

# Heaps of new technology

New ideas, chemicals and technologies in the heap leaching world, John Chadwick takes a look

In their paper at this year's SME Annual Meeting, the University of Utah team commented that "with ever-increasing demand, low-grade complex ores and strict environmental regulations, metallurgical processing options have become limited. Heap leach technology provides several benefits to combat these issues including low cost, flexibility and diversified process conditions." The paper<sup>1</sup> provides an overview of heap leaching technology with specific emphasis on chemical aspects. Hence, influencing factors, advantages and disadvantages, testing approaches and some fundamentals are discussed. Finally, heap leach technology for different ore types (copper, nickel, uranium and gold) is briefly compared.

They conclude that "many factors control the heap leaching process; however, proper heap building, mineralogical evaluation of ore, efficient comminution, and the precise use of available tests (feasibility approach) must be undertaken to ensure a successful heap leach operation. The advancement of heap leach technology can be easily sensed through the presence of technology in different ore types. The growth in modelling studies and fundamentals will make the heap leach technology more adaptable to ever increasing complex ores. Based on the aforementioned evaluations, more heap leaching operations are expected to come into the business. However, many of the areas included in heap leaching remain open to research with regard to comminution effects, characterisation tools, improvements in unit operations (agglomeration and heap building) and modelling approach."

Outotec is a leading SX/EW technology supplier with an extensive track record in building complete plants. Larox, which was

recently acquired by Outotec, is well known for efficient and reliable filtration process equipment.

New Outotec Larox DM electrolyte filters, which are specially designed for efficient removal of entrained organic and suspended solids from electrolyte, using the well proven dual media concept. The Outotec Larox DM filter package can be delivered as an integral part of Outotec's SX-EW technology delivery or stand alone solution to engineering companies and end users.

This electrolyte filter is suitably designed to be backwashed using either lean electrolyte or water.

Outotec says this offers high quality filtration because adsorption filtration using the well proven dual media concept reduces entrained

organic and particulate concentrations to a level of a few parts per million. Production capacities increase, as does the quality of cathode products.

The filters use two separate layers of media for coalescing and for filtration. The upper media layer provides for organic removal while the second layer filters particulates in the electrolyte.

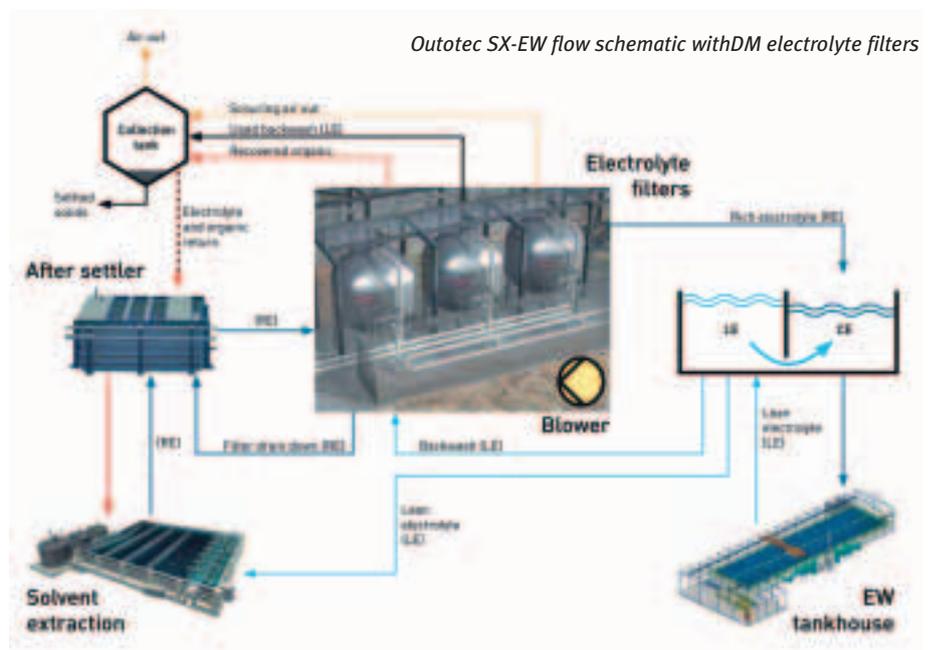
Low electrical energy consumption is a cost-saving benefit, as the adsorption filtration technique uses low pumping pressures compared to alternate solutions utilizing flotation.

Automatic (PLC) control of the electrolyte filtration and media cleaning steps at the end of each filtration cycle ensures maximum filtration time in subsequent cycles. Outotec says "DM electrolyte filters are delivered as an automated operational filtration system which can be fully integrated to any SX-EW solution package.

"Using lean electrolyte for backwashing and returning it to the After Settler after holding in a backwash collection tank (see flow schematic) means [these] filters do not reduce the capacity of SX production. Filter flow rates as high as 275 m<sup>3</sup>/h can be consistently handled by a single unit (5.2 m diameter), greatly simplifying the process.

"Typically, multiple units are installed in parallel for flexibility and expandability to economically accommodate growing plant capacity requirements.

"With no moving parts, the media cleaning system ensures maximum media lifetimes. Typically the anthracite media is replaced every 24 months when combined with Outotec's proven SX process technology. Garnet lifetime is considerably longer."



Outotec SX-EW flow schematic with DM electrolyte filters

Paul Keyser, FLSmidth Global Product Director, SX-EW, says FLSmidth is a relative new comer to SX-EW, but has big plans. For years, through its legacy companies, the company has supplied both liquid/liquid and solid/liquid separation technology to support SX-EW operations. Products such as WEMCO Pacesetters, EIMCO OTG granular media filters, EIMCO Precoat vacuum filters, Shriver filter presses and Krebs liquid/liquid hydrocyclones are widely accepted “and do an exceptional job for their respective duties for raffinate, electrolyte, loaded organic and crud and clay treatment. In addition, FLSmidth is the leader in leaching and supply of solid/liquid counter current decantation (CCD) circuits for production of high quality PLS to feed SX-EW. FLSmidth offers complete SX-EW plants, up to and including overseeing installation and start-up as well as post commissioning support and service.”

“In addition to traditional SX-EW technologies using reverse flow mixer settlers and standard EW facilities, FLSmidth is also investing substantially in R&D to develop the next generation mixers, settlers and tankhouses.

Early results are promising and point to improved and favourable droplet formation and significant reductions in settler footprint. As mineable ores become harder to find and lower in quality and grade, FLSmidth will be there to offer solutions that make exploiting key resources possible.

“Unique to the minerals industry, FLSmidth is the only company that has the breadth and resources to assist customers with not only the SX-EW plant, but to reach much farther upstream and take on project responsibility starting from the mined ore, through both fully mobile and fixed conveying, crushing, heap stacking, leaching and SX-EW. The approach reduces the time to first production. The FLSmidth Ore-to-Cathode, complete solutions approach is what sets FLSmidth apart in the industry and will be a market driver for growth over the next decade and longer.”

### Agitation

M C Process has over 20 years' experience in tank agitator technology with over 100 agitators installed globally. The company says it aims for “optimal performance, reduced wear and optimal use of power.” Its agitators are supplied with a bearing housing which ensures the forces generated by the impeller are not transferred to the gearbox ensuring a more robust design and longer equipment life.

M C Process has developed a constant velocity impeller, which gives constant pumping across the width of the impeller; allowing for reduced impeller rotational speed for the required pumping rate. It says the unique benefits include lower power consumption, reduced ‘crud’ formation, improved mixing efficiency and adjustable head and volumetric throughput.

*Krebs DeOiler (FLSmidth) manifolded system for increased capacity*



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*Knight Piésold works with the world's prominent gold producers providing design and operational assistance for tailings management, water management, and heap leach facilities. Recently, the company's work involved designing a combined heap leach and tailings facility in which the heap leach ore stack provides containment for all the tailings. It has been in operation for over four years and has met or exceeded the design criteria and provided its owner with a unique, cost and space effective solution*

The company also claims to be “to date the only supplier of SX plants to use vacuum infused, fully composite mixer settler tanks which optimise a huge number of benefits.” It also says its Jet Scrubber “is a paradigm shift in attritioning technology.” The principal of the Burgen Turbine attrition scrubber is “that we need to create more attritioning zones within the machine, akin to a jet engine or turbine, where multiple compression vanes in a single vessel.”

### **Flocculation in SX/EW**

Mick Bower of Kemira Oil & Mining commented that “the solids/liquids separation processes in leach/SX/EW plants are very different from most of mining’s typical settling applications. In the case of leach plants the value is actually contained in the liquid rather than the solid such as a concentrate. This means that although the equipment used is essentially similar to that seen elsewhere on a plant (settlers/clarifiers/filters) their operation is different. The settling of solids in low pH solutions is actually straightforward when using the correct types of flocculant, such as Kemira’s Superfloc N100. The most important aspect for reagent selection in these plants is the downstream compatibility with the SX process. The SX stage is very sensitive to contaminants, poor selection and application of reagents can lead to significant problems with crud formation and excessive phase disengagement times. Control over the provenance of the reagents is often overlooked and plant operators should

look to source from the larger manufacturers such as Kemira who can guarantee the consistency and compatibility of their products. What may be acceptable as a flocculant for a tailings thickening application could easily upset the SX circuit.

“Managing the interaction between flocculation and SX is the key to running a successful operation. Having both a qualitative and well as a quantitative aspect to consider makes the process a lot more complex than typical tails thickening. Initially we would look to control the solids in the overflow with a target somewhere between 20 and 50 mg/l but we also need to minimise the residual flocculant effects. This means simply adding a higher dose as you may do with other thickeners is not an option. Minimising the residual floc in the overflow is influenced heavily by having a good addition scheme such as properly designed feedwell lances and effective dilution streams. Design and the maintenance of the make-down and dosing equipment used with the flocs are very important as poorly dissolved material will track through to the overflow and eventually into the SX circuit. One common problem has been that a lot of operators have expanded plants, increasing the flocculant dosage but have not added sufficient extra capacity to the make-down system thereby shortening the effective residence time.

“As the technology becomes more advanced it will also become less forgiving and the level of operators’ understanding of the interactions is key. The processes are becoming more like the chemical industry than a mine and a high level of training is required. Typical reactions such as increasing reagent dosages in the event of a plant upset may not have the desired effect.

“The trend since the early plants has been to move away from filters over to lower cost CCD trains and plants are now starting to be built with high compression thickeners. Clarifiers are becoming more common and Kemira is looking at chemistries for improving this further. The difficulty being that a lot of the conventionally used reagents are incompatible with the SX.

“Scale control in leach plants is of particular interest to Kemira. Heap leach operations are dependent on the effective distribution of the leachate over the heap and scale formation can be a serious problem blocking the wobblers or emitter pipework. Although less common in agitated leach plants it is often seen in the leach pachucas and PLS lines. The most common form is gypsum and although there are a large number of reagents effective against gypsum the issue is again compatibility with the SX and reagent choice needs careful consideration.”

### **SX reagents**

Cytec notes that “largely unchanged over the last 30 years, the SX process employs a very small number of highly specific oxime molecules which are ideally tailored for this application. As a result of this extraordinary class of extractants, copper SX is the least complex process of its kind and also the most versatile. Despite this there are always many ways in which to optimise an SX process, particularly using the experience and toolkit of the reagent supplier. Much value can be generated by optimising parameters such as i) the reagent formulation, ii) reagent concentration iii) the extract O to A ratio, iv) the stage efficiency, v) selectivity of copper over iron, vi) entrainment of organic in the raffinate and rich electrolyte vii) entrainment of aqueous in the loaded and stripped organic as well as many other aspects. Many of these aspects can be optimised using the reagent supplier’s modelling tools that allow one to simulate alternative operating conditions and select the best operating parameters for the given PLS and circuit design.

“Over the last 15 years the market has made a steady shift from aldoxime-ketoxime extractants to modified-aldoxime and modified-aldoxime-ketoxime extractants. In 2012 modified extractants will make up more than 70% of the copper extractant market. The primary benefit of the presence of a modifier is the ability to tailor extractant formulations to precise strengths to maximise copper transfer for specific feed conditions whilst improving selectivity over iron and hydrolytic stability.

“Finally SX refineries are being increasingly built that recover more than one metal by SX and need to capture these multiple revenue streams to be economical. Extraction circuits for metals other than copper are more complicated and these operations need to be optimised for more than one metal and thus are finding even greater need to have expert services delivered with their multiple reagents purchased.”

Over the last few years as copper oxide ores have become depleted, there is increased interest in processing sulphidic ores using hydrometallurgical routes. This allows mine

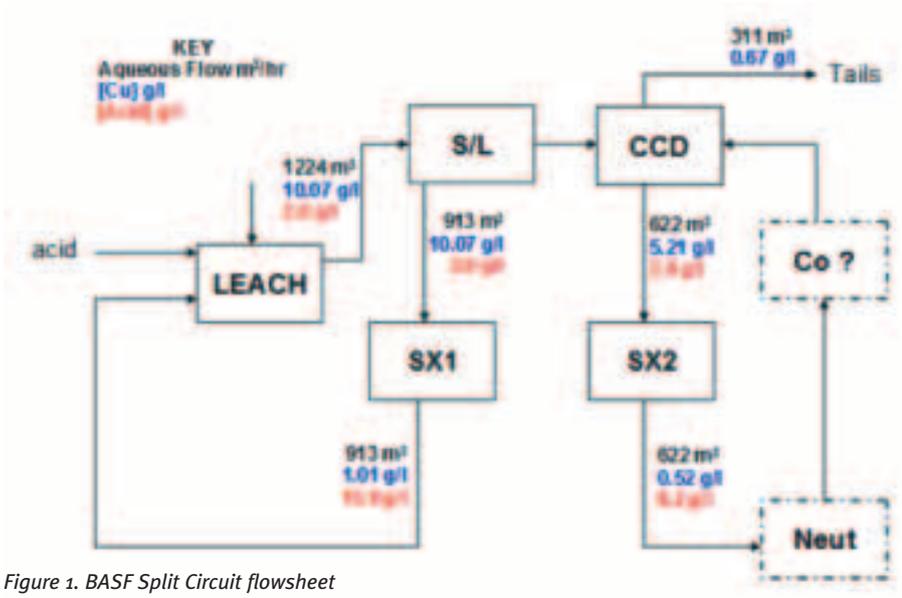


Figure 1. BASF Split Circuit flowsheet

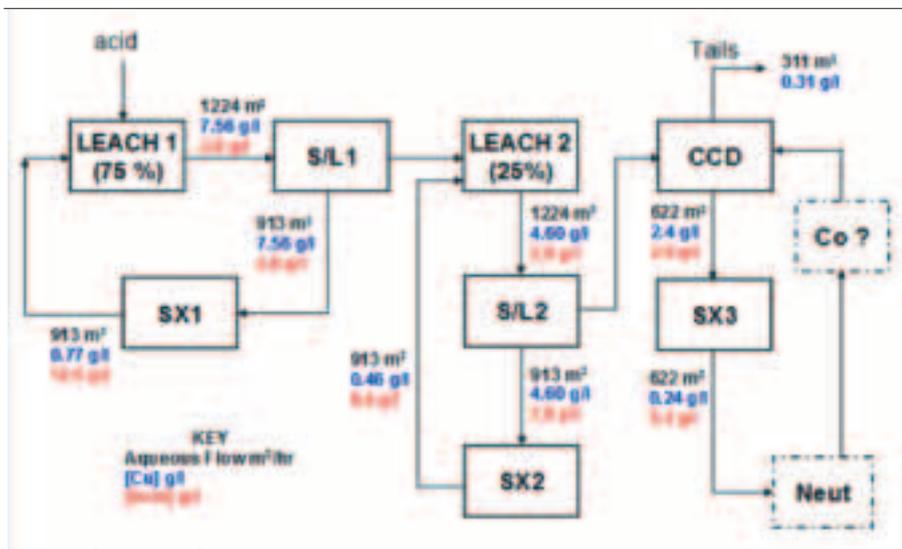


Figure 2. Sequential Circuit flowsheet

operators to use existing SX-EW equipment to produce high quality copper cathode directly. Additionally, in many instances the economics of the oxide ores are substantially enhanced by performing separations of multiple metals. As hydrometallurgical knowledge continues to grow and more advanced flowsheet designs are developed, SX to isolate other metals is becoming more reliable and effective than in the past. Where is the end game many years from now? Cytec believes “eventually ore will be primarily hydrometallurgically refined, extracting many metals from a single ore. Once all the mining, milling, grinding and leaching is complete, the refining of lower concentration metals becomes economical because the primary costs of getting to a PLS are all already spent. So the need for R&D spending on reagent development, formulation and application knowledge continues to grow as the world’s demand for more metals from the same available earth grows. As such advance technology and application support is a critical

differentiator in supplier selection not only to get the most metal possible from a given amount of ore that is already being processed but also because of growing scarcity of metals and energy. Only in the Copperbelt of Africa is there substantial copper oxide ore with a copper

grade above 3%. Most of the other ore that is being processed is less than 1%. So mining companies interested in a long term future, need to align with companies that will be developing these next generation reagents and processing routes.

“Cytec’s Acorga® reagents are the most comprehensive set of solvent extractants for copper in the industry and our Cyanex® Reagents are the leading technology for cobalt nickel separations. We combine our reagents with unmatched application knowledge as well as modelling tools. Cytec is uniquely positioned to offer modelling named MEUM™ Modeling Software for more than copper. Cytec is expanding into other metals at a pace that is unmatched as well with SX products available for copper, nickel, cobalt, rare earths, molybdenum and uranium with more to follow. Thus Cytec has the best tools to aid companies that are developing non-standard flow sheets or are planning to have multiple metals extraction.

“Cytec collaborates with mining companies to ensure that they get the most metal at the least operating cost. We do this by providing superior support that addresses our customer’s site specific needs. Our on-site application technologists ensure that our customers receive extraordinary extraction performance.”

New products include the Acorga® NR series and OR series of products, developed to provide higher degradation resistance in Cu SX circuits that have occasional or consistent exposure to high nitration or oxidative conditions. With these products the valuable extractant inventory is protected.

Cyanex® 600 is used to recover Mo from moderate to high volume acidic streams which contain low concentrations of Mo. Use of this product and Cytec’s unique process allows economic recovery by concentrating Mo by over 1,000 times. This allows existing Cu SX operations and other operations to get an additional revenue stream from already

**BASF split circuit economics**

	Conventional flowsheet	Split circuit flowsheet
Operating days per year		360
Total cost acid+base (Σ\$/t acid)		200
Cu price (\$/lb)		2.50
Acid to neutralisation (t/d)	167.2	107.5
Total cost (\$ million/y)	12.038	7.740
Cost benefit (\$ million/y)		4.298
Cu in soluble loss (t/d)	6.792	5.000
Total revenue loss (\$ million/y)	13.448	9.900
Revenue benefit (\$ million/y)		3.548
Overall benefit (\$ million/y)		7.846

Recovery of copper by solvent extraction.  
 Courtesy of Nord Resources

processed ore or from byproducts that contain Mo. This breakthrough also has the potential to make substantial additional volumes of Mo available to the global market and thus improve the availability and use of high performance alloys that contain Mo.

Cytec can now model the separation of Cobalt and Nickel via SX. This allows mines to partner with Cytec in order to optimise the design of a future operation or to substantially improve the efficiency of an existing operation.

**Split leach solutions**

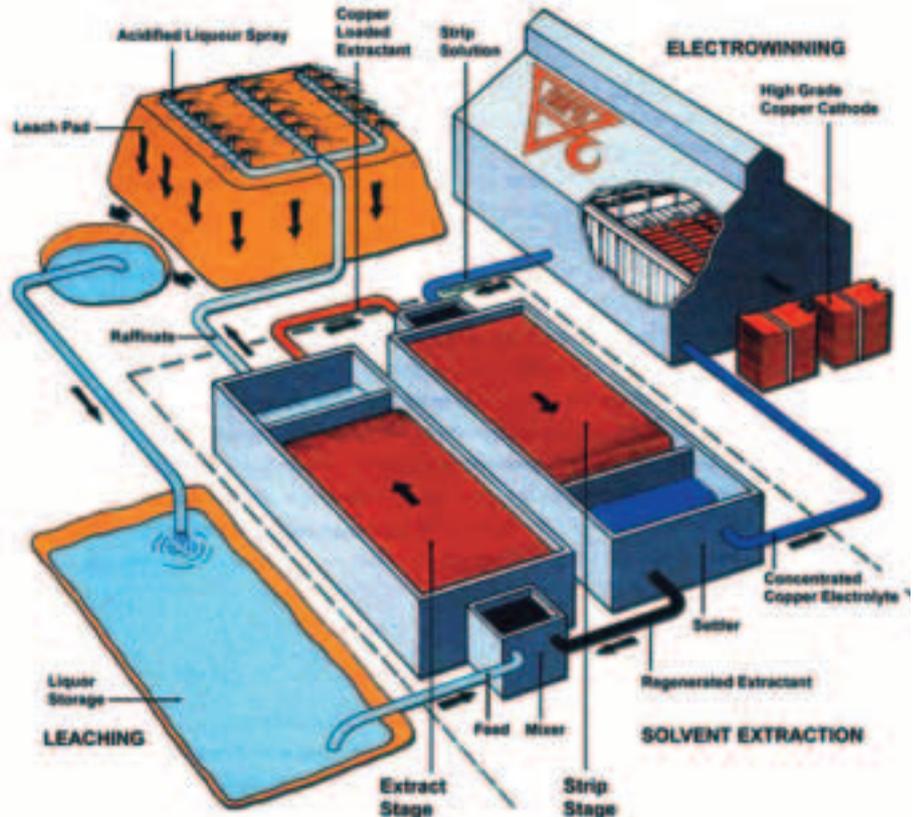
BASF's Mining Solutions Group offers a diverse range of mineral processing chemicals and technologies to improve process efficiencies and aid economic extraction. BASF's offerings include reagents, equipment, process technologies and knowhow, focusing on areas such as grinding, flotation, hydrometallurgy, solid liquid separation, tailings management and materials handling. Stemming from its hydrometallurgical sector, the Mining Solutions Group has been granted US patents covering its split circuit technology which is particularly useful to agitation leach-SX of copper ores. The split circuit configuration effectively splits the leached solution into high and low grade streams which allows one to take maximum advantage of the thermodynamic behaviour of the SX reagent by treating each stream separately in the SX process.

The raffinate produced from the high grade solution is returned to the leaching step to reuse the acid that has been generated. Raffinate produced from the low grade leach solution, which is comparatively lower in concentration in both metal species and acid than in the conventional process, is passed to the washing activity, and a portion is ultimately bled from the circuit as the soluble loss fraction (Figure 1).

In this way, the configuration minimises soluble losses. Other operating improvements are realised due to lower neutralisation costs prior to tailings disposal.

The economic benefits of the split circuit are clearly apparent once a detailed mass balance of both the metal species and acid is performed. The relative simplicity of the concept means that incorporation into an existing flowsheet can be done easily and with a minimum of capital outlay.

The split circuit provides operational flexibility and, in areas of the world where the cost of acid and neutralising agent are high, the operating cost benefits of the concept can be substantial. The results of an economic case study for an agitation leach plant processing



8,700 t/d of ore are summarised in the table.

BASF has also filed for patent coverage on a further refinement of the Split Circuit technology referred to as the Sequential Circuit technology (Figure 2). It involves incorporation of an additional agitation leaching step between the primary leach and the final liquid/solids separation step, resulting in a total of three aqueous streams being generated which are each separately treated by SX. The cost analysis (excluding additional capital cost and fixed costs) indicates that operational savings due to increased copper recovery and acid recovery are potentially double those obtained with the Split Circuit technology.

BASF will host its LIX Users' Conference in Prescott, Arizona this year. The purpose of

this conference is to provide a forum where BASF customers from around the world gather to meet with experts in the field and share

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operation experiences and innovative solutions unique to their plants. The attendees will present technical papers covering a variety of topics including developments in plant design, plant expansions, equipment, new leaching and anode technology, organic recovery systems and new reagent technology. As usual a tour of a commercial mining property will be included as part of the conference. The extensive technical program provides each participant with the opportunity to learn something new that they can apply at their hydrometallurgical operation to improve product quality, metal recovery and/or lower costs and improve sustainability.

### More SX ideas

In March, TNG Ltd advised that the pilot plant test work program for its flagship Mount Peake iron-vanadium-titanium project in Australia's Northern Territory had commenced. The work program, which follows detailed and exhaustive bench scale and optimisation test work, focuses on the final stage of the process, which involves the production of the final marketable products from the Mount Peake deposit – iron, vanadium and titanium.

This phase of the proprietary TIVAN™ SX process test work is a chemical phase which will run continuously during this test work at the ALS-AMMTEC laboratory in Perth using modified SX equipment. It will aim at achieving a definitive test of the commercial potential of the TIVAN process to produce a high-purity aqueous vanadium solution leading to production of vanadium pentoxide of commercial grade.

The new hydrometallurgical process has been jointly developed with TNG's representative metallurgical consultants, Mineral Engineering Technical Services (METS). This new processing route has been successful in recovering the three principal commodities – vanadium, titanium and iron – from bulk samples of Mount Peake ore. TNG and METS have submitted a joint Patent Application to protect the invention and allow commercialisation at a later date.

The Mount Peake deposit – which currently contains a JORC Inferred Resource of 139 Mt grading 0.29% ( $V_2O_5$ ), titanium ( $TiO_2$ ), 23.7% iron (Fe), is amenable to processing using conventional pyrometallurgy and produces smelter acceptable concentrate grades. However, TNG and METS believe that the hydrometallurgical route may provide an alternative route for improving project economics, being cheaper and less environmentally challenging.

Test work carried out by TNG/METS has now shown the magnetic concentrate is amenable to hydrometallurgical processing, resulting in very high recoveries of vanadium (98%) and iron (83-99%) in the acid leaching. These results have

importantly demonstrated that the iron can be separated from the vanadium by using SX, producing high grade Iron.

This new processing route has now been proven to allow more than a single product to be generated and may therefore have a positive impact on the overall project economics. However the anticipated lower capital and operating costs and the higher recovery of the valuable products still need to be demonstrated in further test work.

The process developed by TNG and METS utilises the combined process of acid leaching, SX and stripping to selectively recover the metals. METS Director and Principal Consulting Engineer, Damian Connelly, said the development of the new process had the potential to deliver a significant breakthrough in the processing of vanadium ores globally, subject to further test work.

In mid-May, TNG advised of an important step towards confirming the commercial potential of the TIVAN process after receiving outstanding analytical results from a recently completed continuous-run pilot plant test work program. Importantly, recoveries of 80-90%, which are higher than previous results, were achieved for vanadium pentoxide ( $V_2O_5$ ), which was extracted to a purity of 99%.

The grade and purity of  $V_2O_5$  have been determined by Inductively Coupled Plasma (ICP) analysis. This is now being independently verified at the CSIRO in Sydney. Final grades of the  $TiO_2$  and  $Fe_2O_3$  are currently being assessed via additional analytical test work.

The final PFS is on track to be delivered by the end of June 2012. If proven, TIVAN offers competitive advantages over standard processing including lower capital and operating costs, higher recoveries and purity, and the ability to produce three product streams – vanadium pentoxide, titanium oxide, and ferric oxide.

TNG believes it has the potential to be approximately 40% cheaper than standard pyrometallurgical process costs. The commercialisation of the process underpins TNG's development proposition at Mount Peake. The technology also has the potential to be rolled out and applied to other vanadium deposits globally.

Quest Rare Minerals is working on its Strange Lake B-Zone deposit, where significant improvements in metal extraction have been achieved at Hazen Research. Acid consumptions of approximately 200 kg/t are being achieved with REE (rare earth element) dissolutions in the 90-96% range, niobium dissolutions in the 93-96% range, and zirconium dissolutions in the 85-93% range. Considerable bench scale work has shown excellent reproducibility, and most

operating variables have been established.

Work at Process Research Ortech (PRO) commenced in the first quarter of 2012, and significant progress has been achieved. Flowsheets to achieve the separation of zirconium, niobium, uranium & thorium, and REE concentrate have been developed. Quest reports that bench scale work has confirmed these flowsheets to the extent that a zirconium hydroxide product and a REE+Y oxalate product have been produced. Uranium and thorium have also been extracted successfully from the circuit with the intention of producing an environmentally stable discharge product. Significant work has been carried out on niobium and titanium separation. It was expected that this separation will be resolved in June, 2012.

Extensive bench scale testing of a thermal sulphation process has been completed at Hazen. In the process that has been developed, ROM material is crushed and ground, then mixed with sulphuric acid. The material is then heated and undergoes a thermal sulphation process where the sulphuric acid attacks the ore and forms the sulphates of the contained value metals. The dry calcine proceeds to a water leach where the values are dissolved into solution. The slurry is filtered and washed to produce a pregnant leach solution (PLS).

Extensive testing of the thermal process has determined conditions at which the refractory rare earth containing minerals can be attacked without the use of caustic (sodium hydroxide) or extreme temperatures. Rare earth, zirconium, and niobium recoveries to solution of up to 96%, 93%, and 96%, respectively, have been demonstrated.

Bench scale SX test work to develop the separation processes is underway at PRO. The PLS containing the zirconium, niobium, and rare earth values is the starting point for SX testing. The bench scale testing involves selecting appropriate organic reagents and analysing their ability to separate the value metals from contaminants and each other. All SX separations are achieved using commercially available extractants.

In the flowsheet that has been developed, zirconium and niobium are removed and uranium and thorium recovered for final disposal. Following these initial separations, oxalic acid is added to the main process stream to precipitate rare earths and yttrium. Over 97% of the REE+Y values in solution are recovered to the oxalate precipitate. This oxalate precipitate will then be re-dissolved to produce a concentrated solution of rare earths and yttrium, which will undergo further refining using SX to achieve the individual separations.

Mini-pilot plant testing to confirm individual

product flowsheets established from bench scale testing is scheduled to begin in September, 2012. The results of these pilot programs will be used to finalise the flowsheet for the full scale pilot plant, which is expected to be operational in Q1 2013.

Will Goodall and J.C. Perkins of Aura Energy note that “the development of complex low-grade mineral deposits is becoming an increasingly important target. These deposits often present marginal economic opportunities, which are highly dependent on the development of low-cost and efficient processing strategies and the utilisation of byproducts to become a viable development target. For exploration-focused companies this presents a critical investment decision stage early in project development on whether to pursue potentially expensive resource definition or look for other targets.

“The Häggån project, Sweden has presented a target requiring careful technical evaluation through the early development stages. The project represents a low-grade complex uranium resource, with significant vanadium, molybdenum, nickel and zinc credits.” A process of mineralogical characterisation and multi-directional scoping metallurgical test work has been undertaken. “Implementation of this process has allowed the development of conceptual flowsheets targeted at efficient recovery of value metals and the rejection of

technically ineffective options based on an understanding of the material and its behaviour.

The material is low-grade and complex, with conventional leaching options not proving to be economic. Through thorough evaluation of the mineralogy and using that knowledge to direct and explain test work results, a previously untested leaching option was examined and shown to transform the project both technically and economically. This step forward has opened up a major uranium resource that had previously been considered uneconomic, potentially transforming the approach to recovery of metals from similar deposits.

Examination of operations that treated similar material to the Black Shale at Häggån identified Talvivaara’s polymetallic operation in Finland (*IM*, November 2008, pp8-16). This project effectively utilises a bacterial heap leaching process to recover Ni, Cu and Zn from material similar to the Häggån material but with pyrrhotite as the dominant sulphide mineral, rather than pyrite. Successful implementation at Talvivaara, demonstrated that bacterial leaching could be a technically and commercially viable option. All the preliminary indicators examined to date have shown that the material is ideally suited to bacterial heap leaching, with good permeability and an accessible source of pyrite for bacterial growth.

### SX-EW safety

EW produces carcinogenic sulphuric acid mist which raises health, safety, environmental, efficiency and operating cost issues. Oxygen bubbles are released at the anode as metal is simultaneously deposited on the cathode. The bubbles rise from the anode through an acidic electrolyte solution then burst at the surface, ejecting fine droplets of toxic mist.

CSIRO says “a fundamental understanding of how bubble characteristics influence the size and quantity of acid mist droplets is the first step in reducing, and ultimately eliminating, the mist.” To facilitate this study, it has “built the largest transparent EW rig in the world, which is important because the depth of the solution affects the size of the bubbles that form.

“Data gathered from the study can be further used to develop a computational fluid dynamic model to simulate mist generation and dispersion in operations.” *IM*

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2. Goodall, W.R. and Perkins J.C., *Early stage metallurgical evaluation of a complex low-grade uranium project*, ALTA 2012, Perth, Australia.



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