum solution is limited to quantifying metallurgical benefits and to an extent on the economics trade-off study. This strategy could result in selection of the wrong solution. Unless the evaluation process involves these seven steps, optimum solution from an overall business perspective will be difficult to obtain. In case of a low risk solution, where large capital is not required or when the impact of the solution outside of the concentrator is minimal, then a detailed evaluation of the six steps may not be necessary. The risk factors are often underestimated in identification of optimum solution and this is where cross-function involvement is important.

It is important to emphasise the need for involvement of various stakeholders in the decision making process along with a focus on risk mitigation strategy when there is a need for high capital requirement and also when the impact outside of the concentrator is considerable. These stakeholders should represent areas such as metallurgy, mining, geology, marketing, finance, environmental, water, energy and social responsibility from corporate, regional business units as well as operations. Companies that are best in developing optimum solutions are those that have a cross-functional team involving various disciplines. The key advantages for this strategy are that the process is transparent with effective communication, clearly defined benefits along with risks and also allows corporate to have a better justification of the capital expenditure to support such plant optimization or project improvements initiatives.

Step 4: Scale-up and Large Scale Validation

Once the optimum solution is put forward and there is a consensus by key players to move forward with allocated funds, the key is to make sure a validation of the solution is carried out on a pilot scale if the technology is new or if a large capital investment is required for full scale implementation. In fact this should be part of the risk mitigation strategy.

Scale-up of flotation from bench to full scale is quite challenging as the traditional scale-up factors are not always applicable to a complex ore deposit. The grinding is open circuit in bench and could lead to misleading size by size recovery of valuables in a full scale configuration involving cyclone classification. Also the full impact of recycling is not easily seen in bench even with locked cycle testing. The water chemistry along with impact of media wear on solution chemistry and flotation performance in a plant is also difficult to replicate in bench tests. In case of involvement of gravity and flash flotation, bench test results could be misleading as discussed earlier. The froth recovery and energy inputs in bench cells are also significantly different to plant cells. A properly designed pilot plant testing could help to better understand the impact of various variables involved in implementation of the solution.

It is important to note that even a large scale piloting also has it pitfalls. Many flotation pilot units in commercial laboratories use flotation equipment that are sub-optimal with little or no instrumentation to measure throughputs, air flows, power, reagent and slurry flow rates of flotation products. There is also minimal automatic control and the grinding equipment, media and liners used may not be optimum. Pilot plant trial is a specialized skill and requires trained personnel with clear guidance from the company champion. A mini or small scale piloting with throughputs typically from 10 to 100 kg/hr, though ideal for testing limited drill core samples, could be problematic if cyclones cannot be used in closed circuit with grinding. In addition, for low grade ores especially with precious metals, there is sometimes not enough concentrate flows to conduct proper surveys for metallurgical sampling and any survey of internal streams could disturb the circuit resulting in poor mass balances. A large scale piloting with throughputs ranging from 100 kg/hr to a few tonnes/hr has large sample requirements, which could be problematic for many greenfield projects.

Validation of a solution on a pilot scale is not trivial and requires some thorough investigation and discussion with experts to ensure the trials are carried out correctly to obtain meaningful results.

Step 5: Plant Implementation

There is no realized benefit until the solution is fully implemented in the plant. The first and foremost requirement is that that there must be a strong buy-in from the operations and the need for a site based champion is pivotal. The site must commit time and some dedicated plant personnel during this implementation process. The implications on various upstream and downstream processes must be studied as well to ensure a holistic view of the solution. Technology transfer is the key for a long term solution. Once the solution has been implemented in the plant, the metallurgists, the operators and other plant personnel must be trained with the site champion providing and receiving constant feedback to enable an effective communication. Just like issues during commissioning of a plant, the ramp-up could be initially slow and at times there could be serious setbacks at times. Sometimes there is a tendency to give-up efforts, due to constant drag of limited resources from plant production, without understanding the reasons for any failures or problems. At this time, some patience is warranted and it is even necessary to discuss the issues with external experts not bound with day to day production issues. It is not unusual to take 6 to 18 months for implementation to show any benefits. In many situations, incremental improvements in metallurgical performance in the plant could be easily overwhelmed by noises due to feed or operating variability, hence requiring the know-how of an effective plant trial such as to understand autocorrelation using proven statistical techniques

EXAMPLES AND BENEFITS OF A STEP-BY-BY APPROACH

Working extensively on these five flotation problem solving steps over the last 20 years on various complex ore bodies, the author is of the opinion is that the process works but only if the work is carried out diligently in a systematic manner. Though cost could be a major factor in skipping steps or cutting corners but ultimately a decision is required to ensure the process is seamless to maximize the benefits. The more one works on these steps, significant benefits could be realized but requires some perseverance, effective technology transfer and strong communication between various groups involved in the process. Collaboration and partnerships are critical, and it is important to make sure there is commitment from everyone involved

In the next section, some examples will be presented to show the various technical challenges involved in complex ore bodies and how developing solutions could transform the economics of projects and operations.

Complex Mineralogy

Figure 1 shows an example of double refractory gold ore with significant amount of finely disseminated pyrite along with inter-twined total carbonaceous matter (TCM).

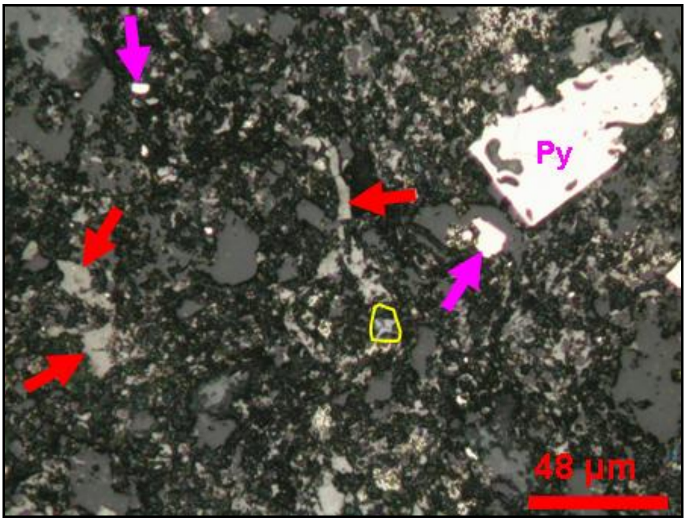

Figure 1 - Micrograph of a high preg-robbing refractory gold ore with fine pyrite and carbonaceous matter.

Figures 2a & b show that the gold associated with carbonaceous matter is lost in the tailings even after an extensive pressure oxidation treatment. These challenges are not uncommon and the solutions require a deeper understanding of the issues using emerging sophisticated tools and techniques. Sometimes the costs in carrying out the problem solving steps could be prohibitive, but then the risks of lost opportunities in not doing such work could easily outweigh the costs in the long run. In this situation, extensive research efforts were carried out resulting in development of a novel flotation process that could separate pyrite from fine TCM effectively for double refractory ores. The resulting cleaner pyrite concentrate is more amenable to pressure oxidation and leach recovery due to lower preg-robbing behaviour. Due to confidentiality, the process and the results from this work will not be presented but the message is clear that problem solving efforts, though costly and time consuming, is well worth the effort as a long term strategy.

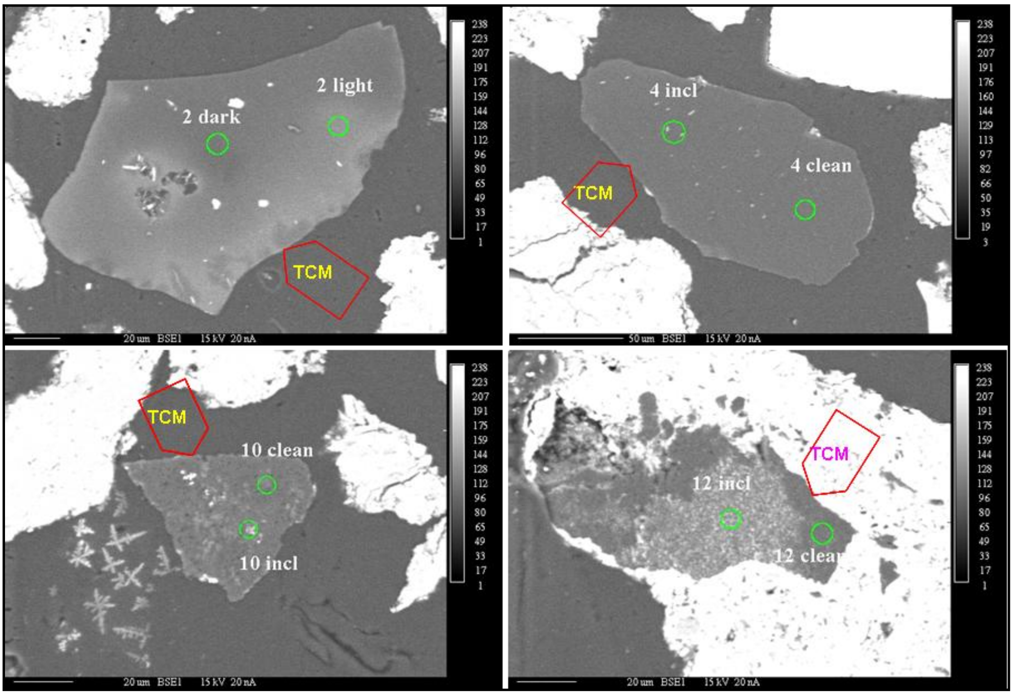

Figure 2a - Back scatter imaging of sulfide inclusions in total carbonaceous matter (TCM) in the process plant feed

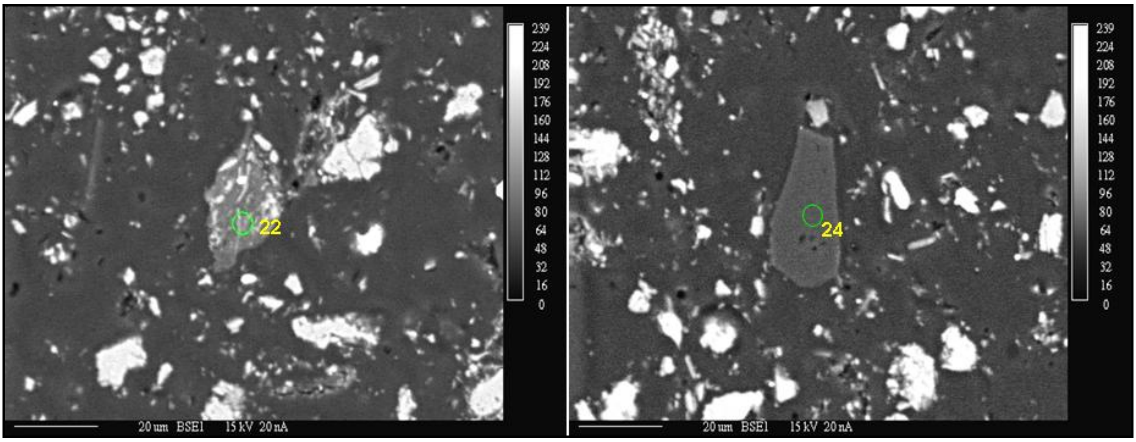

Figure 2b - Back scatter imaging of sulfide inclusions in total carbonaceous matter (TCM) in the process plant tailings

High Ore Variability in Operations

Figures 3a & b show the flotation recovery and tailings grade trend for a gold operation. A systematic declining trend in gold recovery is evident with recovery decreasing from 90 to 96% in January 2007 to 86 to 92%, with an average of about 4-6% decrease in gold recovery. This is due to increasing complexity and variability in ore types, which is becoming more common in many operations.

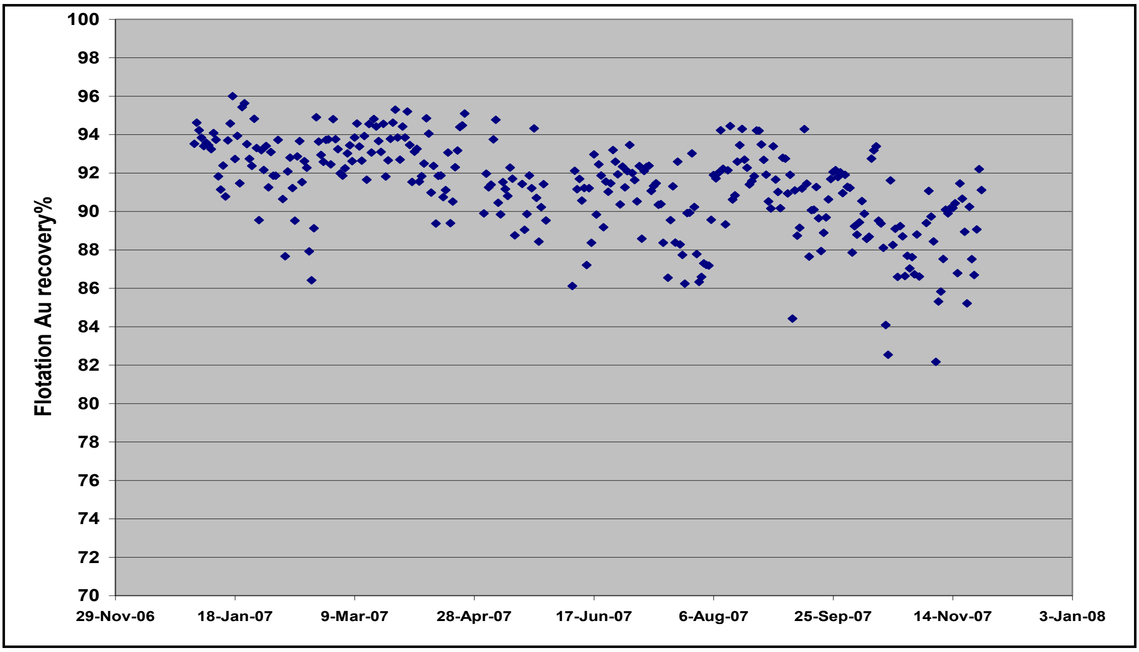

Figure 3a - Flotation gold recovery trend in a refractory gold operation

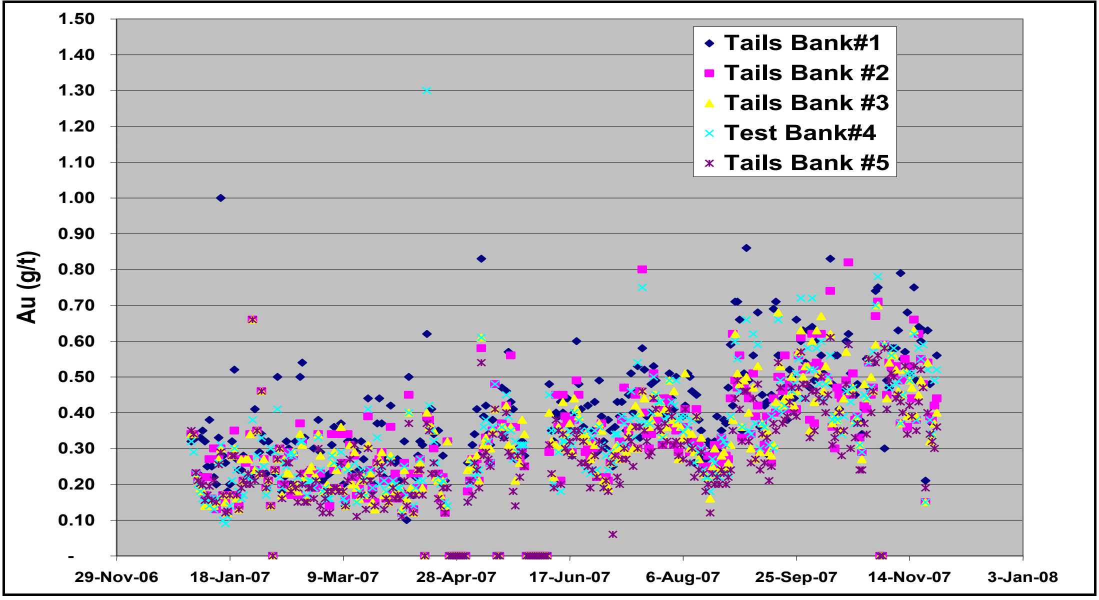

Figure 3b - Fluctuation of gold grade (g/t) in flotation tailings in a refractory gold operation

Figure 3b shows that the gold grades in the flotation tailings are also increasing steadily suggesting the inability of the plant to provide a tighter control of gold losses. Figure 3b also shows the tails grade fluctuations within a short period of time is high varying from about 0.2 to 0.6 g/t or more, suggesting that the bank controls are inadequate. The lost opportunity in good recovery was least 2 -3 % on a day-to-day basis.

A major problem solving program was carried out that suggested that these gold losses are mainly due to losses of fine pyrite (< 20 μm) in flotation tailings. The solution was simple requiring addition of a small amount of copper sulphate in the primary mill to prevent losses of fine pyrite. Plant trial, managed entirely by plant personnel, showed an increase in gold recovery of about 1.5%, which translates to an additional revenue of about $15 million per annum. Importantly, the addition of copper sulphate also benefitted recovery of zinc, lead and other metals that previously reported to tailings with some environmental implications.

It is interesting to note that a more complex solution involving flash flotation requiring major capital and time for implementation could also have been equally effective as shown in bench work, but this was ruled out based on evaluation of the seven stages involved in step 3 of problem solving. This is an example that demonstrates that a step-by-step approach to problem solving is the key to develop an optimum solution

Flotation Benchmarking with Limiting Grade Recovery Curves

Benchmarking an operating plant and developing the KPI’s are key for continuous plant improvements. Limiting grade-recovery curve is an important bench marking tool for an operation and even for a greenfield project. This is typically obtained using mineral liberation data or modal analysis generated from MLA, Qem*Scan or automated optical microscopy. This is also commonly known as mineralogical limiting grade-recovery curve and is a function of grind or particle size. Various mineral liberation classes are used in this analysis. The maximum grade of a mineral is obtained from the fully liberation class data (eg. 90 to 100% mineral liberation) and the associated recovery is the proportion of the fully liberated minerals in the ground ore. This provides the data for one end of the curve. Then the next liberation class (eg. 70 to 90% mineral liberation) is combined with the fully liberated class to obtain the second point in the cumulative grade-recovery curve. The remaining liberation classes are cumulatively added to build the curve and the other end of the curve represents the feed with the head grade of mineral with 100% recovery.

The actual plant grade-recovery curve is always below this limiting curve. A comparison of the actual and limiting grade-recovery curve helps us to evaluate plant’s present flotation performance and the difference between the two represents economic opportunity. Quantifying limiting grade-recovery curves for various ore types helps us to understand the metallurgical variability and improvement possibilities. Even better, if the grade-recovery curves can be tied up with iso-economic curves for maximizing operating profits.

An example of the limiting grade-recovery is shown for a copper-gold operation in Figure 4. The limiting grade-recovery curves for three different size fractions are showing along with the overall profile.

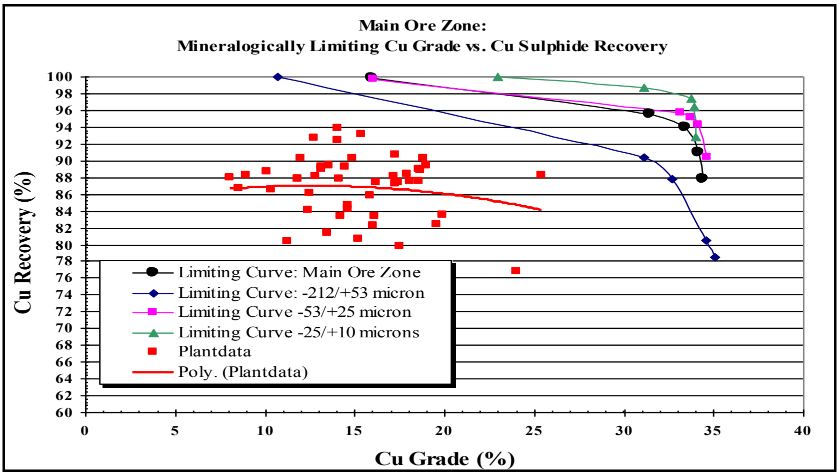

Figure 4 - Comparison of the limiting grade-recovery curve and actual plant operating data for a copper-gold operation

There are four major factors responsible for poor flotation performance resulting in a grade-recovery curve falling significantly below the limiting curve.

1. Chemistry: typical examples are depression of minerals due to reagent dosage problems, slimes coating and formation of iron hydroxide species on mineral surfaces.
2. Machine: typical examples are poor flotation of ultrafine or very coarse particles due to improper bubble size and turbulence generated in the flotation cells
3. Froth recovery: typical examples are poor recovery of the minerals due to detachment of minerals in brittle froth, long transportation distances in large flotation cells.
4. Entrainment: typical examples are high pulling rates in cells, activated non-sulfide gangue minerals, slimes coating.

The first step in optimization of flotation plant performance is to quantify mineral deportment in concentrates and in tailings:

- Size by size analysis: This helps to understand the problematic size fractions.
- Size-by-liberation analyses: This is a higher level analysis aimed to quantify the losses in various size and liberation classes.

Once we have quantified the mineral recovery and losses to concentrate and tailings, respectively, the next step is to understand the reasons for this improper deportment, mainly to see if this deportment is due to chemistry, machine, froth or entrainment factors. There are several tools and techniques available to understand the reasons for this improper deportment.

Synergy of Flotation with Leaching

In many copper-gold ores, gold is mainly associated with pyrite. Hence depression of pyrite to make a saleable copper concentrate results in significant gold losses. Leach plants are often required to recover gold from tailings as shown in Figure 5.

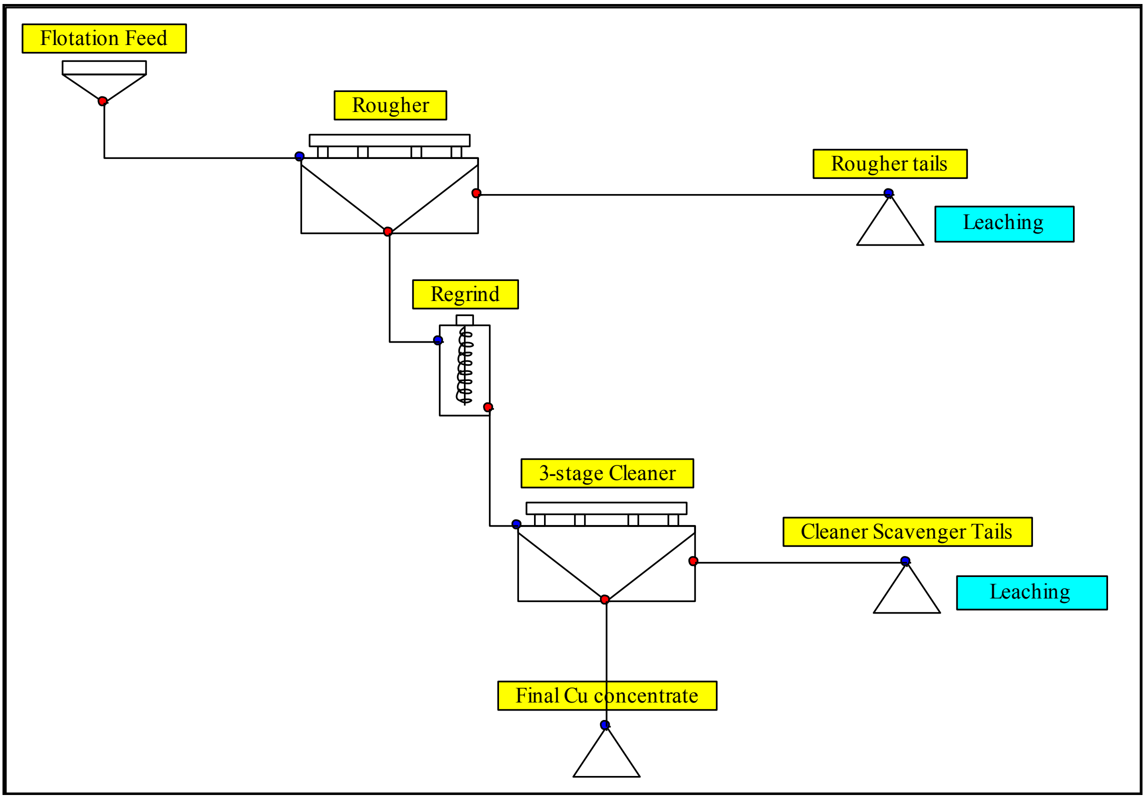

Figure 5 - Flotation program flow sheet showing the need for leaching to maximise recovery of gold for a copper-gold ore

Many of the work carried out for copper-gold ore suggest an optimum copper concentrate grade to maximise overall gold recovery. Figure 6 shows a strong correlation between copper concentrate grade and overall gold recovery (flotation and leach), with gold recovery increasing rapidly with decreasing copper concentrate grades.

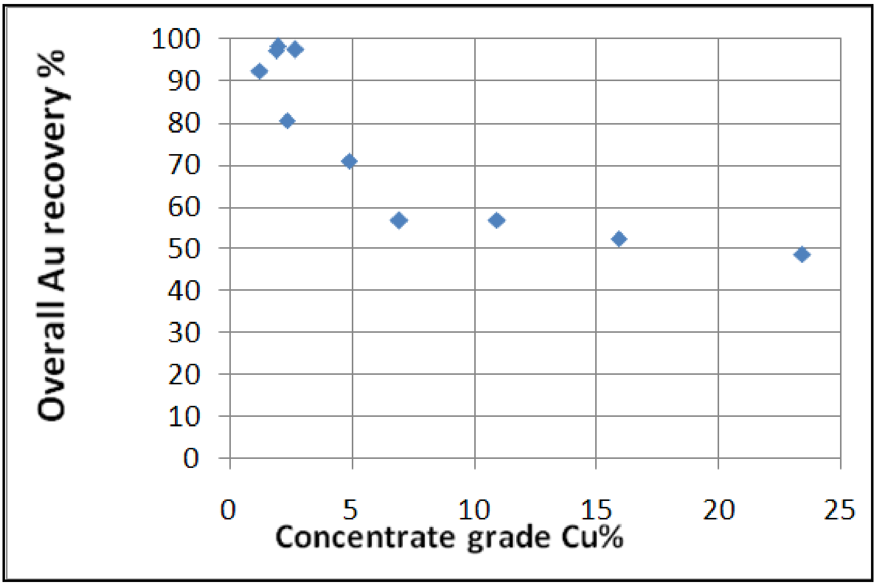

Figure 6 - Relationship between copper concentrate grade and overall gold recovery (flotation and cyanidation).

Quantitative gold deportment studies for some copper-gold ores have showed the presence of high amount of invisible gold as solid solution in pyrite, the values ranging from 25 to 60 % depending on the ore type. This has important implications as this gold in pyrite was shown to have poor leach behaviour. Depression of gold bearing pyrite in flotation, to produce a high grade copper concentrate, may not be favourable due to high gold losses during cyanidation of flotation tailings. Ideally, a lower grade copper concentrate production will be better for an overall gold recovery perspective with the assumption that this lower grade concentrate is marketable and the Net Smelter Return (NSR) favourable. It is important that the flotation process be designed and optimized to meet the needs of downstream processes.

It is often seen that just focusing on the mine and the concentrator may not result in value maximization unless they are integrated with the down-stream processes. Many Barrick operations treating copper gold ores have an integrated copper flotation and gold leaching circuits to maximize gold recovery. This allows production of a saleable copper concentrate but importantly reduces copper deportment to the leach circuit resulting in lower cyanide consumption and cyanide destruction costs along with higher gold recovery. This demonstrates the fact that flotation problem solving must also involve integration of down-stream processes resulting in significant value addition.

Flotation Circuit Design using Modelling and Simulation

The conventional approach to designing flotation circuit focuses on the use of safety factors in scaling-up residence time obtained from bench scale test work. Typically the safety factors range from 2 to 4 depending on ore type, personal preference and inventive guesswork. There is no scientific basis for selection of this scale-up factor although several practitioners have hypothesized the scale-up factor to relate to power input and froth recovery factors. There are several instances of underestimation of flotation capacity leading to the operating plant not capable of meeting the metallurgical design target. This could be a very risky proposition leading to lost opportunities due to production losses and the need for further capital expenditure for additional flotation capacity. The reason for high risks in conventional design is that the safety factors are based on previous experience on simpler ores whereas most of the present ores deposits are metallurgical complex requiring a deeper understanding of the mechanisms that drive flotation performance.

Flotation modelling and simulation techniques have recently emerged as a scientific tool that provides a more rational basis to design of flotation circuits (Gorain and Stradling, 2002; Herbst and Harris, 2007). This initiative has been driven by some of the major mining companies mainly to increase the confidence level in designing flotation circuits with minimal risks. This also allows simulation of "what-if" scenarios mainly to understand trade-off between incremental recovery and flotation capacity requirements or capital expenditure which helps in optimization of flotation circuit. Once a robust model has been developed for a deposit, simulations can be done to understand the effect of ore variability and circuit configuration on flotation performance. Flotation modelling and simulation techniques, although based on scientific basis, are not perfect due to difficulties in modelling complex ore types. The assumptions made for simulations should be carefully judged for better confidence in model predictions.

The author has extensively worked with JKSimFloat flotation simulator for many flotation circuit design assignments. JKSimFloat is a tool developed over many years involving many researchers and its robustness is based on rigorous validation at various operations including refractory and PGM ores. The JKSimFloat database has extensive plant measurement data for rougher and cleaner circuits along with cell hydrodynamic measurement data for various cell sizes and types. This allows parameter estimation with a higher level of confidence. In addition, the JKSimFloat predictions have been found to validate well with plant performance.

The JKSimFloat modelling is based on the model developed by the AMIRA P9 project. The model separates the effect of ore floatability, machine and froth behaviour from the overall flotation rate constant (a lumped parameter), which is explained below:

1. Ore floatability (P): P is dependent on inherent floatability of the ore representing the mineral liberation and flotation chemistry behavior.
2. Machine characteristics (Sb): Sb is a function of bubble size generated by the flotation cell and superficial gas velocity (dependent on air flow rate and cell cross-sectional area)
3. Froth characteristics (Rf): Rf is a function of the froth selectivity and transportation behavior which in turn are dependent on reagents such as frother affecting froth behavior, mineral properties in the froth phase, cell lip length and transportation distance.
4. The gangue entrainment effects are also characterized by separating the flotation rate constant due to true flotation and due to entrainment

Four floatability components viz. fast, medium, slow and non-floating are typically used by the author to model different ore types. The estimated froth recovery numbers could range from about 25% for the first cell in the Rougher bank to about 5% for the last cell in the Rougher bank for some gold ores. Gangue entrainment could also vary significantly for different ore types depending on the reagent scheme, cell type and cell operating conditions. Estimation of entrainment in some pilot runs could be problematic due to very low slurry densities used along with high dosage of frothers sometimes used in pilot runs and therefore caution should be exercised when interpreting survey data.

Working with various precious metal ores, the author is of the opinion that gold and sulphide minerals consist predominantly of fast and slow-floating species. The non-sulphide gangue minerals also consist of some fast-floating and slow-floating species but predominantly non-floating. An example of floatability parameters determined for one complex refractory gold ore is shown in Table 1.

Table 1 - Rougher feed floatability parameters for life-of-mine composite sample for a complex gold ore.

Mineral	**Flotation Rates**			**Floatability Mass Percentages**		
	Fast	**Slow**	**Non**	**Fast**	**Slow**	**Non**
Gold	$1.11E^{-03}$	$4..16E^{-05}$	0.00	78.2	16.0	5.8
Sulphur	$1.11E^{-03}$	$3.59E^{-05}$	0.00	90.1	7.2	2.7
NSG	$7.0E^{-04}$	$1.88E^{-05}$	0.00	1.8	33.3	64.9

Extensive work with different refractory gold ores suggests that bimodal distribution of gold bearing sulphides is not uncommon. In some cases, the Mill-Chemistry-Float-Mill-Chemistry-Float (MCF2) flow sheet could perform better than the conventional one stage grinding-flotation circuit as shown in Figure 7 for one complex refractory gold ore.

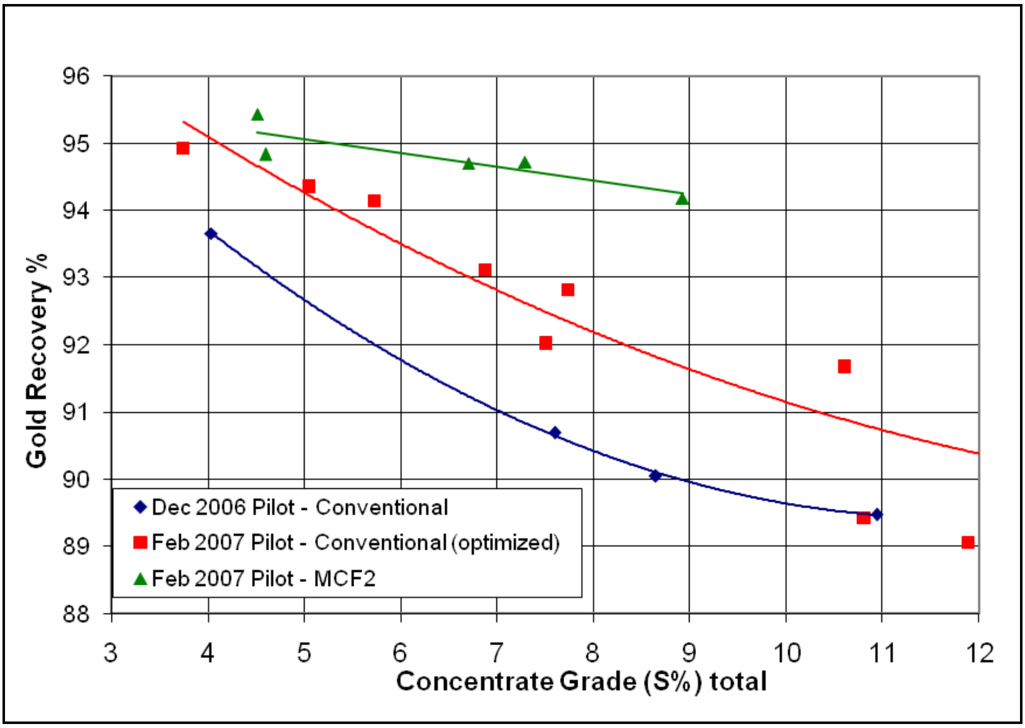

Figure 7 - Comparison of gold recovery for conventional and MCF2 flow sheets during a pilot plant run of a complex refractory gold ore

The floatability parameters for the secondary rougher feed after a secondary grind in a MCF2 configuration is shown in Table 2.

Table 2 - Secondary rougher feed floatability parameters for life-of-mine composite sample for a complex gold ore

Mineral	Flotation Rates			Floatability Mass Percentages		
	Fast	Slow	Non	Fast	Slow	Non
Gold	$1.11E^{-03}$	$4..16E^{-05}$	0.00	0.1	67.7	32.2
Sulphur	$1.11E^{-03}$	$3.59E^{-05}$	0.00	0.2	67.8	32.0
NSG	$7.0E^{-04}$	$1.88E^{-05}$	0.00	0.1	35.2	64.7

Various simulations are typically carried out using different throughput, circuit configuration, bank residence times, cell numbers and sizes, cell operating and hydrodynamic parameters. In one of the projects, economic evaluation was carried out using these scenarios to identify the cost effective circuit design. The MCF2 flow sheet showed at least 2% increase in overall gold recovery for greater than 7% S in concentrate. The improvement in NPV for the project was about US$90 million. This again highlights the fact that a systematic approach to flotation problem solving using necessary tools and techniques could result in significant improvements in project economics

The AMBS process: Impact on Poor Quality Water and Environment

A major test program was carried out for a major copper-gold project with an aim to replace the conventional cyanide and lime based scheme due to concerns of the use of cyanide in an environmentally sensitive jurisdiction where the project is located. The use of brackish site water and sea water was problematic due to pH buffering effects with the use of lime resulting in poor metallurgical performance. Extensive R&D effort was initiated to understand the reasons and to develop a practical solution to the problem. This work included detailed mineralogy, water and solution chemistry evaluation along with testing of various conventional and non-conventional reagent schemes to obtain a deeper understanding of the issues.

A new Aeration-Metabisulfite (AMBS) scheme was developed that resulted in significantly better recovery and grade at natural pH with no need for lime and cyanide.

The AMBS process involves aeration after regrinding of rougher concentrate along with recycled cleaner circuit streams for about 30 minutes followed by staged addition of sodium metabisulfite (MBS) in the cleaners without any pH adjustment using lime. The fundamental reason for including the aeration step is primarily to improve the kinetics of copper minerals and not necessarily to oxidize pyrite as commonly believed. The aeration step also provides the optimum electro-chemical potential (Eh) to make it possible for the MBS to depress pyrite without lime. This combination of aeration with MBS without any addition of lime in the cleaning duty without any pH adjustment is a novel way of separating copper minerals from pyrite when site water poses flotation chemistry problems. Table 3 shows the impact of AMBS process with use of brackish water for a major copper-gold ore.

Table 3 - Comparison of the flotation performance for a copper-gold ore using the AMBS and lime/cyanide schemes using brackish site water

Lime/cyanide process			AMBS process		
Concentrate Cu%	Cu Recovery%	Au Recovery %	Concentrate Cu%	Cu Recovery%	Au Recovery %
30.3	85.7	75	31.3	92.1	75

Table 4 compares the results of the cyanide and AMBS schemes for three different ore types. As shown in the table, the AMBS scheme gave significantly better flotation performance than the cyanide scheme

Table 4 - Comparison of the locked cycle results for three ore types using cyanide and AMBS schemes

Samples	Schemes	Head Cu%	Mass Pull %	Concentrate Cu%	Cu Recovery %
A	AMBS	0.48	1.36	35.1	92.2
A	Lime/Cyanide	0.48	1.31	33.0	86.7
B	AMBS	0.53	1.62	35.6	91.1
B	Lime/Cyanide	0.53	1.73	34.9	88.4
C	AMBS	0.31	0.90	36.1	90.0
C	Lime/Cyanide	0.31	0.84	37.0	84.4

Another major test program was carried out for a different project to identify opportunities with the AMBS process to improve the flotation performance previously obtained with the conventional lime scheme using sea water. Table 5 compares the benefit of the AMBS scheme with the lime based scheme using site water and sea water.

Table 5 - Flotation results of the AMBS and lime schemes for using site and sea water

	Lime Scheme			AMBS scheme		
Water Type	Conc Cu%	Cu Recovery%	Au Recovery%	Conc Cu%	Cu Recovery%	Au Recovery%
Site Water (locked cycle)	27.6	79.5	62	31.2	87.3	62
Sea Water (locked cycle)		poor flotation		30.2	86.6	58.7

Table 5 shows that the AMBS process improved copper recovery by about 7% with significantly better concentrate grade. Importantly the flotation performance of the lime scheme with sea water was poor due to buffering of slurry pH at around 9 resulting in its inability to depress pyrite. The AMBS scheme, however, did not show a significant detrimental effect on flotation performance. This confirms the robustness of the AMBS scheme in depressing pyrite at natural pH even for poor quality water as previously observed for other ore types ores.

This AMBS process was further tested for another challenging project. The problem is that the ore contains a significant amount of soluble copper and iron minerals resulting in a slurry pH of 1.5 to 3 after primary grind. A significant amount of lime is required with the conventional lime flotation scheme resulting in precipitation of various species with a negative impact on flotation selectivity. A major test program was initiated on five major ore types along with two composites to optimize the flotation performance using the AMBS scheme. After an initial open cleaner circuit optimization, a large number of locked cycle tests and piloting work were carried out on individual ores and composites. Table 6 summarizes the overall recovery with the AMBS process when compared with the conventional lime based process.

Table 6 - A summary of the overall recovery with the AMBS and lime schemes for complex copper-gold-silver ores

	Cu Recovery%	Au Recovery%	Ag Recovery%
Lime Scheme	80.0	83.5	84.3
AMBS Scheme (pilot)	86.9	92.8	84.5

Table 6 shows the AMBS scheme gave significantly better overall metallurgical performance than obtained with the lime based flotation scheme for a similar copper concentrate grade. These ores contain a significant amount of refractory gold and therefore improving gold recovery in copper flotation was found to be beneficial as the pyrite associated gold was difficult to leach in the flotation tailings. It is important to note that the AMBS scheme worked well even at a low natural pH despite the complex solution chemistry in flotation.

The AMBS flotation process has now been validated for a number of ore types. The key feature of this process is that the depression of pyrite in cleaner flotation is possible at a natural pH of the ore without the need for conventional pyrite depressants such as cyanide and lime. The AMBS process was effective even for complex copper and copper-gold ores with a high iron to copper ratios. Importantly, the AMBS process also works well when poor quality water, such as brackish or high salinity water, is used in the flotation process. In poor quality water, the lime scheme is not effective in depressing pyrite as obtaining a high slurry pH of 10 to 11 is difficult due to pH buffering effects.

Table 7 shows the economic benefits of the AMBS for one of the major copper-gold projects. The Net Present Value (NPV) presented here are estimates only with an aim to demonstrate the opportunities with flotation problem solving.

Table7 - Key economic metrics for the cyanide and AMBS schemes

Cu price: $1.9/lb Au price: $725/oz	Life-of-Mine	Cyanide Scheme (US M$)	AMBS Scheme (US M$)	NPV Increase with AMBS Scheme (US M$)
After tax	NPV (0%)	11,139	12,779	1640
After tax	NPV (5%)	697	1143	446
Before tax	NPV (0%)	15,124	17,223	2099
Before tax	NPV (5%)	1487	2016	529

Table 7 shows that the AMBS scheme increased the project NPV by about US$ 1.6 billion (after tax) and about US$ 2.1 billion (before tax), both using an undiscounted rate. Using a 5% discount rate, the NPV increase was about US$ 446 million (after tax) and US$ 529 million (before tax). The improvement in economics can be attributed to an increase in copper revenue as the copper recovery was almost 6% higher for the AMBS scheme than for the cyanide scheme.

CONCLUDING REMARKS

The above examples demonstrate that a rigorous approach to flotation problem solving is the key to develop environmentally friendly solutions along with major economic benefits. A five-step systematic approach to problem solving is presented that is applicable to both operating plants and greenfield development projects. Each step involves a different set of skill-set and there is significant amount of knowledgebase, expertise and technologies available to assist in proper evaluation and management of every step involved. Important attributes for success involve perseverance, risk evaluation, effective technology transfer and strong communication between various stake-holders involved. Collaboration and partnerships are critical for realizing the benefits through plant implementation, and it is important to make sure there is commitment from everyone involved including corporate, regional business units, operations management, operating team and external consultants.

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