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Achievements of Project Extension P9M (2000-2003)

Specific areas of research in the P9M extension were comminution, flotation and gravity concentration. This section summarises, by module, what has been achieved in the four years of the program. In addition, a number of applied site visits were completed to the benefit of sponsor operations.

Comminution, Classification and Liberation

Comminution research in P9M was built largely on the foundations of previous work and, in many cases, focuses on process problems identified during earlier studies. It covered topics in crushing, milling, classification and liberation. Autogenous and semi-autogenous milling remained the major topics of interest, though for the first time in many years crushing and fine grinding was included in response to sponsor demand. Achievements in each of these tasks are summarised below.

- A new generic crusher model has been developed that considers the geometry of the crushing chamber and describes explicitly the breakage of each particle as it passes through the crusher. Simple simulation shows that the model behaves in a logical manner. The model has been tested using data from two laboratory crushers – large and small – with satisfactory results.

- The JKMRC high pressure grinding rolls (HPGR) model developed by Luis Tondo has been validated using three sponsor ores. The model is able to predict full-scale size distributions based on tests conducted in a laboratory scale unit. As HPGR machines are much more energy efficient than conventional tumbling mills, this model will help sponsors determine potential energy savings and reduce overall energy consumption in their operations.

- The model developed in P9L by Sanjeev Latchireddi to predict the effect of design and operating conditions on the relationship between slurry flowrate and hold-up in high aspect ratio grate discharge AG/SAG mills has been extended to cover low aspect ratio mills as well. Two other models have been developed to predict the maximum level in the mill for different aspect ratios.

- A new model has been developed to relate pebble flow through AG/SAG mills to pebble port size and pebble port open area. The model incorporates a new function that relates the pebble flow to the volume of pebbles in the mill. The model has been tested successfully using data from Cadia Hill's SAG mill circuit and from six tests conducted at WMC's pilot facility. In the latter work, systematic changes in pebble port open area and pebble port size were made. The new model accurately predicts the pebble flow rate in these circuits.

- During research work conducted on the single-stage, run-of-mine mill at Anglo Gold's Navachab Mine in Namibia, an excessive recirculating load of ball scats was noted on the feed belt to the recycle crusher, and scattered within the mill charge. Removal of the scats, by reversing the direction of the magnet ahead of the crusher, resulted in a step change of 9% in mill throughput. In the long term this has resulted in a greater (nearly 100%) utilisation of the recycle crusher, and a 5% increase in throughput while treating more competent ore.

- During field trials conducted in South Africa, a number of mills were identified as having deficiencies in shell liner design and problems of slurry pooling. The raised awareness of these issues in the P9 program led to close interaction between the project team and a number of sponsor sites on shell liner and mill discharge grate designs. Six existing sites received advice and input on improved liner and discharge design. Four new operations had their shell and discharge designs conducted or vetted by the project team.

- Arising from P9 classification work, a pilot plant facility with provision for linking comminution and classification to the Floatability Characterisation Test Rig (FCTR) has been built at Karee. This will be used for testing the influence of classification on both grinding and flotation circuits. It will be used for

testing the three product cyclone in a circuit configuration with screens (Panseps) linked to the FCTR. There is a lot of scope in the number of projects that can be conducted on the pilot plant and more students from UCT will be involved in most of the projects that will be conducted on the pilot plant. The pilot plant will also serve as a tool for internal training of Metallurgists at Lonmin.

- On Lonmin sites the ongoing contact between UCT and site operations has grown to the point where MPRU is now an integral part of the sites' optimisation efforts. Many examples of the sites and UCT jointly addressing problem areas have been implemented.

- Post graduate students provide trained labour for the plants that do not have sufficient people and can not afford to dedicate any of their staff to conducting research full time. Input from independent external research is valuable in highlighting areas that need consideration in the operations that may otherwise be overlooked if assessed by members of staff from the same plant.

- Features of various existing discrete element (DEM) and finite element (FEM) methods of numerical simulation that would be critical when simulating the comminution process of ball milling have been reviewed. The findings suggest that existing DEM codes compromise modelling the deformation (fracture) of particles, thereby gaining computational ease and speed, while FEM schemes account for particle deformation but incur considerable computational expense. The concept of supplementing a DEM framework with a deformable particle module was proposed; as a consequence, the commercial Itasca-2D and 3D DEM packages have been obtained. These codes are robust and well proven, and permit users to extend the DEM formulation within the program framework, e.g. the inter-particle contact formulation has been modified to meet the specific modelling conditions. Custom user-output of variables considered important is also possible during a simulation. Other DEM codes did not provide this flexibility.

- In order to provide rigorous and accurate verification data to test the fundamentals of DEM models, a biplanar angioscope has been used to measure 3D particle trajectories in a small perspex mill for different speeds, lifter profiles, and a range of tracked-particle sizes and densities. A rigorous technique has been developed for comparing the charge profiles of 3D numerical DEM simulations and 3D experimental trajectory data statistically, in terms of shape and location, and particle velocity and acceleration. DEM simulations were applied to improving the SAG mill model.

- The JKMRC Verti (tower) mill model has been validated using samples of six ores. Breakage rates have been scaled up successfully from laboratory to full size units using either of two models (based on power draw and rate of breakage sites generation, respectively). Reliable predictions of full size mill performance can be obtained using this model. Currently, the procedure used by the industry for sizing tower mills is imprecise and tends to predict a higher capacity mill. This model will reduce the likelihood of over capitalisation on mill capacity.

- Currently the procedure used for predicting steel wear in mills is based on Bonds abrasion test, which is very imprecise. This project on media wear in mills has developed a significantly more precise procedure for characterising wear and predicting media consumption. This model will allow more accurate prediction of operating costs in greenfield operations and optimisation of existing milling operations.

- Acoustic measurement of mill load using strategically placed high precision microphones has been validated at a number of sites and found to be both reproducible and sensitive. This technique can be used to estimate the ball load inside a tumbling mill (particularly SAG) on line and enable optimisation of ball load and maximisation of throughput.

- A new model developed in P9L to predict the non-linear change in throughput and size reduction in AG/SAG mills as the load volume in the mill is altered has been further validated at a number of sites. This model can be used to estimate the load level that maximises energy utilisation efficiency in SAG mills. In conjunction with the acoustic technique for measuring ball load, it is now possible to maximise throughput in mills.

- A new multi-phase model of liberation for comminution has been successfully developed, based on a maximum entropy approach to relate parent particles to progeny particles. This model can be used to determine how the grinding circuit can be operated to provide a target liberation distribution. Linked to flotation, this can then be used to maximise recovery.

- A new model of the 3-product cyclone has been applied successfully to six data sets from tests conducted with a 254-mm three-product cyclone on a cyclone feed sample from WMC's Leinster Nickel Operations. Parallel work was carried out using a 600-mm diameter three-product cyclone at Lonmin's Eastern Platinum UG 2 ore concentrator in South Africa. The inner overflow stream was found to contain fine chrome that could be screened out at 100 μm, leaving the oversize to be sent to regrinding to liberate the PGMs locked in the coarser silica.

- If used in the appropriate environment this new classification device has the potential to reduce over-grinding and improve recovery of values in subsequent concentration processes.

Flotation

The main deliverable of the flotation work in P9M is a comprehensive methodology for modelling industrial flotation cells and circuits, incorporating both true flotation and entrainment, using the models developed in projects P9K and P9L. Achievements in each of these tasks are summarised below.

Floatability component model and circuit modelling methodology

- A methodology has been developed for operating the WEMCO Floatability Characterisation Test Rig (FCTR) to obtain data for modelling and simulation purposes. The most comprehensive test program to validate the P9 flotation modelling methodology was undertaken at WMC's Kambalda Nickel Operation (KNO) near Kalgoorlie in Western Australia. Results show that the model developed from four circuit configurations was able to predict the valuable mineral (NiS and CuS) recoveries accurately in a further five circuit configurations.

- The inclusion of a single scale-up number has allowed the plant rougher bank performance at KNO (in terms of nickel, iron, copper and non-sulphide gangue) to be predicted successfully from FCTR results. The scale-up factor appears to approximate the ratio of absorbed power between the FCTR and the plant cells. The same finding was made at WMC's Mount Keith Nickel Operation.

- Investigations using the FCTR at Lonmin's Eastern Platinum concentrator have laid the foundation for the implementation of fine grinding in the cleaner circuit at the mine. Another, hydrodynamic, study using the FCTR to determine the effect of power input on the flotation of platinum (PGMs) has indicated clear increases in platinum recovery from primary cleaner tails with increasing impeller speed and air flow rate.

- The floatability of particles with changing grind size has been investigated in a small flotation pilot plant facility (not the FCTR). Modelling the results assuming that the ore floatability parameters (P values) of the fast and slow floating components remain constant, and that the only effect of the grind is to shift the proportions of fast, slow and non-floating fractions (m values) between the floatability classes, gave an excellent fit to the experimental data. This work has been repeated using Anglo Platinum's mini-plant (these results will also be analysed on a size-liberation basis).

- The new P9 methodology for modelling flotation cells and circuits was applied to a full-scale industrial plant for the first time at WMC's Mount Keith Nickel Operation in Western Australia. The model was used to simulate a number of changes to the circuit flowsheet configuration. Reasonable agreement was found between actual samples and trends predicted from the simulations.

- The new modelling methodology has also been used to develop circuit models for the copper concentrator at Mount Isa Mines, Rio Tinto's Northparkes Mine in New South Wales, Western Metals' Pillara Mine in Western Australia, and Teck Cominco's Red Dog Mine in Alaska. At MIM (Xstrata), the model was used to simulate a number of circuit changes with the aim of improving overall recovery. At Pillara, strategies were developed for the lead and zinc circuits to improve the final zinc concentrate grade. At Red Dog, model simulations were used to uncover the reasons for sphalerite recovery being limited in the zinc retreatment circuit.

- At Rio Tinto's Northparkes Mine, the new P9 flotation modelling methodology has been used very effectively for flotation plant performance diagnosis. The application of the methodology is able to discriminate between the effects of gas dispersion, froth performance, flotation capacity and ore floatability on the ultimate copper recovery achieved in the circuit. A strategy for improving the

metallurgical performance, implemented as a result of this work, has supported the major conclusions drawn from the study.

- Nodal analysis, a technique for determining whether the inherent floatability of particles is conserved around the flotation circuit, has been employed extensively during testwork conducted on sponsor sites. In the majority of cases, the principle of conservation of floatability has been upheld. Where regrinding or reagent addition occurs, nodal analysis has been used to quantify the effect on floatability, e.g. within Teck Cominco's Red Dog zinc retreatment circuit. More surprisingly, nodal analysis indicated that the addition of lime in the Red Dog retreatment circuit depressed sphalerite in preference to pyrite.

Flotation cell and circuit simulation software (JKSimFloat)

- In a project funded in parallel with P9, a new Windows based steady state computer simulation package, JKSimFloat V6.0, has been developed that will allow users to predict the metallurgical performance of a flotation circuit based on defined flotation models and flotation circuit stream data. Data entry and data viewing are via a flowsheet based graphical interface. A feature of the new software package is that the simulation engine consists of a flexible stream structure that will accommodate both current flotation models and models developed in the future. The first calibrated copies of the simulator will be distributed to sponsors of the software development project in the third quarter of 2003.

- A new project has been initiated to determine the floatability distribution or spectral function F(k) from the time dependent concentration C(t) data obtained in the current flotation circuit modelling methodology. The work forms part of the development of an algorithm (for implementation in JKSimFloat V6.2) to determine the number of floatability components and their amplitudes when modelling a flotation circuit from survey data. This work will continue into P9N.

Flotation cell characterisation

- The testwork to develop flotation circuit models at the sponsor sites included the measurement of gas dispersion characteristics in many different flotation cells of different types, sizes and duties. The data is available and suitable for the construction of a database of cell properties. The S_b predictor model was also tested and used in a number of the campaigns.

- The measurement of gas dispersion in cells on sponsor sites has provided some unexpected results, including the detection of faulty air valves and gas flow meters that needed to be fixed before systematic measurement of gas dispersion could be initiated. In several cases, gas velocity measurements down a bank revealed wide variations from cell to cell which, when addressed, resulted in significant benefits in the metallurgical performance of the bank. In the final zinc cleaning stage (bank of seven cells) of Noranda's Brunswick Mine Concentrator, increasing J_g steadily down the bank consistently produced the best metallurgy (down-the-bank grade / recovery), attributed to the low gas rate in the first cells reducing water recovery and hence limiting entrainment of NSG gangue. The increasing J_g profile was subsequently configured for all four stages in the zinc cleaner circuit.

- The two methods used in the project for measuring the superficial gas velocity through a flotation cell have been compared. It was found that both the JKMRC and McGill methods require a pressure correction factor, after which both methods give the same, accurate, results.

- The gas hold-up sensor developed by McGill University and based on the use of two flow cells for measuring the conductivity of the pulp with and without air has been shown to be robust enough for industrial use. It has been used in plant tests ranging from paper to mineral pulps, and mechanical cells to columns, and can be integrated into plant control systems.

- A new method of sampling and presenting bubbles for imaging, using a "bubble viewer", has also been developed at McGill University. Data have been collected using the device at several concentrators on different types of flotation cells. The device has also been used to investigate the $k=PS_b$ relationship at the micro-level. The range in S_b, up to 50 s^{-1}, is comparable to full-scale machines. Results suggest that the linear $k–S_b$ relationship is reasonable, though the data cannot distinguish unambiguously among various $k \propto 1 / d_b^m$ relationships where m may range up to 2.

- Statistical analysis of the homogeneity of gas dispersion (J_g, ε_g, and d_b) measurements in a 3 m^3

glass rectangular flotation cell has shown that there is "quarter symmetry", i.e. that there is no significant difference between equivalent positions in different quarters in a horizontal plane. Comprehensive measurements have been made using the same sensors as used on sites in order to construct empirical models of gas dispersion characteristics in a flotation cell and for the validation of CFD models of flotation cell hydrodynamics.

Froth performance modelling

- The effect of five different frothers on metallurgical performance has been investigated at Western Metal's Hellyer lead-zinc operation in Tasmania, in experiments using a small pilot flotation cell. The results show that the entrainment recovery-water recovery relationship may be described by a simple power model, which is independent of frother type and concentration. This indicates that the performance of a froth is a function of its structure and not how it was created, which is very important from the viewpoint of froth modelling.

- Acceptable linear relationships between overall rate constant k and froth depth have been obtained for each of eight size fractions, in an analysis of samples remaining from previous (P9L) testwork using the 3 m^3 Outokumpu pilot cell operated at the MIM (Xstrata) copper concentrator. Froth recovery R_f was found to decrease as particle size increased, as expected. R_f values for pyrite and chalcopyrite were very similar, suggesting that froth drop-back is the same for both minerals.

- The same results from the 3 m^3 Outokumpu pilot cell operated at MIM (Xstrata) copper concentrator have been analysed in terms of the recovery of different minerals by entrainment on a size-by-size basis. The effects of cell operating conditions on the entrainment process have also been considered. A new entrainment model, which determines separately the entrainment recovery of the free non-floatable particles from the pulp to the froth and the froth recovery of the entrained particles into the concentrate, has been developed.

- A prototype new instrument to measure the bubble load in the pulp zone of industrial scale flotation cells has been developed, which has been used in the determination of froth recovery, producing results different from those obtained using the varying froth depths method, and casting doubt on the validity of the assumption of R_f being non-selectivite. The device is simple, inexpensive and non-intrusive, and will be developed further during P9N.

- A preliminary investigation has been carried out into the possibility of measuring the rheology of froths, and whether any result obtained might be related to metallurgical performance. Readings obtained using a modified Baroid viscometer in testwork at MIM indicated differences in froth rheology in going from rougher to cleaner to scavenger streams, and from the zinc to the lead circuit.

- A prototype mechanistic model of flotation has been developed that can be used to simulate the responses of all the constituents of a flotation cell and circuit (including water). The aim of this model is to provide a tool for testing and refining new models prior to implementation in JKSimFloat. The model has been tested with very encouraging results on a data set gathered previously (during P9L) in the copper concentrator at Mt Isa Mines.

Property-based floatability model

- A new laboratory test rig has been constructed to estimate the floatability (P) of a hand picked high grade ore specimen from BHP-Billiton's Cannington mine by size, mineralogy, liberation and collector dosage. A special feature of the new rig is the conditioning vessel, designed to have plug-flow mixing characteristics. The experiments provided an opportunity for collaboration with Drs Ewen Silvester and Fuping Hao of CSIRO Division of Minerals in Melbourne, who transported their laboratory to JKMRC in Brisbane to measure collector adsorption during the flotation tests. Samples were also despatched to the Ian Wark Research Institute (IWRI) at the University of South Australia for TOF-SIMS analysis, to assess the extent of surface oxidation and/or copper activation, and to determine the distribution of collector on the mineral surfaces.

- Preliminary results from the above investigation have shown that variations in particle size and froth depth have a much stronger effect on the froth zone recovery of sphalerite than galena. Visual observation and TOF-SIMS analysis of the flotation concentrate suggest that the galena is being recovered by true flotation, while the sphalerite is being recovered by entrainment and flotation in

composite particles (with galena). The findings also suggest that less hydrophobic particles might have been selectively rejected at deeper froth depths, contradicting an important assumption of the current flotation model. These results are being reassessed on a size-by-size and mineral liberation basis. The P (floatability) values calculated for seven size fractions at five different collector dosages show that the addition of even a very large quantity of collector hardly improves the very poor floatability of the –5 micron particles, but significantly improves the floatability of otherwise poorly floating 128 micron particles. The effect of liberation is still being assessed.

- In a separate analysis of previous results (obtained as part of the AMIRA P336 project) particle size and mineral surface composition has been found to be insufficient to account for the distribution or ore floatability detected in Teck Cominco's Red Dog lead cleaning circuit. Nodal analysis indicates that the floatability of different types of particle classes within the circuit was conserved during the lead cleaning stage. It is suspected that non-uniform hydrophilic surface coatings, occurring prior to this stage of flotation, were affecting the floatability of the particles. This confirms the need to develop a property-based floatability model which includes chemical effects.

- A methodology has been developed for inferring the liberation distribution of particles in the concentrate and tailings streams from a flotation cell, from the liberation distribution of the feed and the size-by-size mineral assays of the concentrate and tailings. The methodology is based on probability theory (the principle of maximum entropy). The methodology was validated successfully using laboratory flotation test data.

CFD studies of mechanical flotation cells

- In a project funded in parallel with P9, the CSIRO was engaged to develop a CFD model of flotation hydrodynamics, and validate the model through pilot scale physical measurements. Two of the flotation equipment supplier sponsors in the project (Svedala and Outokumpu) agreed to supply specifications of their mechanisms for CFD modelling and actual mechanisms for use in the physical modelling work, which provided results for testing the CFD models. To date, good general agreement has been obtained between the measured and CFD predicted data (velocity, bubble size, void fraction and solids distribution) in air-water and air-solids-water systems for both mechanisms studied. A second phase of work, AMIRA P780, commenced in May 2003 and involves some further model validation, studies of the effect of through-flow on cell hydrodynamics, studies of the hydrodynamics in a larger 3 m^3 cell, and parametric studies using the models of the Outokumpu and Metso-Svedala impellers.

Gravity Concentration

The gravity concentration module was a modest research program aimed at developing an improved understanding of a range of gravity separation processes not investigated in previous JKMRC research. The achievements were as follows:

- A mathematical model has been developed of the sedimentation behaviour of solid particles flowing down a sluice (flowing film separator). Fluid velocity profiles have been derived from a fundamental analysis of fluid mechanical theories, and particle settling profiles from the well-known equations of Richardson and Zaki and Brauer and Thiele. The model has been validated with experimental data obtained from a 2m sluice rig constructed and commissioned at the JKMRC, and operated using various concentrations of glass beads and mixtures of different proportions of glass beads and ilmenite particles, of different sizes. Reasonably good agreement was obtained between the model and the experimental data, particularly at low solids concentrations. The equations are being applied to gravity enhanced rotating flowing film concentrators (the Falcon concentrator).