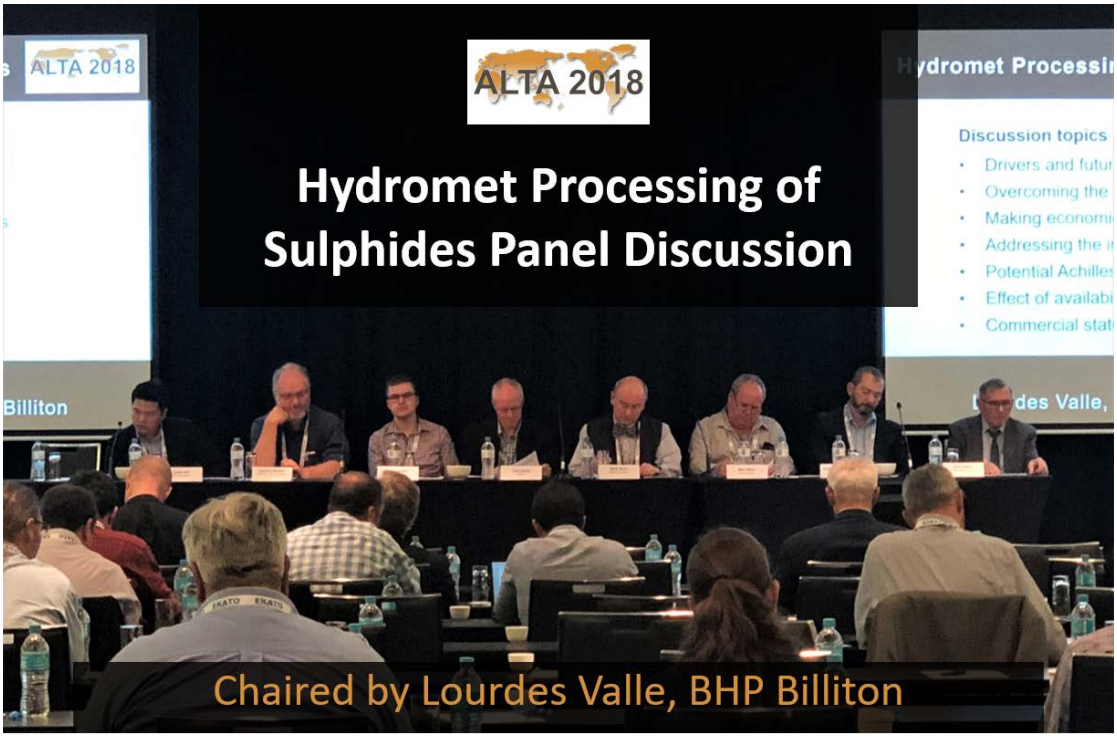

ALTA 2018 HYDROMET PROCESSING OF SULPHIDES PANEL DISCUSSION

May 2018

The panel discussion was held Wednesday 23 May, immediately following the Hydromet Processing of Sulphides Forum during the Nickel-Copper-Cobalt Sessions at ALTA 2018 in Perth, Australia.

Panel Chair: Lourdes Valle (LV), BHP Billiton (Australia)

Panel Participants (left to right): Justin Wu (JW), Teck Resources (Canada); Jacques Eksteen (JE), WASM, Curtin University (Australia); Arto Laukka (AL), Mondo Minerals (Finland); John Neale (JN), Mintek (South Africa); Mark Benz (MB), MRB Consulting (Canada); Mike Miller (MM) , SNC Lavalin (Australia); Aleksandar Nikoloski (AN), Murdoch University (Australia); Alan Taylor (AT), ALTA Metallurgical Services (Australia)

***Editor's Note**: The contributions of the panel members and delegates are not presented verbatim, but rather have been paraphrased and condensed for clarity and brevity. They are not necessarily recorded in order, but are grouped into major topics. Also, it is not feasible to include all contributions made during the discussions, and they are limited to some that are representative of the key points raised and debated.*

The Future for Low-Grade Ores and Concentrates

LV (Chair) opened the discussion by asking the panel what does the future look like for low-grade ores and concentrates?

AT (panel) observed that for low grade ores there has clearly been a trend towards heap leaching which is now well established for secondary copper sulphide and has now begun to be applied to polymetallic ores. A lot of work has also been done on nickel. The focus is now on chalcopyrite heap leaching which is on the verge of commercialization with a few semi-commercial operations already underway. A notable example is Olympic Dam in South Australia which involves the use of chloride to surmount the passivation layer, which requires a temperature of about 60^{o}C with typical sulphuric acid solutions.

LV (chair) agreed that saline heap leaching is something to watch in the future. Spence had successfully applied it on a commercial scale to their low grade mixed hypogene – secondary sulphides. Cerro Colorado in Chile and Olympic Dam (ore contains 70% chalcopyrite) are currently developing the process in advance demo and pilot stage respectively and achieving promising results.

JE (panel) said that while alkaline glycine is not a contender for regular chalcopyrite concentrates, recovery of copper and gold from low grade chalcopyrite concentrates and heap leaching of low-grade whole ore are potential niche applications, which are currently being evaluated for a number of prospects. A significant advantage of glycine over sulphuric acid is that it recovers gold as well as copper. On the other hand, it operates at a high pH of 10-11, which comes at a cost.

MM (panel) Pointed out that energy cost is a driving force towards heap leaching because of the elimination of the power intensive grinding needed for sulphide flotation.

AT (panel) reported that Glencore announced at the conference the first commercial copper application of their Albion Process for chalcopyrite concentrates at a 10,000 tpa plant in Zambia, which has achieved 99% recovery of high-grade copper. Other emerging news is that the FLSmidth ROL hydromet process is moving into the demonstration stage in Peru, and the Morenci copper pressure-ox plant is in operation.

AT (panel) said that at the previous ALTA panel on this topic, the consensus was that the presence of impurities in concentrates, especially arsenic, is a big driver for hydromet processing. It remains an area of opportunity for hydromet to gain ground against smelting and provide a platform for expansion into other applications. However, hydromet still has a way to go to challenge smelting, especially for concentrates containing gold, which has often been the Achilles heel of hydromet processes.

Possible Recovery of Iron and Other By-products from Hydromet Processes

Mike Dry (MD), Arithmetek (Canada), floor, pointed out that we are typically digging a lot of rock for a tiny amount of ore and rejecting the rest into a dump, the major part of which is often iron. Philosophically one of the challenges for hydromet is to turn that iron into a saleable iron.

JE (panel) Responded that one of the challenges is reducing the base metal and sulphur levels down to the extremely low levels required for steel making.

MD (floor) agreed but said that we should be thinking about how it can be done. Given the bright minds in the hydromet field, as represented in this conference, surely nothing is Impossible.

LV (chair) pointed out that Coral Bay in the Philippines have explored the recovery of hematite from their nickel laterite HPAL plant tailings.

Fumio Iwamoto (FI), Sumitomo Metal Mining Company (Japan), floor, advised that it was actually at the Taganito HPAL operation. It was viable at the then iron ore price of $140/t, but became uneconomic when it dropped to %50-70/t, and also the grade of the iron was less than 60%.

MD (floor) re-emphasized that it is not about recovering iron from residues from current operations, but rather the further development of hydromet technology to recover high grade iron, which will significantly reduce the problem of residue disposal.

MB (panel) observed that the long-term view of such issues is generally set by society and government rather than the private sector. For example, if government started to tax what goes back into the ground, as they already penalise things like arsenic, then the economics would suddenly change.

MD (panel) added that the industry is already being taxed for things released into the air, such as CO_2.

MM (panel) added that nickel pig iron producers exploited the iron in laterites when the price of nickel was $50,000/t and iron ore was worth $140/t, but when prices fell, the operating cost, e.g. energy, became too high.

JW (panel) agreed that it is energy intensive to recover the iron, and added that the amount of iron available in tailings is a drop in the bucket in the overall market, and is more suitable for niche markets.

Implications of More Stringent Water Management

MB (panel) raised water management as a key issue in the application of both new and existing hydromet processes. Problems include too much, too little, the wrong quality, reuse, and importantly managing the impact of the potential discharge on the environment and relations with the local stakeholders. In some parts of

the world traditional tailings dams are becoming extinct. They have become undesirable from the perspective of long-term risk, and in some of these operations a huge part of the sustaining capital is involved in initial construction and ongoing maintenance

Stephen Grocott (SG), Clean TeQ/AMIRA (Australia), floor, following up, added that it is inevitable that the industry will be approaching closer and closer to zero liquid discharge, which involves a host of issues such as filters, thickeners, and paste disposal. Also, as water circuits are tightened, an increasing amount of impurities are retained which makes processes more complex and leads to the involvement of a number of other technologies for water treatment, and impurities management or for different processes that can accommodate the impurities.

JE (panel) responded that the first thing to consider is leach technology that doesn't bring many impurities into solution. Another factor, particularly in South America, is the trend towards tailings filtration which becomes economically attractive when the value of water reaches $3-5/m^3$. However, as pointed out, this can lead to an accumulation of undesirable impurities. Counter measures include treating the recycle or bleed stream by either reverse osmosis or, more recently, by nanofiltration.

Another strategy, being developed by Curtin and other universities, is to reduce water usage by preconcentration of the feed ore by removing gangue material using relatively simple mineral processing techniques such as screening, jigs, reflux classification, and dense media cyclones. The rejects can be useful for the structural improvement of the tailings dam.

The Impact of Logistics on the Battery Metal Product Chain

Patrick Jay (PJ), Adroit Process Equipment (Australia), floor, referred to conference papers about the very high cost of transport to China and the choice of battery metal products such as nickel metal rather than nickel sulphate. Given that nickel sulphate contains 6 H_2O and cobalt sulphate 7, why not ship metals to reduce costs and produce the nickel and cobalt sulphates at the batteries factory?

MM (panel) could not comment on the process aspects but is familiar with logistics at the Ravensthorpe operation who found it very expensive to ship MHP to China. They were able to reduce cost by finding ways to increase bag capacity. However, a longer-term solution for MHP producers would be to calcine it to nickel oxide which has a higher bulk density. Production of metal is probably the ultimate answer.

Mark Weatherseed (MW), Outotec (Australia), floor, asked why not make the precursor material in Australia and ship that instead of nickel sulphate to China?

JE (panel) agreed, and advised that the convergence of various battery raw materials at Kwinana, Western Australia, including production of nickel and cobalt sulphates by Nickel West, can facilitate the production of premixes and even batteries. Queensland University of Technology under Prof. Peter Talbott have built a pilot plant to produce commercial grade lithium-ion batteries, so the technology is available.

He also expressed concern over the need for Australia to move into downstream processing to make products to avoid the "dig it and ship it" mentality which has become prevalent in recent years.

JW (panel) added that making batteries at the source of the metals is also possible in Europe and the USA, yet the China is still dominating the market.

James McQuie (JK), BHP (Australia), floor, advised that Nickel West in Western Australia, while understanding the issue of the water content, consider producing sulphate as an interim step because it is a tradeable commodity. Transition from supplying Class I nickel for stainless steel to a high purity manufacturing, almost pharmaceutical type business, will take time. He agreed that the convergence of battery raw materials in WA is promising for the future production of cathode precursor type material.

The Need to Understand the Market and What is Being Done with the Product

MB (panel) emphasized that the battery supply chain, and the business models, are extremely young and immature. The situation can be compared with the early establishment of nickel as a metal. It wasn't necessarily better than ferronickel, but was convenient for trading around the world as it was relatively fungible. Nowadays there is a bifurcation of the nickel market. Sub LME grade metal (e.g. Nickel Pig Iron) is still good

for the austenitic stainless steel market, but outside this market, metal is not particularly useful and making an intermediate further down the value train can be more attractive.

While all battery manufacturers know what to do with sulphate, in fact they reject the sulphur. The LME is even talking about having a nickel sulphate contract, but that doesn't necessarily make sense from a business value chain even as a basic nickel or cobalt product. So new projects need to understand the market and exactly what is being done with their product. They may well be able to create much more value close to their operation.

Guillaume Lefort (GL), Cleanmetals (Switzerland), floor, followed up with another example of a product further down the value chain being a better choice for the end user. The local fertilizer industry requires 100,000 to 150,000 t of copper for adding to NPK. This is obtained as high purity cathode copper whereas Cleanmetals ELSA technology can make a cement copper product of acceptable purity which can be used directly without the need for dissolving or melting it.

MB (panel) added a further example in which zinc producers are unaware of the amount of zinc sulphate consumed as fertilizer in India. He concluded that it is necessary to really know the market and how to access it instead of always sticking to the same sequence of unit operations as everybody else.

LV (chair) read a comment by Ivan Glasenberg, CEO Glencore saying that if anyone thinks China will just make batteries they are wrong, they will make electric cars. Now China is the biggest producer.

Designing Processes Capable of Reacting to Future Changing Market Conditions

LV (chair) raised the question as to whether the increasing demand for cobalt is just a temporary economic disruption, and if so, how can we design an economically defensive flowsheet if the price falls or the market demands alternative products?

JN (panel) responded that flexibility is a word we need to consider and reported that Terrafame are already starting to respond to the nickel market. He said that designing a process "bullet proof" against market changes is tough as they tend to be unpredictable. The Keynote Address reported that the DRC dealt with the problem of transporting water in cobalt products by imposing taxes, which became the driver for process selection. As said earlier by MB, if governments change tax regimes, you have to be able to respond, which requires building flexibility into the process.

Glen Smith (GS), Sherritt International – Technologies (Canada), floor, pointed to the need to consider that a good portion of the cobalt, nickel, manganese and aluminium in batteries, will be recycled in about 7 to 8 years' time. To recover the metals will require technology to break open the spent batteries and separate the contents. The development work for that has to start now, which has already been realized in China.

SG (floor) said that we are "dreaming" to hope for a "bullet proof" flowsheet. We live in an economic world and the reality is that the process users and shareholders are looking for a process with production costs in the first quartile, or at worst in the second quartile, of the industry to be robust to the inevitable swings.

MB (panel) added that we should never underestimate how reactive and flexible end users can be if they have to. As was well pointed out by the CESL presentation, when disruption occurred in 1980-81 in the DRC the cobalt market adjusted quickly. Suddenly users didn't need 99.80 cobalt any more, and, for example, they learned how to adjust to the cobalt coming out of the Soviet Union.

JE (panel) said that there is an extremely short-term view in the market, which makes it difficult to develop innovations through to commercialization, which is one of the Achilles heels of hydrometallurgical processes . In contrast, many Chinese institutions are government supported or owned and are more able to adopt a long-term view and take a loss if necessary.

Prospects for Development of New SX and IX Extractants for Purifying Battery Metal Products

JK (floor) challenged suppliers to develop new solvent extraction or ion exchange products for the stringent purification of battery metal solutions, which is likely to be a long-term requirement.

Jack Bender (JB), BASF (USA), floor, advised that it is now extremely expensive to register new chemicals. It involves a long lead time for research which has to address toxicity, the effect on the human body, and the effect on animals, and the mining industry is typically unwilling to pay the required high price. The result is that suppliers focus on the same 2000-3000 molecules rather than developing new products.

Owen Tinkler (OT), Solvay (USA), floor, added that over the years Solvay have carried out many development programs such as one to develop a more robust alternative to Cyanex 301. He agreed with JB that it is extremely expensive and is comparable to working in the pharmaceutical field; but a top pharmaceutical can result in a pay back in the billions while the mining industry is unwilling to pay for the high cost of development. So, a breakthrough in chemistry is unlikely.

AT (panel) asked for comments on the relative cost of developing IX resins and SX extractants.

JB (floor) responded that extensive IX research has been carried out outside of the mining industry, resulting in the availability of many polymers. However, a lot of work by relatively larger research groups is required to develop applications for specific metals. One of the problems is that many major mining companies have significantly cut back research to reduce costs or increase shareholder dividends.

Peter Jolly (PJ), Consultant (Australia), Asked whether the absence of research into new SX and IX products has created a vacuum across a broad front which China is able to fill due to their loss leader mentality, and have potential users moved past quality concerns?

JE (panel) added that in his experience a Chinese supplier responds much faster to requests for samples for university research work than established suppliers. This can lead to the development a product which, while not of the same quality as its established equivalent, is marketable due to lower cost.

JB (floor) responded that the industry's willingness to buy lower cost copies will makes it very difficult to justify high cost research into the development of new products.

The Need and Benefits of Collaboration to Meet Industry Needs

SG (floor) pointed out that the need to develop new SX and IX products is a classic space for collaboration. The high cost could then be shared by a number of organizations including a supplier, end users and university researchers together with a facilitating organization such as AMIRA.

Mark Martin (MM), Koch Knight (USA), floor, gave an example of the benefits of collaboration whereby one of the divisions of his corporation significantly reduced the cost of solving a problem from about $400,000 to $50,000 through collaboration with other companies led by MTI, Materials Technology Institute, a facilitating organization similar to AMIRA.

JE (panel) as another example pointed to the AMIRA gold co-operative program which is currently sponsored by 15 very diverse companies. Important components include short, medium, and long-term outputs and technology transfer which includes training of metallurgists on best available practices.

He also reported that a co-operative research centre is being established in Western Australia focusing on all the battery related materials and looking at the full value train from resource through extraction, battery materials, battery assembly and recycle. He also reported that a co-operative research centre is being established in Western Australia focusing on all the battery related materials and looking at the full value train from resource through extraction, battery materials, battery assembly and recycle.

Lourdes Valle (chair) closed the panel discussion and thanked all panel members and participants from the floor.

Summary of Key Points

- There has been a trend towards heap leaching of low-grade sulphide and transition ores, with the focus being now on chalcopyrite heap leaching which is on the verge of commercialization with a few semi-commercial operations already underway. Developments include the use of saline leach conditions to overcome the passivation layer issue and alkaline glycine leaching for its ability to reduce solution impurities and to co-extract copper and gold.

- Developments in the hydromet processing of chalcopyrite concentrates include:
  - the first commercial copper application of the Albion Process in Zambia
  - the establishment of a FLSmidth ROL Process demonstration facility in Peru
  - the Morenci copper pressure-ox plant is in operation.

- Further development of hydromet process to recover iron as a by-product is desirable to increase the productive usage of resources, reduce waste disposal, and increase revenue. Challenges include achieving the grade and purity and requirement for steel making and the market value of the by-product as demonstrated by Sumitomo's experience in recovering hematite from their tails at Taganito HPAL nickel laterite operation in the Philippines.

- Limited water resources, environmental issues with process solution discharge streams, and increasing political and social pressure to eliminate traditional wet tailings dams, are pushing the industry to maximize process solution recycle by dewatering tailings using paste thickeners and pressure filters. The resulting accumulation of impurities can cause process and product purity problems which lead to the need to purify tailings recycle solution and/or bleed streams using technologies such as reverse osmosis and, more recently, nanofiltration. Other approaches include preconcentration of the ore feed to reduce the water requirement, and the use of a lixiviant such as glycine which generates solutions with lower impurity levels.

- The high cost of transport to China is a significant factor in the choice of battery metal products such as nickel and cobalt sulphates, which have a high water content, and mixed hydroxide (MHP) which has a low bulk density. From the supplier's viewpoint, metal products would have the lowest transport cost , though this may be offset by increased production costs. Other options include moving up the supply chain to local production of cathode precursor type materials or even batteries. It was noted that the convergence of various battery raw materials at Kwinana, Western Australia, including production of nickel and cobalt sulphates by Nickel West, can facilitate the production of premixes, and Queensland University of Technology have built a pilot plant to produce commercial grade lithium-ion batteries.

- It was emphasized that the battery supply chain, and the business models, are extremely young and immature. New projects need to understand the market and exactly what is being done with their product. They may well be able to create much more value close to their operation. Other examples were presented supporting the need to understand the market and select the optimum point in the supply chain.

- It was recognized that it is very difficult to design a cobalt production process to be "bullet proof" to price volatility, which can be due to government decisions as well as supply and demand issues. The common strategy in the mining industry is to look for a process with production costs in the first quartile, or at worst in the second quartile, in order to be robust to the inevitable swings. It was also noted that end users can be reactive and flexible to alternative sources if they have to as proven in previous times of cobalt market disruption.

- The need for suppliers to develop new SX and IX products for the stringent purification of battery metal solutions was emphasized. Suppliers BASF and Solvay both advised that this is unlikely due to the very high development and permitting costs and the unwillingness of the mining industry to pay the necessarily high sale price. Another obstacle is the willingness of the industry to buy lower cost copies. The result is that suppliers focus on incremental improvements to products based on existing chemical types. The question was raised as to whether this created a vacuum which China is able to fill due to their ability to adopt a loss leader approach to research and development.

- It was pointed out that the need to develop new SX and IX products is a classic space for collaboration. The high cost could then be shared by a number of organizations including a supplier, end users and university researchers together with a facilitating organization such as AMIRA. Some existing successful collaborative programs in Australia and the USA were described in support of this concept. It was also reported that a co-operative research centre is being established in Western Australia focusing on all the battery related materials and looking at the full value train from resource through extraction, battery materials, battery assembly and recycle.

The Editor acknowledges the efforts of the student volunteer from Curtin University, Mojtaba Saba, for providing notes on the discussion.

Pressure Acid Leaching is the featured topic for the ALTA 2019 Nickel-Cobalt-Copper Forum and Panel, which will be held 18-25 May in Perth, Australia. A fitting topic on the 20-year anniversary of the commissioning of the Bulong, Cawse and Murrin Murrin PAL operations.

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MetBytes are metallurgical commentary and insights written by Alan Taylor who has 40+ years' experience in the metallurgical, mineral and chemical processing industries.