Flotation data for the design of process plants Part 1 – testing and design procedures

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This paper discusses the methods used in the design of flotation plants, including benchscale batch and locked cycle tests and pilot plant trials. The methods used to establish appropriate flotation circuits as well as the interpretation of the test work data are also discussed in this paper. Careful and appropriate sample selection must be followed by equally carefully designed and executed flotation test work if a successful outcome is to be achieved. These steps are detailed and the correct use of each type of test and the information which can be obtained is described. Practical design considerations such as flotation time, type, number and size of flotation cells, and the means of froth transport are all important and appropriate test work can guide decisions on all these factors.

Keywords: Base metals, Flotation, Test work, Recovery, Mineralogy, Liberation, Flowsheet

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Introduction

This paper discusses the steps associated with the development of a flowsheet, from mineralogy through test work, equipment selection to plant design.

Irrespective of the project, the development of the optimum flotation process is reliant on four key factors:

- understanding of the geology and associate mineralogical variations that impact on metallurgical performance
- definition of the mining method and the relationship between the ore reserve and mine production
- evaluation of mineral and water chemistry which can affect the flotation process
- completion of adequate metallurgical and process test work to allow the design of flowsheet, reagent scheme and process control requirements.

Steps in the development and design of a flotation circuit

Background

There are many papers in the literature that discuss the development and design of flotation circuits for mineral concentrators. These range from texts of 'biblical status' such as Taggart[1] to research oriented texts such as MacDonald and Brison[2] to more applied papers such as MacDonald *et al.*[3] and Bulatovic.[4] This paper describes the outcomes of the authors' experiences in the development of base metal projects in Australia.

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Sample selection

The first stage of process design is a thorough review of the geology and mineralogy of the deposit. Mining methods and mine plans/schedules need to be assessed when selecting samples for the various phases of the flotation test work programme. Ore selection must take account of the fact that orebodies are not homogenous and consequently flotation response will vary within the deposit. Changes in head grade, value and gangue mineralogy and redox profile will lead to changes in flotation response. The basis of sample selection includes the following:

- rock type and rock alteration
- mineralogical characteristics
- ore depth and redox profile (oxide, transitional, supergene hypergene)
- geological model and ore deposition theory
- chemical assay, or grade
- mine schedule.

Sample types

Three major sample types are typically chosen.

Samples are selected for initial reagent definition to achieve the desired mineral separation. Separation may be a simple bulk float (i.e. pyritic gold ores, some copper ore with negligible pyrite) or as is the case for polymetallic ores, a complex multistage sequential separation (i.e. copper, lead, zinc).

Variability samples are selected to assess orebody variability on the basis of known physical and chemical characteristics. As an absolute minimum, samples should be selected on the basis of spatial distribution in the orebody if no other characteristics that indicate variable flotation response are apparent.

Bulk samples are usually selected for pilot plant trials or large scale flotation tests. The extent to which the sample is representative of the ore requires careful

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consideration.[5] The 'representative sample' is useful for development of a general flotation procedure, but additional testing may be desirable on individual samples from various areas or depths of the deposit to establish the optimum conditions in each case and to obtain mill design data valid over the expected range of ore variation. Obtaining only a single bulk sample from a large drill hole, winze, trial pit or development face is an option. However, unless the relationship between the metallurgy, mineralogy and geology of the bulk sample can be related to the variability test work then it is not recommended.[6] This is particularly important with massive sulphide orebodies where deleterious penalty elements may only be found in particular structures/ areas and not observed in bulk samples used to provide concentrate samples for market assessment. Furthermore, ore types that perform poorly on their own may be 'masked' if combined with ores having good flotation response.

Fresh diamond core or mined rock (occasionally available in 'mature' orebodies) is preferred for laboratory flotation test work. The use of reverse circulation drill chips should be avoided due to the oxidation of minerals, stratification of heavy particles, loss of softer components and fines and overproduction of fines. Generally, reverse circulation drill samples provide unrepresentative metallurgy. Ore samples that are prone to oxidation (i.e. massive sulphides and pyrrhotite ores), and require storage for future test work should be stored at low temperature ($<4^\circ$C).

Flotation test work and flowsheet development

Test work definition

The purpose of a flotation test work programme is either diagnostic (in the initial evaluation and development phase), to develop design parameters (for an engineering phase), or for modelling purposes (for geometallurgical block modelling or performance forecasting). As such the test work aims to define one or more the following:

- valuable mineral kinetics and separation response (from gangue minerals)
- valuable mineral recovery and grade of the saleable concentrate
- type and quantity of deleterious elements (e.g. mercury, arsenic) in the concentrate that will incur financial penalties from a smelter or create downstream processing problems
- operating costs (power, reagents, etc.)
- capital costs (flowsheet, residence time, etc.)
- flowsheet flexibility for treating the mine output.

Many factors that affect flotation are largely beyond the control of the investigator. These include characteristics of the ore such as fineness of mineral dissemination, the presence of surface active gangue minerals, degree of oxidation, and presence of soluble constituents. The quality and quantity of water are also in this category although these factors sometimes can be controlled by treatment and by recirculation.

Variables that are subject to control include: grinding factors such as fineness of grind, pulp density, type of grinding medium and chemical additives;[7] conditioning factors such as collectors, depressants, pH, time, intensity and temperature; and flotation factors such as type of cell, collectors, frothers depressants, pH intensity of agitation and time. Other variables may include desliming, in continuous or cycle tests, circulating loads in grinding and flotation, and recirculation of water.

Laboratory batch flotation test work

The open circuit batch flotation test work is generally the first step in an investigation. While the conditions employed in batch testing should be readily transferable to plant-scale operations, this is generally less important than the use of a procedure that can be closely duplicated.[8]

An important rule in flotation process development is to aim for simplicity. A process with unnecessary steps or reagents is difficult to investigate and analyse. There is a tendency to add new reagents or steps without proper evidence that such changes really provide an improvement.

Many different makes and types of laboratory flotation machines have been used over the years. In recent times the preferred makes are those supplied by Agitair, Denver or Wemco. For a test work laboratory treating a wide variety of ores, the most useful laboratory flotation machine is probably one with cells of 500, 1000 and 2000 g capacities, with a different diameter impeller for each cell, with stainless steel or rubber covered impellers, glass or plastic cell bodies, and requiring an outside source of low pressure air. A rotameter installed in the air line allows for control and duplication of the airflow from test to test.

The initial assessment usually involves grinding the ore sample (drill core samples) to various particle sizes and applying a reagent regime that is known to give the desired mineral(s) separation. Following a review of the initial flotation test work results alterations are made to grind size (coarser or finer), reagent system and flotation times to further enhance mineral recovery. Recovery and selectivity problems can be anticipated by conducting a detailed mineralogical examination before (or in some cases due to pragmatism, in parallel to) the flotation programme. Optimisation of the cleaning stage or stages, that may include further reagent addition and regrinding, follows once acceptable recoveries are attained in the rougher float.

Several ingredients go into planning a good test programme. Characteristics of the ore, empirical knowledge of related flotation separations, and economic considerations are all important factors in the selection of the reagents and conditions that should be studied. An understanding of experimental methods, that is, how to conduct the laboratory work efficiently, is a basic requirement. The evaluation of results as the work proceeds is fed back to the planning phase. Most experimental programmes in flotation necessarily consist of a series of planning, experimental and evaluation phases.

The relationship between laboratory and plant metallurgy is often complex. The flotation feed preparation process (grinding and conditioning) produces different size distributions and chemical environments. These relationships must be understood by the metallurgist.[7,9]

Laboratory locked cycle test work

A locked cycle test is conducted when the open circuit batch test procedure is established.[10] Analysis of the locked cycle test stability is critical in assessing the metallurgical recoveries. It is important to ensure that the product mass and metal flow is equivalent to the feed to each cycle thus ensuring that equilibrium is reached and recoveries and concentrate grades are not overstated.

A locked cycle test is a repetitive batch test used to simulate a continuous circuit. The basic procedure has a complete batch test preformed in the first cycle which is then followed by similar batch tests which have 'intermediate' material from the previous cycle added to the appropriate location in the current cycle. These batch tests, or cycles, are continued in this manner for an arbitrary number of cycles (usually more than six). The final products from each cycle, i.e. final concentrate and final tailings, are filtered and removed for further processing. At the end of the test, all the products, final and intermediate, are dried, weighed and subjected to chemical analysis. The test is balanced and a metallurgical projection is made.

The main objectives of the locked cycle test are to simulate plant operation with regard to the build up of fines (typically gangue) or composites; recirculating loads, water quality, reagents and soluble metal species. Even where separation by batch test is good, locked cycle tests may be used to determine the impact of recycled reagents in process water for multistage flotation.

Locked cycle analysis is time consuming but provides the best simulation of plant conditions at benchscale. However, ores that yield very low middlings deportment of values (very clean separation of value minerals from gangue) may not benefit significantly from locked cycle test work for determination of the metallurgical balance or flowsheet design. The number of stages required to achieve optimum separation of the middlings defines the number of cycles required in the lock cycle test.

Six cycles is generally considered the minimum, with the tailings of each subsequent stage of processing recycled to the feed of the next cycle. Problematic ores may not reach equilibrium even after 10 stages, and the assessment of water quality may take significantly more effort.

The assessment of equilibrium conditions and the prediction of metallurgy from locked cycle tests is a matter of much discussion among practitioners. Simple methods, such as averaging the recovery and grade of the last two or three cycles may be adequate for simple process routes. For complex separations, a detailed assessment of the equilibrium conditions for mass, values and gangue is required by determining a detailed balance for each cycle and considering the build-up or reduction in middlings mass and metal deportment. These methods vary from a simple check that concentrate and tailings deportment equate to feed inputs, to complex statistical assessments based on in-house databases.

Mini pilot plant

The availability in recent years of mini flotation pilot plants[5] provides an alternative method for predicting the effects of circulating loads and changes in the solution chemistry using drill core samples. The mini pilot plant allows great operational flexibility and therefore permits optimisation of operating conditions during its execution. Recent work has shown the results obtained from the mini pilot plant can be equivalent to that of a conventional scale pilot plant. The key differences between the mini pilot plant and the full scale plant relate to grind size distribution (often broader in the plant and high specific gravity minerals are finer) and energy input (plant flotation cells have a lower energy intensity).

Pilot plant operation

Pilot plants should generally only be undertaken to validate the outcomes of the benchscale test work programme and not to develop or conduct preliminary evaluations of flowsheets. Some exceptions occur when only a continuous process will allow flowsheet definition and, even in these cases, parallel benchscale test work should be undertaken in parallel as a control.

The level of control over the process diminishes from bench scale to pilot scale (even when on-stream analysis is included in the pilot plant) and the amount of effort, resources and cost increase dramatically. However, pilot plants offer the opportunity to produce concentrates for dewatering, marketing and downstream processing test work and tailings streams for dewatering, rheology, and downstream test work.

Variability assessment

The selected flowsheet should be assessed and optimised for the variability samples. Failure of the base flowsheet may occur during this evaluation due to a number of reasons, including the oxidised nature of the sample, changes in mineralogy or head grade, and changes in liberation requirements.

Locked cycle tests may be conducted on variability samples if the outcomes of the batch test work are significantly different to those observed in the composite test work programme.

An outcome of the variability test work programme may be the need to campaign or blend particular ore types to maximise revenue from the plant. This may impact on the mine plan and the optimum project concept.

Flotation circuit design

Parallel or series

A flotation circuit is a combination of flotation cells and auxiliary equipment arranged to deliver the optimum results from an ore following grinding and reagent treatment on a continuous basis. The circuit is designed from the results of laboratory results and pilot plant testing of ore samples. The arrangement of flotation cells is usually for both series and parallel flow. Some designers prefer parallel lines for flexibility and operating availability, others maintain that operating availability is a function of the design of the processing lines and of the ease and type of their maintenance and not of their number. Single line designs can have significant advantages in conserving floor space and building volume, in reducing operating labour and in reducing the hardware for measurement and control.

Flotation circuit complexity

Flotation circuit details and complexity depend upon a number of factors of which the numbers of commodities to be recovered, their values, and the ore texture are the most important. The simplest flotation circuits are found with a single, low value commodity (i.e. coal). Slightly more complex circuits have a rougher and two stages of cleaning. Porphyry copper ores represent a further degree of complexity that involves roughing, with or without scavenging, regrinding of the rougher concentrate followed by two or more stage cleaning. More complexity is involved with ores that either require very high grade concentrates because of rigorous specifications due to downstream processing requirements, or with very finely disseminated complex sulphide ores containing copper, lead and zinc or platinum group metals. Fineness of dissemination of minerals, and the required concentrate purity all contribute to the degree of elaboration of the flotation flowsheet. The flotability (measure of how fast or slow minerals float) of each mineral component will dictate where these particles report in the flotation circuit. For example on cleaning, the finer, coarser and partially liberated particles are less likely to re-float and thus report to the recycle stream. Excessive build-up of particles in recycle streams creates instability in flotation circuits.

Flotation time and number of flotation cells

The final design of a flotation circuit is only determined from the result of laboratory and pilot plant testing, guided by experiences gained from other operations with similar types of ores and ore textures. Estimation of flotation cell requirements as to size (volume) and numbers, once the tonnages, time requirements, and safety factors have been decided is more routine.

Scale-up rules are driven by consideration of hydrodynamics (superficial air flowrate and energy intensity), flotation kinetics, short circuiting (tanks in series modelling), froth recovery characteristics and experience.

An example of the estimation of a rougher circuit's flotation cell requirements is given in the Denver Bulletin (M75125). This recommends ratios of plant circuit retention times to laboratory batch times in the range 1·6 to 2·6 with an average of 2·15.[11] While there is a considerable variation in the magnitude of the safety factors, the following considerations enter into their determination. One option is to provide a greater rougher circuit volume than required by the design criteria to allow for feedrate variances originating in the grinding circuit, as well as from spillages and recycle streams. A 25% increase has been common, but where the variability in grinding circuit product is likely to be unusually large, this may increased to 50%.

Wemco's scale-up flotation time factors are based on a scale-down from continuous cells to a 7 L batch cell and considering all aspects of hydrodynamics, including mechanical froth removal. Plant installation surveys determined that froth removal rate was the key to equating batch and continuous test results. In a batch cell test, pulp level is at a relatively high level for good froth removal. In a plant, the pulp level can be varied. For those installations where the pulp level in the plant was relatively high, the scale-up factor was 2·5. For plants with low pulp level, the scale-up factor was substantially greater. This scale-up factor is related to the 'froth factor,' measured as the percentage of the froth over the lip of the weir, and then related the 'froth factor' to the ratio of rate constant of laboratory batch cell to that of the plant. For cells operating with froth factors of 55–60%, the scale-up factor is ~2·5. For lower pulp levels in the cells, the difference between the batch and continuous cells is greater.

Regarding the question of the appropriate number of flotation cells in series, the ultimate performance will be a function of the flotation kinetics, the degree of 'short circuiting' due to the number of cells in series, and the required total installed volume. A cell is considered as having no or limited backflow to the previous stage. The more cells-in-series the better the 'plug flow' characteristics of the installation and the less short circuiting which will occur; a condition which must be considered favourable for most flotation systems. A minimum of six cells in series is usually recommended, but some circuits have been installed with as few as three or four.

Scale-up criteria

Up until the early nineties, the air flow number was the most commonly used approach for scale-up criterion for similar metallurgical performance between cells of different sizes.[11,12] More recent work at the University of Queensland (Julius Krutschnitt Mineral Research Centre) has shown the bubble surface area flux, a parameter which is determined by bubble size and superficial gas velocity, has been identified as an alternative criterion for flotation scale-up from a metallurgical point of view.[13] Investigations have demonstrated a strong correlation between the flotation rate constant and bubble surface area flux S_b. Scale-up test work has shown that S_b could be used to scale-up from a 250 L cell to a 3 m^3 at similar froth residence times.[14] Work conducted at the Pasminco Broken Hill concentrator indicated the S_b was able to scale-up from a 60 L pilot cell to a 100 m^3 Outokumpu tank cell. Their results have further demonstrated the importance of froth residence time in determining the overall kinetics of flotation.

Froth transport in a flotation circuit

Froth transfer is generally by gravity where possible due to the lower flows when compared with tailings streams. In some flow sheets, for example the reverse flotation of iron ores, the silicate rich concentrate may be transferred by gravity in preference to the iron rich flotation tailings.

The transport of froth (synonymous with concentrate transport) has its own unique set of problems. Froth is a three-phase system or air, water and solids. The 'froth factor' is a measure of the air contained in the froth and quantified by filling either a measuring cylinder or bucket, of known volume, with froth and measuring the froth column. After air dissipation the remaining water and solids volume is measured. The original volume of froth divided by the combined volume of water and solids is the 'froth factor'. Measured 'froth factor' values are not employed by the flotation cell or pump designers. They are modified based on experience and application.

Froth transfer from flotation cell to cell requires either gravity flow or pumping. The characteristics of the froth depend to a large degree on the type of ore being treated, the fineness of the particles, the solids concentration, the amount of air in the froth slurry and the type of reagents used.

Froth factors for launders and sumps are dependant on reagent addition rates and reagent type, the ability to add spray water, the nature of the sprays, the design of the launder or sump and the fineness and nature of the particles. Froth factors for up to 8 to 10 have been measured/reported for ores with a stable froth structure (but should never be used for pump calculations). These froths require high volume launders, energy to release air and effective addition of spray water (to avoid excessive dilution). Open launders assist in effective froth transport and air/slurry separation. A minimum width of 300 to 400 mm is recommended.

Froth can vary from brittle (easily broken down and the bubbles are generally large) to tenacious (the air is tightly bound in the froth and will remain a froth for many hours – bubbles tend to be very fine). Froth characteristics will vary from day to day and even hour to hour depending on these many parameters, so it is important to select froth pumps for the worst pumping scenario. The main requirement is to select the correct size pump and impeller type for the type of froth and then the correct pump speed (Warman Bulletin, no. 28). Over-speeding is one of the parameters that will affect pump performance dramatically and deleteriously when handling froths. As a guide, vertical pumps are good for pumping brittle type froths. For medium type froths to very tenacious froths, horizontal froth pumps are generally superior. Recommended froth factors are shown in Table 1.

Flotation equipment

Conventional flotation cells

Convention flotation equipment has changed radically in the last decade and very large cells up to 300 m^3 are now available[15] and larger cells in design. Cell volumes range from a couple of square metres up to 300 m^3. Flotation cells come in varies shapes, from square and rectangular (<30 m^3) to U shape and circular (tank cells) for the very large flotation cells. Smaller cells have external or peripheral froth launders whilst the larger cells have both internal and external launders. Internal launders promote froth removal and thus improve single cell mineral recovery, promoting coarse particle (>100 μm) removal. Improper design of internal launders will lead to bubble coalescence, below the launder, and hence froth collapse. Furthermore, insufficient launder width and slope will result in poor froth transport and lead to decreased cell performance.

Impeller speed and design are important factors in ensuring proper slurry mixing, air dispersion and a quiescent pulp/froth interface, to prevent froth collapse.

Column flotation cells

Column flotation underwent a revival in the late 1980s and early 1990s due to its capability to replace multistage cleaning and low capital cost. In Australia, there was a trend to installing columns in rougher flotation applications as well as cleaner flotation driven in the main by the cheaper installation costs of column circuits when compared with conventional cells.

The general consensus is that these columns worked well where the value minerals are fast floating but failed to yield optimum metallurgy where the fast float components had been removed in preceding flash flotation, or the flotation kinetics were affected significantly by power input and preflotation conditioning was inadequate.

Table 1 Froth factors for pumps

Type	Froth factor
Brittle froth	1·1–1·25
Medium froth	1·25–1·5
Tenacious froth	1·5–1·6

Column cells are no longer cheaper (capex/opex basis) on a capacity basis, although they do offer reduced footprint and short circuiting per stage when compared with conventional cells.

The selection of columns, including Jameson Cells is appropriate when the following apply:

- replacement of multistage cleaning applications where froth wash water is advantageous
- non-sulphide and non-floating gangue is the principal component to be removed
- the value component is fast floating, and/or
- the flotation kinetics are not significantly impacted by power input.

The acceptance of column cells in Australia has diminished to such a degree that they are now rarely considered in mineral flotation being restricted predominantly to coal, final cleaning stages or molybdenum flotation.

The evaluation of column circuits is typically conducted at pilot scale (>5 m height × 0·1 m diameter) after initial benchscale test work to establish appropriate kinetics or the need for multistage cleaning.

Conclusions

The design and selection of the required flotation process for the recovery of valuable minerals must follow an established and methodical approach. This will include, but is not limited to the following:

- thorough review of the deposit's geology and mineralogy
- determination of the best method of sample selection, taking into account mine life and schedule, chemical assay or grade
- a mineralogical investigation in concert with the flotation test work
- definition of the grade and recovery of the valuable minerals, the extent and effects of deleterious minerals
- quantifying all the controllable flotation variables
- sequencing the flotation test work into a defined programme, starting with laboratory batch tests and on to locked cycle tests and finally, if required, a pilot plant test work on a representative bulk sample
- assessment of the selected flotation process through test work on variability samples
- consideration of the impact of the laboratory and pilot plant grinding circuit product size distribution and the impact that plant cyclone classification may have on flotation performance
- use of established and appropriate scale-up factors based on experience and knowledge gained during the flotation test work
- the selection of appropriate flotation cells based on the observed flotation behaviour.

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