MINERAL PROCESSING

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The following review is a snapshot of some of the papers presented at last year's IMPS 2000 and the 10th Minerals Engineering Conference.

Since their conception in 1986, the biennial International Mineral Processing Symposia with venues in different cities of Turkey have become an influential international forum for the presentation and discussion of recent scientific and technological advances in the field of mineral processing. IMPS 2000, held in Antalya, Turkey, on October 16-18 last year, was organised under the auspices of a number of leading state and private mining companies and institutions of Turkey. The spectrum of papers presented was rather wide, including the traditional areas of mineral processing, as well as chemical processing, bioprocessing, waste treatment and utilisation.

The following month, the 10th Minerals Engineering conference, held at the Mount Nelson Hotel in Cape Town on November 17-19, was attended by delegates representing 18 countries from as far as Australia, North and South America, Europe and Asia. The 46 oral presentations were delivered in five technical sessions over the three days of the conference and covered the following broad topics associated with mineral processing and extractive metallurgy:

- Comminution
- Hydro and Pyro metallurgy
- Control, simulation and optimisation
- Froth Flotation
- Physical methods

Comminution, Liberation Sizing and Material Transport

Besides mechanical energy, the liberation of minerals by microwave heating is starting to find commercial application in recovering gold, copper and other metals from refractory ores[1]. Applied to sulphide flotation concentrates, the technology could have huge potential to replace historical pre-treatment processes such as autoclaving, roasting or smelting. It would also be far more environmentally benign.

Results from microwave assisted mineral treatment tests to assess the effect of microwave energy intensity and exposure time on microwave heating behaviour and grindability of materials indicate that particle size has a significant effect. The coarser particles (-9.50 mm +4.75 mm) of limestone and quartz resulted in increased product fineness after subsequent dry milling. Silicate and carbonate minerals, meanwhile, were found to be difficult to heat at lower microwave energy intensities (<7kW) during a short exposure (<30 min) due to their transparency or reflective nature. Thermal stress fractures in a copper ore, however, occurred readily, resulting in a better and cleaner liberation of sulphide minerals from the ore matrix.

US Borax is upgrading its primary ore crushing system at its open pit and refinery near Boron, California[2]. Since the installation of an in-pit Jeffrey Slugger impact crusher in 1961, the mining equipment at the site has become larger, making truck dumping into the dump hopper impractical. Consequently, large loaders were used to feed the system, resulting in an extra handling stage. Furthermore, surge feed problems, an 18°-incline product conveyor and a 254 mm top size product caused excess spillage, thereby preventing the system operating at its 1,090 t/h design rate.

The new crushing system as developed and tested by the US Borax Technology Department will incorporate two reduction steps using MMD toothed double roll sizers.

The system is rated at 1,500 t/h and will reduce ROM tincal and kernite ore from 1.25 m lump size to 90 mm top size, yet, achieve improved granulometry and material handling characteristics.

A model has been developed in Simulink to provide the means for online inferential measurement of semi-autogenous grinding (SAG) mill parameters[3]. The model is capable of providing estimates of SAG mill rock load and ball load based on plant operating data and equipment specifications. Sensitivity analysis is now underway to determine the effect of errors in the plant data and model parameters on the estimates. The objective of the work is to provide reliable inferential measurements for control purposes.

Two independent estimates of the SAG mill charge inventories in the Module 1 grinding circuit at the Northparkes copper-gold mine in NSW, Australia, have been developed that utilise mill powerdraw or mill weight data. A sensitivity analysis of the effect of errors in the plant data and model parameters is being conducted. Preliminary results suggest that the estimates from powerdraw are least sensitive to data error.

Namdeb Diamond Corp. commissioned a Floating Treatment Plant at its operations in Namibia in 1996 to screen out and concentrate gravels from an overburden dredging operation. The installed trommel screens proved inadequate to achieve the primary screening requirements at 2 mm apertures and a number of solutions to the screening problem were investigated. Using conventional screening would have required building a separate screening barge at an exorbitant cost. The idea of splitting the flow in the feed pumping system to remove part of the 90% fines in the feed, thus reducing the duty required of the trommels was pursued and the Namdeb Elutriator was born[4].

The feed from the dredge is split into two streams. The underflow reports to the trommel screens and the overflow by-passes the screens and reports directly to the screen underpans. The overflow stream flows vertically upwards through the elutriator column. The upward velocity in the column is monitored using a magnetic flow meter and controlled to a set value using a valve. Particles with settling velocities greater than the column rise velocity fall to the bottom of the column while smaller and lighter particles rise to the top of the column. The nominal cut size is a function of the column rise velocity.

The elutriator designed for the 2,500 t/h treatment plant has an internal diameter of 2.35 m and a total height of 12.73 m. The nominal diameters of the feed, overflow and underflow pipes are 600 mm, 500 mm and 400 mm respectively. Of the various inlet geometries tested, a 45^{o} inlet with a sudden transition gave the best performance. This was also the most suitable configuration for the prototype installation. Furthermore, the performance of the elutriator is not affected by the solids concentration in the feed stream for the range of expected operating solids concentrations (up to 42% by mass). Also, the tonnage of material reporting to overflow increases linearly with the percentage of feed mixture flow rate reporting to overflow.

Physical Enrichment Processing

It is generally accepted that gravity concentration is the simplest and the most economical methods of mineral concentration. For the recovery of very fine, high specific gravity particles, centrifugal mineral concentrators are finding increasing application – the Falcon concentrator, the Kelsey centrifugal jig, the Knelson concentrator and Mozley's Multi Gravity Separator are probably the best known of these new-age fine gravity separators.

The high value of fine chromite in the tailings streams of gravity chromite plants has been widely investigated and the MGS concentrator has seen remarkable success at operations in Turkey, Greece and Finland[5]. One of Turkey's most important chrome ore

regions is around the Kop Mountain in the Erzurum-Erzincan-Bayburt provinces and the main producer in the area is Birlik Madencilik. A study to evaluate the MGS's upgrading capability at the company's Kop concentrator showed that the spiral tailings can been beneficiated for recovering fine chromite below 100 microns. Fine concentrate with a grade of 48% Cr_2O_3 was obtained in a 24% mass for a 70% Cr_2O_3 recovery (on the basis of total minus 100 micron tails). On this basis, an MGS fines recovery unit retrofitted in the spiral section of the concentrator could increase the plant concentrate yield by up to 11%.

For bauxite producers, reducing or eliminating the volume of red mud (a by-product of the Bayer process for extracting aluminium oxide from bauxite ore) would mitigate a major cost. In addition, a further driving force for the reprocessing of red mud is the value of its components such as TiO_2. However, a common feature of all red muds is the presence of substantial levels of iron oxide which, whilst not particularly valuable, reacts with the agents in most processing schemes, adding to their cost and complexity. As a result, many proposed red mud treatment schemes incorporate a preliminary iron-removal step.

Xiang, Schlessinger and Watson have proposed an approach to reduce haematite to magnetite which is ferromagnetic and can be recovered by low-gradient magnetic separation[6]. By investigating the reduction of haematite in red mud to magnetite by varying the reduction temperature, reaction time and the type of reducing agents for three feed materials, it was found that the ferric ion is readily reduced to magnetite at temperatures below 500^{o}C. Also, it was determined that sawdust and bagasse (the fibrous material remaining after the extraction of the sap from sugar cane) were more effective reductants than coal and charcoal.

Magnetic separation techniques are used extensively in mineral processing operations. However, the method used to optimise this equipment uses trial and error techniques and laborious assaying methods. Such techniques can only provide information for one set of operational parameters.

A joint venture between Bateman Engineering and South African company, The Winning Solution has facilitated the development and manufacturing of magnetic tracers[7]. Magnetic tracers are simulant minerals with similar size and density to that of the minerals in the ore body they are simulating. The development of magnetic tracers enables magnetic separation equipment to be set up efficiently and rapidly. Magnetic tracers offer additional benefits in that they can also provide information on the separation efficiency when various operation parameters change such as size range, temperature or relative humidity.

Magnetic tracers provide critical information on the operational efficiency of the separation process and identify which parameters need to be controlled. Magnetic tracers can be used to determine the suitability of a magnetic separation process when treating an ore-body and indicate where improvements in the process can be made.

The Reflux Classifier is a novel device for classification of particles according to size and density[8]. The device consists of a conventional rectilinear fluidised bed containing sets of parallel inclined plates at different elevations. Each of these lamellae of plates spans the whole cross-sectional area of the vessel. Particles are fed into the middle of the vessel, and are fluidised within the vessel with an upward stream of liquid.

Well-defined separations of particles are produced through the use the inclined channels. Particles of coarser size or higher density, having higher settling velocity, settle over short distances within the channel onto the upward-facing plates, form sediment streams, and slide down below. Finer or less dense particles are carried through by

fluidisation into the zone above. The sets of inclined plates are the classification zones of the Reflux Classifier.

An internal self-mixing and recycling action is a result of combining the lamellae of inclined plates with the fluidised bed, and is referred to as the reflux action. The uniform flow provided by the fluidisation and the synergy of the reflux action enhance the quality of the separations.

The lamellae of inclined plates bring about a significant throughput advantage to the Reflux Classifier, in the same fashion as in the Lamella Settler. With multiple inclined channels, the effective area for segregation is increased significantly and is responsible for the throughput advantage of the Reflux Classifier.

The cut-size (D_{50}) for each classification zone is largely governed by the liquid fluidisation rate and the geometry of the inclined plates. Thus, by using multiple sets of inclined plates, the Reflux Classifier can be used to generate multiple products from one feed stream.

Fine Particle Processing

Waterjet technology has already found application in many fields of rock and stone engineering (excavation, slotting, cutting, drilling, surface finishing) but no commercial developments can yet be found in the areas of mineral comminution and separation. Researchers at the University of Cagliari in Italy, however, are studying and developing waterjet technology with a particular focus on mineral and coal processing[9].

For example, owing to the strong agitation and to the onset of cavitation when water is injected into a slurry at high velocity, a waterjet can be applied to prepare a better surface for flotation by removing the clay coating from mineral particles. In the area of comminution, the assistance of water jets to the mechanical action of conventional gyratory crushers can considerably increase the throughput capacity for coal up to five times.

In another application, the use of water jets generated at moderate pressure is believed to offer some distinct advantages over conventional mechanical machines for the selective agglomeration of coal particles into coalescent floatable aggregates. The use of water jets at moderate pressure is also considered a suitable method for improving the flotation of very finely ground ores, perhaps forming the basis for the design of a new sparger device in column flotation.

Although normally used as a grinding mill, the Hicom mill has found application in intensive attritioning areas such as diamond recovery and mineral sands[10]. A batch and pilot-scale study has shown that the Hicom mill can be used as a high-intensity attritioning device to remove alumina-silicate coatings from the surface of ilmenite grains, leading to increased product quality. Results are comparable to leaching for removing these coatings in some instances.

The best results were obtained at a slurry density of around 75% solids and with the use of a chemical viscosity modifier. The Hicom attritioning tests showed that significant reductions in surface coating levels were obtained at energy inputs of 5-20 kWh/t, with negligible reduction in size of the ilmenite grains. At 10 kWh/t, Al_2O_3 coatings were reduced by 34% and SiO_2 coatings by 30%. These reductions add significant value to the final ilmenite product.

Flotation Fundamentals

The production of separate concentrates from complex ores containing economic amounts of copper, lead and zinc is complicated, and selective flotation seems to be the only viable method. In most cases, however, concentrates are produced at relatively low grades and recoveries. Smelting charges, often containing contaminated concentrates, become excessive and penalties are often imposed for the presence of zinc and lead in

copper concentrates. With the imposition of stringent limits on these contaminants, cost effective and more efficient methods of removing copper, lead, zinc and nickel sulphides from iron sulphide minerals has, therefore, attracted much attention over the past ten years.

Collectorless flotation of sulphide minerals from their gangues through electrochemical control is gaining importance as a cost effective and environmentally benign method of copper recovery. Investigating the influence of pulp chemistry on the collectorless flotation of chalcopyrite and galena, Matabishi, Handfield-Jones and Akdogan found that chalcopyrite exhibited good flotation response at pH values between 8 and 10[11]. At pH10 and pulp electrochemical potentials of between +100 mV and +120 mV, flotability reached the highest level at around 73%. Flotation was depressed significantly at electrochemical potentials outside this range. Galena, meanwhile, showed good flotability at pH 8 and pulp electrochemical potentials between +190 mV and +230 mV. At pH 8, addition of ferric nitrate depressed the flotation of galena to its lowest limit of around 3%.

Conventional gravity/electromagnetic techniques for the separation of rutile and ilmenite only work efficiently on particles coarser than 100 mesh. Significant loss of productivity occurs in finer sizes in current heavy mineral process industries, and the separation process becomes uneconomical at particle sizes below 45 microns. Despite the similar flotation responses of the two minerals, froth flotation remains a sensible research alternative for the selective separation of fine-sized ilmenite-rutile mixtures.

Studies into the flotation behaviour of rutile and ilmenite in aqueous solutions of a cationic collector, hydrogenated tallow amine acetate (HTAA), show that there is a different flotation response between the two minerals at a temperature of 25°C and pH12[12]. In the presence of 7.5 x 10-6 M HTAA at this pH, the flotation recovery of ilmenite reached 84% while that of rutile remained at only 16%

Flotation Technology

The iron-ore mining industry in the US is facing strong competition from high-grade ore from overseas. In order for the US to remain competitive, research on low-cost beneficiation methods that ensure high quality and uniform quality products will be essential in preparation for ever-tightening specifications on raw feed materials for blast furnaces and for direct reduction processes.

Current interest centres on the cationic silica flotation of magnetic concentrates in which the selectivity of separation can be improved, particularly in the presence of ferromangesian silicate materials, while protecting the environment[13]. While surface chemistry plays a fundamental role in the selection of an effective reagent suite, attention should also be paid to the engineering aspects of the system, such as flotation machine type, design and operation, pre-classification of flotation feed and the application of a magnetic field in the flotation cells.

The possibilities of using flotation techniques to beneficiate gold-bearing ores containing enargite concentrates for pyrometallurgical treatment are being investigated at Sardinian Gold Mining's Furtei operation in southern Sardinia. Mining operations at the site have thus far been confined to the upper oxidised zones of the orebody which are amenable to cyanidation. But, with the exploitation of these reserves now at an advanced stage, the mining and beneficiation of the deeper refractory sulphide ore zones which account for around 60% of the total measured resource is now all the more pressing.

Experimental investigation has demonstrated that the proper choice of flotation reagent suite and their optimal dosage allows the recovery of concentrates that meet market specifications at least as far as minimum copper content is concerned[14]. However, the

presence of enargite as the copper carrier yields concentrates that are relatively high in arsenic.

A proposed pre-treatment procedure for removing the arsenic ahead of pyrometallurgical treatment is currently being evaluated at the University of Cagliari. The procedure involves alkali leaching of enargite in a sodium sulphide medium, and achieves more than 90% dissolution efficiency with significantly higher extraction rates when mechanical activation is ensured by means of fine grinding. This yields an environmentally benign solid leach residue, in the form of covellite, for pyrometallurgical treatment.

Coal Processing

One of the most significant fine particle separation developments is the successful industrial application of several enhanced gravity separators (EGS). Such units incorporate a mechanically applied centrifugal field to accelerate the separation kinetics of several conventional gravity-based techniques such as jigs, riffle tables, teeter-beds and flowing film devices.

The separation performance for fine coal provided by an EGS can be significantly improved by the used of a dense medium comprising an ultra-fine magnetite suspension[15]. High efficiency values were obtained from the cleaning of 1,000 x 44 micron coal. Organic efficiency values greater than 95% were obtained while reducing the ash content of a fine Illinois No.6 coal from 16.9% to values below 5%. Although the effect of particle size was not eliminated by the use of dense medium, high process efficiencies were achieved from the coarsest particle size fraction (1,000 x 600 micron) to the finest fraction (150 x 44 micron).

Medium density and bowl speed were identified as providing the most significant impact on product ash content and mass yield. An optimum bowl speed of 20 Hz, corresponding to a centrifugal force of around 30 g, provided the optimum separation performance. It should be noted, however, that this optimum g-force is a function of the magnetite properties, especially the particle size distribution.

The major problems with the coal flotation process are the large amounts of valuable material that are lost due to the inability to float coarse middlings within the nominal minus 0.5 mm feed, and the entrainment of fine gangue particles into the concentrate. Testwork using a low rank coal from the El-Magahra coal mine in Egypt indicates that fuel oil collector emulsification using pine oil can result in improved recovery of all involved particle sizes in the flotation feed, in particular fine coal particles[16].

By increasing pine oil concentrations to about 0.25% (pine oil/fuel oil by volume), coal recovery increased rapidly to about 95% then decreased to about 87% at a pine oil concentration of 4%, rising again to a maximum of 97% at 10% pine oil. This improvement in coal recovery is attributed to reducing the tension of the oil/water interface which subsequently facilitates fuel oil collector spreading onto the coal surface. Also, the flotation rate is increased due to increased number of oil droplets, which increase the probability of particle/collector contact.

Hydrometallurgy and Bioprocessing

The general industrial practice for the recovery of tungsten is through the production of tungsten salts or oxides that are then reduced using hydrogen to produce tungsten powder. Conventionally, pure WO_3 is produced through a multi-step alkaline-based leaching process of either scheelite or wolframite concentrates.

Researchers at the Istanbul Technical University have discovered, however, that although WO_3 is acidic in character, it can be dissolved in the form of poly-tungstate ions by changing the ligand mantle of WO_3[17]. In this way, it is possible to produce low cost and

pure WO_3 via fewer process steps compared to conventional alkaline routes.

The chelate-added acid leach is carried out under atmospheric conditions, at low temperatures and without generating a waste stream. Results of the experimental work show that it is possible to reach about 93% tungsten extraction efficiency by leaching a concentrate below 325 mesh at 70-80°C using 2M hydrochloric acid at a solids to liquid ratio of 1:5. The technique proposed reduces the number of processing stages from eleven to just four and uses the same leach solution at least 20 times without purification. After 20 cycles, the solution is purified and returned to the process, leaving behind only gypsum as a solid residue.

Concentrated and dilute tungstic acid solutions are neutralised with alkaline reagents, and poly-tungstate salts are precipitated within minutes using phosphate heteroatoms. These salts are then converted to sub-micron, pure WO_3 particles by simple thermal decomposition at 650°C.

Recovery of gold from refractory ores requires a pretreatment step, usually oxidation, to liberate the gold particles from the host mineral. Gold-bearing refractory stibnite, for example, is pyrometallurgically treated to recover antimony in a process that involves the generation of toxic gases. As an alternative, several hydrometallurgical processes have been proposed whereby chemical leaching is applied to liberate the gold particles from the sulphur matrix.

Ubaldini *et al* have carried out experimental work to develop an innovative process, including an alkaline chemical pre-treatment and a conventional treatment, for gold extraction from refractory stibnite ores[18]. Two lixiviants for stibnite dissolution were evaluated – sodium sulphide and sodium hydroxide – the antimony being recovered from the pregnant liquor by electro-deposition. After the alkaline leaching pretreament, the solid residues were then leached using cyanide to recover the gold.

Experimental results showed that around 75% of the antimony, in a high purity and quality form, and up to 80% of the gold in the ore can be recovered. The chemical alkaline leaching pretreatment improved the gold extraction yield with a low reagent consumption and it is believed that the incorporation of a gold purification/gold electro-deposition step within a potential industrial circuit could improve the efficiency and economy of the process.

Heap leaching with cyanide solutions has become an attractive route for gold extraction from certain oxidised ores. The current technology for gold recovery from such pregnant heap-leach solutions usually involves the adsorption of the gold-cyanide complex onto activated carbon followed by stripping to produce richer gold solutions. These solutions are then electrolysed using steel wool as a cathode.

Several researchers have proposed a simplified flow sheet, whereby gold is directly electrowon from the pregnant heap-leaching solutions, eliminating the gold adsorption and desorption steps. This work deals with the performance evaluation of electrolytic cells, with three-dimensional electrodes, for the electrowinning of gold from diluted cyanide solutions.

A recent study by researchers in Brazil[19] has shown the significant effect of two competing reactions in the gold deposition stage – oxygen reduction and water reduction (with consequent hydrogen evolution). An auxilliary electrolyte recirculating device incorporated in the circuit increased significantly the transport of the electroactive species to the cathode surface, enhancing the gold recovery from diluted liquors to over 99%.

Furthermore, the performance comparison among different cell configurations showed that higher gold recoveries were achieved

with a steel mesh cathode compared with a steel wool cathode. This was due mainly to the better surface area distribution and homogeneity, which allows a better flow of the electrolytic solution through the mesh, avoiding the by-pass of electrolyte. The solution re-circulation system has shown to be highly efficient for the purpose of this work.

Over the past 25 years the carbon-in-pulp (CIP) process has become accepted as the main technology in the Western World for the recovery of gold from low grade and complex ore types. However the resin-in-pulp (RIP) process for precious metals recovery has been practised widely in the former Soviet Union for many years.

Resins are more versatile substrates than activated carbon because specific functional groups can be introduced onto the resin matrix during synthesis to alter their sorptive properties. Consequently, several resins have been developed that are able to sorb the gold cyanide complex selectively. It has also been demonstrated that resins in comparison to carbon have superior kinetics and greater equilibrium loading capacity of gold cyanide. Moreover, they do not appear to be 'poisoned' by organic foulants that severely inhibit carbon sorption.

Several suitable eluants have been proposed for the efficient recovery of gold and other metal cyanide complexes from anion exchange units, including ammonium thiocyanate, thiourea and zinc cyanide. However, a simple and cost-effective elution procedure has yet to be developed that is able to selectively strip metal cyanide complexes from ion exchange resins[20].

The results of a current study show that saline solutions can be used to elute copper cyanide and iron cyanide complexes selectively from a variety of anion exchange resins containing different quaternary ammonium functional groups. The behaviour of ion exchange resins in saline solutions is of particular interest to Australian mining companies because of the saline process water used on the goldfields of Western Australia.

The salinity of the available groundwater at these locations is reported to be 200 g/litre of total dissolved solids. It was found that for most resins an elution efficiency of greater than 80% copper and 99% iron was achieved within 16 bed volumes of a concentrated KCl or $MgCl_2$ eluant containing 200 mg/litre free cyanide. Poor elution of metal cyanide complexes was observed when a concentrated $MgSO_4$ eluant containing 200 mg/litre free cyanide was used. It is proposed that the chloride anion successfully competes with copper cyanide and iron cyanide complexes for active sites on the resin. Furthermore, the stereochemistry and degree of hydration of these complexes facilitate their selective elution by saline solutions. The study has also investigated the elution of metal cyanide complexes using conventional eluants such as 2M KSCN or 0.5M $[Zn(CN)_4]^{2-}$.

The results of the study suggest that a sequential elution procedure is possible for ion exchange resins, whereby the elution of copper and iron cyanide is achieved by saline water, and conventional eluants such as thiocyanate or zinc cyanide are used to elute the gold cyanide complex efficiently. The resin can then be regenerated using conventional acid treatments.

Solid-Liquid Separation

Within the mineral industry there is a need to eliminate the dependency on tailings dams for water recovery and solids disposal. Increasingly popular methods of alternative solids disposal is to use tailings for the production of mine backfill or surface stacking. Both of these methods, however, require a very high solids content in the final plant tails and this can be achieved in one solid-liquid separation unit operation with the use of the Deep Cone thickener.

Paste thickeners have been used by the alumina industry for over twenty years, and, more recently, Baker Hughes has combined its expert knowledge of thickener technology with Alcan's operational experience to introduce this concept to the minerals industry[21]. Deep Cone thickeners are now in operation, producing pastes of over 70% solids, suitable for both mine backfill and surface stacking.

Process Control

Leaching, solvent extraction and electrowinning (LX-SX-EW) processes have become increasingly important to concentrate, purify and separate metal ions and inorganic salts, most commonly in the copper industry. Although the leaching of oxide mineralisation is preferred, many operations also leach sulphide ores as well.

The overall control objective of a LX-SX-EW plant is to produce high quality commercial cathodes, which meets certain standards, while maximising the net revenue of the operation. Ideally, real time plant-wide optimisation should be the most effective approach to LX-SX-EW plant control, as in other processes, i.e. the adjustment of the operating conditions of the various units as a function of the raw ore properties and feed rate, metal market prices and energy and reagent costs.

However, LX-SX-EW optimisation and control cannot be performed without a minimum amount of information on the input disturbances, the state of the processes, and the final product quality. This is in fact the bottleneck of LX-SX-EW control and, because of both instrumentation and modelling problems, the usual approach is to separate the optimisation and control problem for each unit operation.

Control of an SX/EW pilot plant developed at the Santa María University at Valparaiso in Chile[22] is organised at three levels: a field level for frequency variators (mixers and suction pumps), speed controllers of peristaltic pumps, and electrical current at EW. A second level of control is organised in a PLC which handles all field measurement inputs, while all the local controller setpoints are outputs from the PLC; and the high level functions, such as process monitoring, processing of information, process supervision (including fault detection, data validation, supervisory control) and data base generation which reside in a PC server.

The plant has been constructed and installed to produce repeatable results. The first objective is centred on the organic-aqueous phase separation problem. Two main problems are considered: the estimation of interphase position and the supervisory control. The conductivity profile data will be analysed by using simple empirical models and by artificial neural networks. Fault detection and supervisory control will be developed as hybrid systems, where conventional techniques (control and statistics) and Artificial Intelligence techniques (expert systems, fuzzy systems, neural networks) will be combined.

Variability in the concentrator feed type may cause problems in process control. This is the case at Outokumpu's Hitura mine. These problems can be alleviated, however, by a system producing on-line information of the feed type to the process operators[23]. Such a system can be created if the plant laboratory and automation system can produce information of the feed type. However, it is crucial that the proper variables for analysis are selected

At Hitura, the information originated from the plant laboratory where samples of the concentrator feed, concentrate and tailings are analysed daily. At Hitura eight parameters of the concentrator feed were used. This off-line data was mapped onto the Self-Organising Map (SOM) and the mapping result was clustered. The clustering produced eight clusters representing as many concentrator feed types. The clustering result was verified with mineralogical analysis

based on X-ray diffraction (XRD) of selected samples. The off-line classification was able to predict the mineralogy of the samples. Thus the off-line result can be used as the basis for the on-line analysis.

For the on-line determination, only on-line data can be used. The difficulty is that from hundreds of on-line measurements the correct set must be found. The correct set is found by an iterative analysis. Prior to the iteration, a set of potential on-line measurements is collected. In Hitura this set contained 55 on-line measurements available from the automation system.

At the beginning of each iteration round, all measurements in the studied set are scanned for their ability of separating between the feed types. The study is done using the Davies-Boulding index. The worst of the measurements is discarded from the set and the iteration is restarted. The iteration is continued until only one measurement remains in the set. In each iteration round the overall performance of the variable set is determined by calculating the Davies-Boulding index over all cluster pairs and taking the average of these values.

After 51 iterations, only five variables remained at Hitura which were used to create a SOM mapping of the feed types. With this SOM mapping and the above off-line classification result the accuracy of the on-line tool can be assessed.

The drawback of this system is the operator dependency of the found on-line variables. The operators study the quality of the concentrator output and make conclusions of the feed type. According to this they make changes to the process. A variable that appears to contain explicit feed type information may only contain information of the operator decisions. Such measurements must manually be discarded from the set after the analysis. In the case presented above, the froth level in the rougher is such a variable.

The Measurement and Control Division of Mintek has been involved in the development of mineral processing control systems for industrial application for many years. Mintek has recently completed a new control product that incorporates milling and flotation control strategies and functionality of its MillStar and FloatStar systems, as well as others, into a single unit[24]. This new plant-wide control system is called PlantStar.

In order to fulfil PlantStar users' requirements for an open, easily understandable system, the Interpreting Expert System (IES) developed for MillStar has been incorporated into PlantStar. This Artificial Intelligence (AI) solution provides 'on-line training' to the unskilled plant operator using the system, by translating the numerical results of the algorithms in use into understandable human sentences. By doing this, the operator becomes more familiar with PlantStar and hence has fewer reservations about its use.

The advent of the Internet and the increasing power of the PC have released the potential for real time communication of plant data around the world from the desktop. Applications are continually being developed to exploit the latest technology and to enable businesses to lever data into knowledge that enables continuous and rapid process improvement and business optimisation. Bascur and Stead have highlighted some of the current information technologies that are being applied in the development of enhanced dynamic performance monitoring systems and integrated workflow systems[25].

A robust environment at the industrial desktop provides with real time, historical process/equipment information and business information for all functions in mining/metallurgical complexes. This environment enable users to build, construct and maintain their views of the plant for simplified performance monitoring, process and equipment troubleshooting, continuous improvement and innovation.

The key to re-engineering is linking people, business processes, strategies and the best enabling technologies. Many benefits are available that do not require disruptive re-engineering. The major ingredients for successful implementation are:

- An open scaleable infrastructure that follows the suggested computer architecture (technology);
- The integrated process management workbench using the industrial component desktop metaphor to unify the access of information according to user role (business processes); and
- Implementation of total quality management guidelines and people empowerment (strategies and people) for continuous improvement and innovation.

References

1. Wang, Y. and Forssberg, E. 'Microwave assisted comminution and liberation of minerals', *Mineral processing on the verge of the 21st Century*, Proceedings of the 8th International Mineral Processing Symposium.
2. Griffin, T.S., Downing, T.L. 'New primary crushing system for processing of borate ores', in Ref 1.
3. Apelt, T.A., Asprey, S.P., Thornhill, N.F., 'Inferential measurement of SAG mill parameters', *Minerals Engineering 2000*, Proceedings of the 10th Annual Minerals Engineering Conference, Cape Town, South Africa.
4. McDougall, S., Cooke, R., 'Elutriation – a novel way of solving a screening problem', in Ref 3.
5. Ciçek, T., Cöcen, I., Birlik, M., 'Applicability of multi-gravity separation to the KOP chromite concentration plant', in Ref 1.
6. Xiang, Q., Schlessinger, M.E., Watson, J.L., 'Red mud minimisation by iron removal - iron reduction', in Ref 1.
7. Ennis, J., 'Magnetic tracers' , in Ref 3.
8. Nguyentranlam, G., Galvin, K.P., 'Dynamics of the Reflux Classifier', in Ref 3.
9. Carbini, P., Bortolussi, A., *et al*, 'Prospects of high-velocity waterjet in mineral processing', in Ref 1.
10. Hoyer, D.I., Mulvihill, B.M., 'Hicom attritioning to remove alumina-silicate coatings on ilmenite sand grains', in Ref 3.
11. Matabishi, M.K., Handfield-Jones, R., Akdogan, G., 'Effect of electrochemical environment on collectorless flotation of some sulphide minerals', in Ref 1.
12. Köse, M., Hosten, Ç., Topkaya, Y., Akser, M., 'Selective flotation of ilmenite from ilmenite-rutile mixtures,' in Ref 1.
13. Iwasaki, I., 'Iron ore beneficiation in the US: past and future', in Ref 1.
14. Ghian, M., Serci, A., Peretti, R., Zucca, A., 'Beneficiation of gold sulphide ores from south Sardinia, Italy', in Ref 1.
15. Honaker, R.Q., Singh, N., Patil, D.P., 'Enhanced gravity beneficiation using a dense medium for fine particle gravity separations', in Ref 1.
16. Saleh, A.M., 'Effect of collector emulsification on coal flotation kinetics and on recovery of different particle sizes', in Ref 1.
17. Gürmen, S., Timur, S., Arslan, C., Duman, I., 'A new alternative in tungsten production: chelate-added acidic leaching', in Ref 1.
18. Ubaldini, S., Abbruzzese, C., Vegliò, F., Trifoni, M., 'Leaching pretreatment for gold-bearing refractory stibnite', in Ref 1.

19. Sobral, L.G.S., Dutra, A.J.B., Barbosa, L.A.D., 'Gold electrowinning from diluted cyanide liquors: performance evaluation of different reaction systems', in Ref 3.
20. Lukey, G.C., van Deventer, J.S.J., Shallcross, D.C., 'The selective elution of metal cyanide complexes from ion exchange resins containing different functional groups', in Ref 3.
21. Shelley, J.L., MacNamara, L., Slottee, S., 'An introduction to Deep Cone thickening technology and its application', in Ref 1.
22. Luis G. Bergh, L.G., Yianatos, J.B., 'Instrumentation, control and information system of a SX/EW pilot plant', in Ref 3.
23. Laine, S., Simula, O., 'Selecting the on-line variables used for the on-line determination of the concentrator feed type', in Ref 3.
24. Houseman, L., Schubert, J., Babarovich Hansen, V., Smith, V., Hart, J., 'A plant-wide control system for mineral processing', in Ref 3.
25. Bascur, O.A., Stead, N.K., 'Mineral processing optimisation and collaboration at the industrial desktop', in Ref 3.