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# Designing the Optimal Flotation Circuit – The Prominent Hill Case

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## ABSTRACT

OZ Minerals' Prominent Hill copper-gold concentrator in South Australia was built in 2008 with commercial production commencing in early 2009. In addition to recovery of valuable minerals, the flow sheet for this iron oxide-hosted copper-gold deposit has to address the issue of producing a good quality saleable copper concentrate by high selectivity against non-sulfide gangue. Detailed mineralogical studies integrated with the metallurgical test work highlighted that liberation of fluorine-bearing minerals and subsequent very efficient rejection in cleaner flotation was necessary to produce a commercial quality copper-gold concentrate.

Bench scale laboratory metallurgical tests and mineralogical studies identified the need to regrind rougher concentrate to a $P_{80}$ of 20 - 25 microns or finer for adequate liberation of the fluorine-bearing minerals. Satisfactory separation of the fluorine-rich gangue material from the valuable copper sulfides requires highly efficient cleaner flot- ation. This is done by a combination of washed froth cleaning and conventional dilution cleaning.

Proven equipment developed to meet similar taxing liberation and separation duties for the treatment of the refractory zinc-lead-silver ores of the Carpentaria-Mount Isa Mineral Province have been selected.

The combination of Xstrata Technology's IsaMill™ and Jameson Cell technologies addressed both the liberation and separation issues in the Prominent Hill concentrator. The energy efficient IsaMill™ technology both regrinds the rougher concentrate while its inert grinding environment prevents contamination of mineral surfaces with "debris' ensuring subsequent optimum flotation performance. Heading up the cleaner circuit with a 'scalping' Jameson Cell followed by conventional flotation equipment allows this section to take advantage of the Jameson Cell's high intensity flotation environment and froth washing capability to achieve maximum concentrate grade (at minimum fluorine levels) while maximising recovery through the use of conventional flotation machines.

This paper looks at the development of the Prominent Hill flow sheet from the initial mineralogical and laboratory test work to the design, scale-up and early operation of the Prominent Hill regrind and cleaner flotation circuits.

The mineralogically-based approach of domaining metallurgical ore types combined with the axiom of size-by-size mineral particle behaviour by liberation class gave a clear understanding of the liberation and separation issues involved in the processing of Prominent Hill ore.

Technologies developed to meet much more onerous liberation and separation duties for the treatment of the refractory zinc-lead-silver ores of the Carpentaria-Mount Isa Mineral Province were successfully used to improve concentrate quality by rejecting non-sulfide gangue containing impurities. An IsaMill™ and a Jameson Cell are included in the circuit for fine grinding and for additional concentrate cleaning.

Plant performance since commissioning has justified the approach for metallurgical test work and equipment choices for the flotation circuit.

## INTRODUCTION

OZ Minerals Limited's Prominent Hill copper-gold mine is located 650 km NW of Adelaide, 130 km NW of BHP Billiton's Olympic Dam operation and 130 km SE of the town of Coober Pedy in the Gawler Craton of South Australia.

The deposit was discovered in 2001 by Minotaur Resources who entered into a joint venture with Oxiana Limited in 2003 with the latter securing 100 per cent ownership in 2005.

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Project milestones are as follows:

- 2005:
  - prefeasibility study,
  - conceptual development plan, and
  - agreement on approval process with Primary Industries and Resources South Australia;
- 2006:
  - bankable feasibility study,
  - issue of mining lease,
  - board approval for development, and
  - commencement of mining;
- 2007:
  - project development and construction, and
  - first ore reached October 2007;
- 2008:
  - Oxiana Limited merges with Zinifex to form OZ Minerals Limited, and
  - operations team build-up;
- 2009:
  - first production and sales February 2009, and
  - first concentrate exports from Port of Darwin in April 2009.

## SCHEME OF METALLURGICAL TEST WORK

Given the nature of the Prominent Hill deposit, conventional grinding and flotation were proposed as the treatment route for the copper-gold sulfide ore.

Metallurgical test work was aimed at producing a process flow sheet with a predictable metallurgical performance to a level of accuracy and sophistication for a bankable feasibility study. It was not aimed at optimisation or detailed research of any particular aspect of the process.

The test work was carried out on samples representing specific mineral entities or domains rather than on composite samples in the absence of a final mining schedule. This follows Mineralurgy's practice on flow sheet development (Johnson and Munro, 2008). Variability tests were used to determine the metallurgical performance over a range of sample locations.

The main organisations engaged to carry out the metallurgical test program were:

- MacArthur Ore Deposit Assessment (MODA), Burnie, Tasmania – optical mineralogy of selected polished sections;
- JK Mineralogy section of JKTech Pty Ltd (JK Tech), Indooroopilly, Queensland – automated measurements using the Mineral Liberation Analyser (MLA) on crushed diamond drill core and copper concentrates;
- SMCC Pty Ltd (SMCC), Chapel Hill, Queensland – calculations to size comminution equipment;
- Amdel Ltd, Mineral Laboratory Services, Thebarton, South Australia – bench scale gravity and flotation tests and determination of ore comminution characteristics;

- G&T Metallurgical Services Pty Ltd (G&T), Kamloops, British Columbia, Canada – bench scale flotation tests and quantitative mineralogy;
- AMMTEC Limited, Balcatta, Western Australia – bench and pilot scale flotation test work;
- Slurry Systems Pty Ltd, Sydney, New South Wales (NSW) – slurry rheology test work;
- Outokumpu Technology Pty Ltd, Sydney, NSW – thickening test work;
- GL&V Australia, Sydney, NSW – thickening test work;
- Xstrata Technology, Brisbane, Queensland – rougher concentrate regrind test work;
- Metso Minerals, Inc, York, Pennsylvania, USA – rougher concentrate regrind test work; and
- TUNRA, Newcastle, NSW – ore flow characteristics test work.

The main items in the metallurgical test program relevant to the development of the flotation flow sheet and reagent regime consisted of the following:

- Copper-gold breccia 'sighter' and characterisation tests – Amdel: 'sighter' flotation tests were conducted on material from five reverse circulation (RC) drill holes. Conventional grinding and flotation was proposed for the copper-gold sulfide ore. Gold occurrence was characterised using gravity concentration, amalgamation, cyanidation and flotation. Four composite samples were prepared according to the then known mineralisation types of chalcocite-bornite, chalcopyrite-bornite, chalcopyrite-pyrite and eastern gold-only (EGO). For the copper mineralisation types, test work included grinding and flotation tests at different primary grind sizes.
- Copper-gold breccia optical mineralogy – MODA: 13 thin sections were selected for detailed optical examination.
- Copper-gold breccia – quantitative mineralogy – JK Mineralogy: 20 samples from nine different diamond drill holes were submitted for automated analysis using the MLA.
- Copper-gold breccia flow sheet confirmation – G&T: using the previous copper-gold breccia characterisation work as a starting point, 17 samples of sections of PQ core representing the three mineralisation types of chalcocite-bornite, chalcopyrite-bornite and chalcopyrite-pyrite underwent flotation testing, with back-up quantitative mineralogy to confirm the validity of the conceptual flow sheet. Detailed chemical assays were done on the copper concentrates.
- Copper-gold breccia flow sheet development – G&T: this was an extension of the flow sheet confirmation and included examination of the following:
  - the relationship between primary grind sizing-collector addition (and type), and regrind sizing;
  - the rejection of non-sulfide gangue, particularly fluorite, from the copper concentrate;
  - increasing gold recovery, especially with respect to copper recovery for bornite-chalcopyrite and chalcopyrite-pyrite mineralisation;
  - gold deportment model for each copper mineralisation type;
  - the mode of copper and gold losses;
  - the effect of ageing on flotation performance;
  - prediction of metallurgical performance using locked cycle tests;
  - blending different ore types, the emphasis being on those blends of mineralisation expected to be treated in the first three years of production; and
  - concentrate quality, with emphasis on payable and penalty elements.
- Copper-gold breccia variability testing – G&T: variability testing was conducted on 50 × 0.25 NQ core samples. Sample selection was weighted towards chalcocite-bornite mineralisation, as this type predominated in years 1 and 2 of the national mine production schedule.
- EGO variability testing – Amdel: this work was done on 48 samples, mostly 0.25 NQ core to give additional spatial coverage. Selection was weighted towards the material expected to be within the notional pit shell. The test protocol followed that previously used in EGO zone characterisation, with a target grind to a $P_{80}$ of 106 µm followed by rougher flotation only.
- EGO flow sheet development – G&T: this used suitably-composited samples of sections of PQ core representing the known domains of 'steely haematite', 'earthy' and 'dolomite'. This work included:
  - maximising gold recovery and minimising concentrate weight, since the gold flotation concentrate would be blended with the copper-gold concentrate;
  - determining the nature of gold occurrence and losses;
  - determining the effect of blending by doing locked cycle tests on both individual mineralisation types and blends of EGO material with the three copper mineralisation types;
  - quantitative mineralogical support for the metallurgical tests; and
  - concentrate assays including payable and penalty elements.
- Copper-gold breccia process verification and plant design data – AMMTEC: some of these items were not strictly part of the metallurgical test program, but suitable data was needed for other aspects of the project, eg plant design, equipment selection and sizing. This involved pilot scale testing at AMMTEC using a 1460 kg sample of copper-gold breccia material. This produced sufficient quantities of rougher concentrate for test work to size regrinding equipment; copper concentrate for thickening and filtration tests; and tailings for further thickening and slurry rheology tests. This test work was also used to confirm the predicted metallurgical performance.

## GEOLOGY AND MINERALOGY – EFFECTS ON PROCESSING

### Geology

Geological and mineralogical work on the Prominent Hill deposit shows that it is an iron oxide hosted copper-gold orebody (Belperio and Freeman, 2004; Belperio, Flint and Freeman, 2007) similar to Olympic Dam (Reeve *et al*, 1990) and Carrapateena (Fairclough, 2005) in South Australia, Warrego in the Northern Territory, Ernest Henry (Ryan, 1998) and Osborne in Queensland, La Candelaria in Chile, and Sossego, Alemão and Salobo in Brazil.

The process plant feed will be mined from the copper-gold breccia zones with mineralisation types of chalcocite-bornite, chalcopyrite-bornite, chalcopyrite-pyrite and from the EGO zone.

The mine reserve is 72.4 Mt with a grade of 1.3 per cent Cu, 0.6g/t Au and 3.2g/t Ag.

The orebody is such that the chalcocite-bornite mineralisation, which constitutes over half the current resource mineable by open pit, will be the dominant feed for the first five years of operation. Bornite-chalcopyrite and chalcopyrite-pyrite mineralisation types are 16.2 per cent and 15.7 per cent respectively of the material intended to be mined.

The EGO mineralisation zone is an 'outlier' to the main copper-gold breccia sulfide zone. It will be approximately 11 per cent of the plant feed, but has very low sulfide content within a host rock of predominantly iron oxides. It should exercise negligible to minimal influence on plant flotation behaviour when treated in a mixture with the copper-gold breccia mineralisation types, because of the very low mass recovery to concentrate (down to 0.1 per cent recorded in test work). Its main influence will be on comminution performance, because of its relatively low grindability and high abrasivity.

The following major rock types and approximate proportions were identified by the geologists:

- haematite breccia – sediment clast approximately 30 per cent of the rock, porphyry and volcanic clasts approximately 55 per cent of the rock;
- andesite – unaltered approximately one per cent of the rock, altered approximately ten per cent of the rock;
- carbonates – dolomitic and argillaceous rocks approximately four per cent of the rock; and
- steely haematite – a diluent, considered to be around ten per cent of the rock mass feed to the process plant.

Rock type will control comminution performance and, hence, concentrator throughput (Strohmayr *et al*, 1998; Tew *et al*, 2003). OZ Minerals' geologists advised on selection of material for determination of ore breakage characteristics to ensure that appropriate rock types have been included.

For grinding and flotation, mineralogy and textural association are the major influence on the grades and recoveries of copper and gold to the flotation concentrate.

## Mineralogy

### *Copper and associated minerals*

The following observations relating to mineralogy were made by MODA, JK Mineralogy and OZ Minerals' geologists. While indicative they were subsequently confirmed by the result of extensive metallurgical test work and quantitative mineralogical examination.

MODA reported on copper microtextures as follows:

- Chalcocite – coarsest of the copper minerals, with 50 per cent greater than 40 μm and commonly occurs in symplectic intergrowths with bornite.
- Bornite – finest grain size of all the copper minerals, with 50 per cent finer than 24 μm. Bornite usually occurs as symplectic intergrowths with chalcocite. When fine-grained, bornite is generally hosted by chalcocite or chalcopyrite.
- Chalcopyrite – intermediate grain size with 50 per cent less than 33 μm and, when finely-grained, is generally hosted by bornite. Chalcopyrite has a much higher non-haematite gangue association than chalcocite or bornite. Chalcopyrite is often accompanied by bornite.

JK Mineralogy used its Mineral Liberation Analyser (MLA) on 20 mineralised rock samples selected to represent typical rock types and copper mineralisation textures. The finest copper sulfide mineral particles, as represented by the 20 per cent passing size, are especially relevant to evaluating the amenability of a copper sulfide ore to concentration by flotation. High liberation values of around 80 per cent measured in two dimensions are necessary to make a high grade copper concentrate. The term used by automated mineralogical systems such as QEMSCAN and MLA to indicate mineral size is the measured phase specific surface area (PSSA), quoted as $mm^2$ of surface area of the mineral per $mm^3$ of mineral volume. Higher values indicate finer grain size.

The MLA work produced the following observations:

- The lithology and alteration styles across all samples indicated pervasive brecciation/veining of variable host lithologies, including sandstones, fine-grain sediments, porphyritic volcanics, carbonates and possible greywackes.
- The clasts/relict clasts of the host rock appeared to be highly altered, being variably rich in sericite, quartz, haematite, siderite, chlorite and minor biotite, titanomagnetite, rutile, anorthite and sulfides.
- The breccia matrix was predominantly haematite, with variable concentrations of quartz, siderite, sulfides, fluorite, barite, apatite and rare earth-bearing minerals.
- Trace amounts of molybdenite, cobaltite and the uranium-bearing minerals uraninite and coffinite were detected in some samples.
- Sulfide mineralisation included variable concentrations of chalcocite, bornite, chalcopyrite and pyrite. There were strong associations between chalcocite and bornite, with intergrowths and symplectic textures commonly encountered.
- Pyrite, while in minor concentrations only, displayed a strong association with bornite and chalcopyrite. It was frequently rimmed by these two copper sulfides.
- The copper mineralisation was strongly associated with the haematite-rich matrix and/or vein-hosted minerals. The copper sulfides were relatively coarse, euhedral grains, often associated with some unusual textures.
- Minor to trace amounts of chalcopyrite were measured in the chalcocite-rich and bornite-rich samples but there were essentially no bornite or chalcocite mineralisation in the chalcopyrite-rich samples.
- Quantitative data on the copper sulfide minerals confirmed the MODA ranking of textural complexity:
  - chalcocite: mean 20 per cent passing 60.1 μm and PSSA 90 - 190 for samples where chalcocite is a major copper mineral species,
  - bornite: mean 20 per cent passing 35.6 μm and PSSA 170 - 240 for samples where bornite is a major copper mineral species, and
  - chalcopyrite: mean 20 per cent passing 40.8 μm and PSSA 99 - 290 for samples where chalcopyrite is a major copper mineral species.
- The association between pyrite and the copper sulfides, fluorite inclusions and intimate intergrowths of haematite and copper sulfides were expected to impact on grind size for processing, concentrate quality and recovery.
- Clays were not detected by MLA measurement, but low concentrations intergrown with sericite and chlorite may be present.
- Organic carbon species are not detected by the MLA technology and thus their presence or absence could not be confirmed.

The following general conclusions were also drawn from geological observations, optical mineralogy and the MLA work:

- Prominent Hill material is more competent than Ernest Henry being more akin to Olympic Dam ore in its grinding characteristics. The ore could be expected to be more variable in its grinding characteristics than the primary ore zone at Ernest Henry, as Prominent Hill material goes from quartz to steely haematite.

- The ore can be very porous with 20 per cent void space in some of the specimens examined.
- Around 70 per cent of the copper minerals are associated with haematite and gangue, with at least 15 per cent of the copper mineralisation being associated with pyrite.
- Chalcocite is 'primary' or hypogene mineralisation.
- Mineralisation can look simple, but has many different textures. Sulfide complexity comes from pseudomorphs of bornite-chalcopyrite on pyrite. There is some complex bornite-chalcocite fracture filling in haematite.
- Some pyrite is intimately associated with the chalcopyrite. However, the pyrite content is less than that for Ernest Henry.
- Some chalcopyrite textures were coarse and readily liberated.
- Complex haematite textures were observed.
- Minerals identified in the Prominent Hill drill cores that carry fluorine are as follows:
  - Fluorite ($CaF_2$), containing 48.67 per cent F, is relatively abundant and accounts for 60 - 90 per cent of the fluorine present in copper concentrate.
  - Sericite, which can be 10 - 50 per cent of the mineral in the plant feed, is the second major carrier of fluorine, contributing 3 - 32 per cent of the amount in the copper concentrate. Electron microprobe analyses of 100 sericite grains measured 0.26 - 1.72 per cent F, with a mean of 0.96 per cent F. Sericite at Olympic Dam is also reported to contain up to one per cent F (Reeve *et al*, 1990).
  - Apatite (fluoroapatite) ($Ca_5(PO_4)_3(F,Cl,OH)$) containing 1.25 per cent F is the third main carrier.
  - The rare earth element (REE) minerals bastnasite and florencite are minor fluorine carriers.
- Uranium is present as uraninite and coffinite. Uranium is more associated with chalcopyrite mineralisation, possibly with bornite, but less with chalcocite. MODA observed pitchblende associated with chalcopyrite. JK Mineralogy noted very fine intergrowths of a uranium mineral with bornite.
- No oxide or supergene zone has been identified.
- Hydrophobic species, such as talcose minerals and those with organic carbon were not reported by geological logging or mineralogical examination nor observed in any of the metallurgical test work.
- Similarly, clay minerals were not reported by geological logging or mineralogical examination nor observed in any of the metallurgical test work.

Figure 1 provided by MODA plots copper mineral recovery (assuming a perfect separation) against particle size. The inferences from this diagram subsequently proved to be prescient, despite being based on very limited observations. It shows that a particle sizing of around 20 - 30 μm is needed to make a high grade copper concentrate at a high copper recovery.

This was subsequently borne out in the metallurgical test work where it was found that fine regrinding of rougher concentrate to 80 per cent passing 20 - 25 μm was needed to reduce the amount of non-sulfide gangue reporting to the copper concentrate to lower the fluorine content to an acceptable level.

### *Gold and silver*

There are four identified associations of gold in the deposit as follows:

1. Gold with copper mineralisation in the breccia: the majority of the gold in the concentrates was locked in copper sulfide-bearing composite particles almost equally divided between adhesions and inclusions. Using automated digital image searching (ADIS), the average gold sighting was very small at 5 μm equivalent circle diameter. Gold can be considered to be 'associated' with copper, with metallurgical test work showing that ~80 per cent of the gold deportment is explained by the copper deportment.
2. Gold (possibly associated with silica) 'proximal' to the copper-gold breccia mineralisation zones, but outside them.
3. Gold-only 'outside' the copper-gold breccia mineralisation zones in the upper part of the eastern end of the deposit associated with silica in steely haematite. This EGO mineralisation falls within the boundary of the open pit.

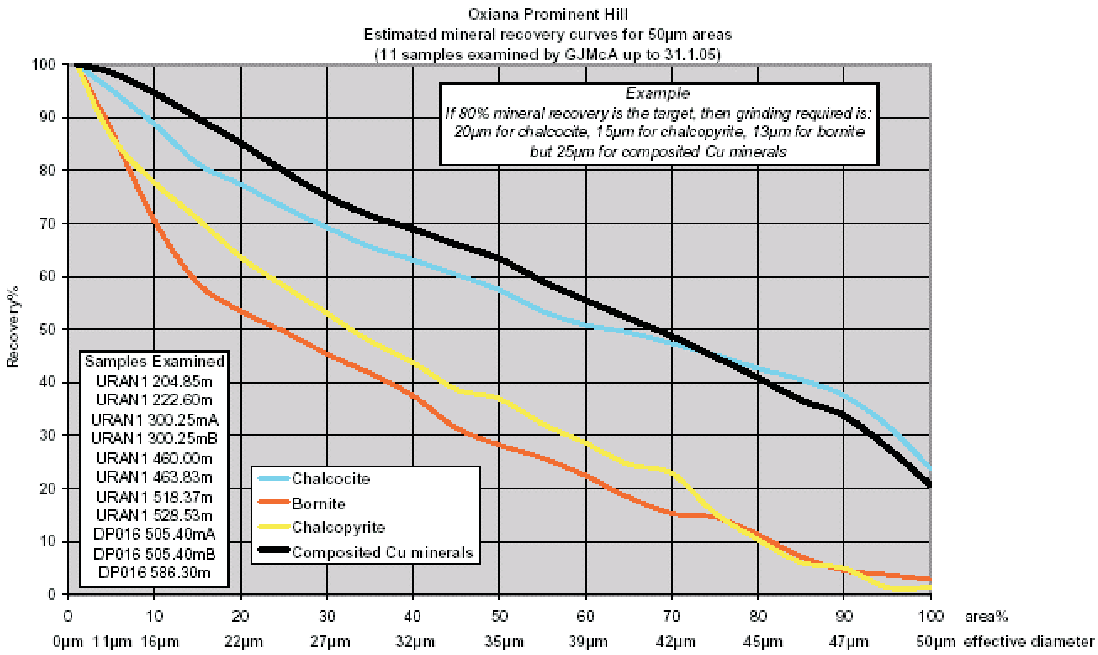


FIG 1 - Estimated copper mineral recovery versus sizing.

ADIS examination of metallurgical test products found that approximately two thirds of the gold located in the flotation feed was present as liberated grains ranging from 7 μm to 36 μm equivalent circle diameter. The remaining gold occurrences were as adhesions to chalcopyrite grains or as adhesions to chalcopyrite-gangue binary composites. Almost three-quarters of the gold occurrences in the flotation concentrates were liberated grains, averaging 8 μm equivalent circle diameter.

4. Gold 'outside' the copper-gold breccia mineralisation zones in the lower part of the western gold-only (WGO) end of the deposit, visible as coarse particles in carbonate veinlets in dolomite-sandstone. This should be readily recovered by a small gravity concentration facility treating a portion of the hydrocyclone underflow in the grinding section. The WGO mineralisation did not appear on the mine schedules.

Silver is present in the orebody, but no information is available about its mineral form though it is the element with the strongest relationship to copper occurrence.

## Comparison with similar Australian deposits

The Prominent Hill deposit is much more like the Olympic Dam orebody than Ernest Henry despite being hosted in sediments, while Olympic Dam is in granite.

Some significant points of similarity and/or differences affecting processing are as follows:

- Only Ernest Henry has a zone of supergene mineralisation.
- Chalcopyrite is the only economic copper mineral in the primary ore zone at Ernest Henry, whereas chalcocite and bornite are dominant at Prominent Hill and significant in the sections mined to date at Olympic Dam.
- The copper mineralisation is coarser-grained at Ernest Henry than for the other two deposits. Ernest Henry achieves 70 per cent two-dimensional liberation of chalcopyrite at a $P_{80}$ of 140 μm, whereas, at Olympic Dam, sulfide liberation is only 65 per cent at a flotation feed $P_{80}$ of 74 μm, with 40 - 55 per cent at a grind $P_{80}$ of 150 μm for Prominent Hill. PSSA values quoted for Olympic Dam are 150 - 160, compared with ranges of 90 - 190 for chalcocite, 170 - 240 for bornite and 99 - 290 for chalcopyrite. Thus, only a minor portion of the Prominent Hill ore can be considered to have more complicated textures.
- Gold is strongly associated with copper in the primary sulfide zones of all three deposits.
- The mean sulfide grade of the Ernest Henry ore is nine per cent, of which pyrite is the major component (Ryan, 1998). Iron sulfide levels are relatively low at both Olympic Dam and Prominent Hill.
- While all three deposits contain fluorite and apatite, fluorine levels can be a magnitude higher at Prominent Hill and Olympic Dam compared with those at Ernest Henry. Sericite containing up to one per cent F is a significant fluorine carrier at Olympic Dam and Prominent Hill.
- Uranium minerals are present in all three deposits, but Olympic Dam values are an order of magnitude higher than those of the other two deposits (Reeve *et al,* 1990).

# RESULTS OF METALLURGICAL TEST WORK

In terms of metallurgical response the bornite-chalcopyrite mineralisation domain was subdivided into bornite-chalcopyrite and chalcopyrite-bornite.

A conventional grinding-flotation treatment scheme was appropriate for processing the seven ore composites examined. Grinding the flotation feed stream to a nominal $P_{80}$ of 150 μm ahead of rougher flotation initially appeared to offer a pragmatic compromise between grinding energy allocation and maximising copper and gold recoveries into the rougher concentrate. Locked cycle test work on multiple composite samples were somewhat equivocal in demonstrating significant metallurgical advantage in selecting a flotation feed $P_{80}$ less than 150 μm. However further quantitative mineralogical work showed that in the $P_{80}$ range of 70 μm - 150 μm, copper sulfide liberation is about ten per cent lower at the coarser grind size. There were some indications at the time that the upper portion of the Prominent Hill orebody had a lower grindability. Combined with the 'driver' of the economic benefit of one to two per cent copper recovery increase at the prevailing high copper price, the conservative feed $P_{80}$ of 106 μm was selected. Interestingly, this is closer to Olympic Dam practice than Ernest Henry.

A simple xanthate-based reagent regime was used, occasionally requiring pulp pH modulation by lime. The scheme provided a low cost, but reliable, chemical environment for capturing the majority of the copper sulfides and gold in the ores into saleable grade copper concentrates.

In the initial flotation studies, a perceptible deterioration in flotation response was recorded during sample storage, being particularly evident for those composites containing significant amounts of covellite and chalcocite. Visible evidence of copper ion migration was noted. These ageing effects could be reversed by the simple expedient of increasing collector dosage to the rougher flotation stage.

Regrinding of the rougher flotation concentrate to a nominal $P_{80}$ of 35 μm ensured substantial, but not complete, liberation of the copper sulfides in the cleaner block feed. Locked cycle tests demonstrated that regrinding was critical to maximising the grade of the copper concentrates.

Three stages of dilution cleaning produced acceptable grade copper concentrates containing significant amounts of gold from the majority of the test composites.

Copper concentrate grades of about 25 per cent Cu and 5 - 10 g/t Au were produced from the chalcopyrite-pyrite ore. At the other extreme of copper mineralisation, the chalcocite-rich ores produced copper concentrates which assayed better than 60 per cent Cu and contained 5 - 10 g/t Au. In both cases, the copper and gold recoveries to these concentrates were of the order 87 per cent and 70 per cent, respectively.

Detailed chemical analyses were done on copper concentrates produced in cycle tests at equilibrium conditions. The Prominent Hill copper concentrates contained low and quite consistent levels of the deleterious elements arsenic, antimony, mercury, bismuth, selenium and chlorine. Lead and zinc were present in very low concentrations.

There was appreciable variability in the gold deportment profiles. However, overall about 80 per cent of the gold appeared to track the copper sulfide minerals through the flotation process. The remaining gold followed the non-sulfide gangue and, to a lesser extent, the pyrite. Some of the concentrates contained sufficient silver to warrant a modest smelter credit.

All of the concentrates produced in this phase of test work contained significant amounts of impurities, particularly fluorine. A statistical analysis on an extensive array of size-by-assay data suggested that these impurities are principally associated with the non-sulfide minerals. Thus the amounts of fluorine reporting to the copper concentrates will be minimised by minimising the non-sulfide mineral content of the concentrates.

A special series of flotation studies showed excellent precision and reproducibility of flotation response estimates in replicate laboratory tests.

Initial tests on EGO material showed rapid flotation kinetics, with more than 64 per cent of the gold recovered in the first two minutes for coarse grind sizes ($P_{80}$of 250 μm). At $P_{80}$of 106 μm, more than 72 per cent of the gold was recovered within the first two minutes of flotation. Mean gold recovery was over 80 per cent. The EGO composite reacted most favourably to flotation treatment with gold recovery approaching 90 per cent into a concentrate which assayed about 1100 g/t Au.

Locked cycle tests, which involved blends of the EGO composite with the three copper-gold breccia copper mineralisation types, also yielded relatively favourable responses compared with those predicted from the baseline performance data. Copper and gold recoveries into these concentrates were close to those predicted by simply summing the weighted arithmetic averages of the flotation responses of the baseline composites. This observation implies that no adverse synergistic effects will be encountered by treating EGO and copper-gold breccia blends through the plant.

## COPPER CONCENTRATE QUALITY

### Background

When results of the initial flotation work at Amdel became available, elevated fluorine levels was identified as a potential issue for the marketing of Prominent Hill copper-gold concentrates.

The concentrate market typically penalises fluorine above approximately 350 ppm F, and most copper smelters want levels below 1000 ppm F.

The two issues with fluorine in copper concentrates from Prominent Hill are:

1. minimising revenue losses from penalty payments, and most importantly
2. making a concentrate acceptable to custom copper smelters.

Fluorine values in concentrate were highly variable and above the Prominent Hill project's internal limit of 800 ppm F. The chalcopyrite-rich ore zone samples displayed the highest fluorine concentrates at 5700 ppm F. The lowest values were recorded for the chalcocite-rich ores, which averaged much less than 1000 ppm F.

Fluorine is not a common issue in copper concentrates. At Ok Tedi it can vary between 400 ppm and 1500 ppm in the concentrate (Lauder, Mavotoi and Glatthaar, 2003), and they have installed a reverse flotation process using sodium hydrosulfide to depress the copper minerals in the concentrate with two rougher and cleaner flotation stages using Jameson Cells to remove the strongly hydrophobic talc.

The technical literature has reported on elevated fluorine levels in the iron oxide-hosted copper-gold deposits owned by Companhia Vale do Rio Doce (CVRD) in the Carajás region of Pará State, Brazil. At Alemão fluorine is contained in the minerals fluorapatite, biotite, chlorite, fluorite, allanite, monazite and amphiboles. Bench scale flotation tests produced concentrate containing ~1100 - 2700 ppm F though this was low grade at only 20 per cent Cu. Regrinding to 70 per cent - 16 µm and using hexametaphosphate depressant in the cleaning stage reduced the fluorine level to 200 - 300 ppm (Andrade, Santos and Nardi, 1999).

Salobo is the deposit with the most publicised fluorine problem. Fluorine in the copper concentrate made in laboratory and pilot scale tests is reported to vary from 1450 ppm to 2215 ppm (Pereira *et al*, 1987; Pereira, Peres and Bandeira, 1991; Viana *et al*, 1998) though there are anecdotes of significantly higher levels. Minerals containing fluorine are intimately associated with copper sulfides (Fernandez *et al*, 2004). CVRD are testing a hydrometallurgical pressure leach process to treat Salobo and Alemão copper concentrates (Jones *et al*, 2006).

Analysis of the test work data for Prominent Hill shows that fluorine in copper concentrate will be the same proportion in the non-sulfide gangue in the concentrate as it is in the non-sulfide gangue in the feed. This is clearly demonstrated in Figure 2 below which shows a very high correlation coefficient between fluorine recovery to the copper concentrate and non-sulfide gangue recovery.

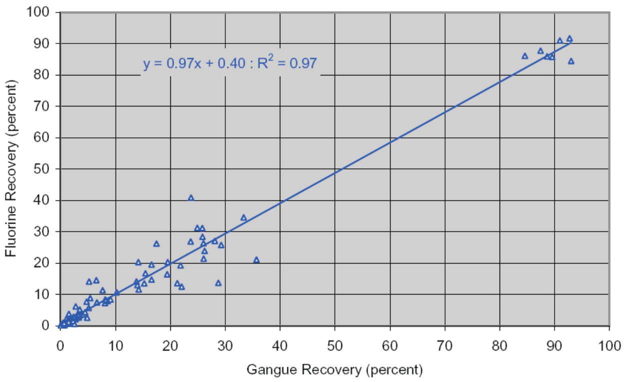


FIG 2 - Relationship between non-sulfide gangue recovery and fluorine recovery to copper concentrate.

This strong relationship is expected as the minerals containing fluorine are non-sulfides and should not be recovered by true flotation. They will report to the concentrate:

- as composite particles associated with sulfide minerals; and
- as liberated particles recovered by entrainment, whose effect is strongest in the finest particle size fractions below 10 µm nominal quartz, ie -Cyclosizer C5.

Assay-by-size data for fluorine for the copper concentrates from laboratory tests suggested there could be a composite issue as almost all samples had the fluorine assay decreasing with finer particle size. Only in tests for the chalcocite-bornite mineralisation did the F assay increase in the finest size fraction which is characteristic of recovery by entrainment.

Thus the fluorine content of the concentrate should be reduced by rejecting non-sulfide gangue minerals and replacing them with copper and iron sulfides. Reduced uranium levels should also result.

### Reducing the fluorine content by conventional mineral processing

Prominent Hill does not require a reverse flotation process such as Ok Tedi because the minerals containing fluorine are hydrophilic and should not be recovered by true flotation.

Acid leaching of the copper concentrate was avoided because of concerns about dissolution of the chalcocite.

For the composites chalcopyrite (Cp), chalcopyrite-bornite (Cp-Bn) and chalcocite-bornite (Ch-Bn) a series of three batch cleaner tests per composite were performed investigating the effect of regrinding on fluorine content in the concentrate. Nominal primary grind size of 100 µm $P_{80}$ was used while three different regrind sizes were investigated within the range 32 µm $P_{80}$ to about 20 µm $P_{80}$.

The overall fluorine contents of the copper concentrates produced from the batch cleaner tests are displayed in Figure 3 below. Both the chalcopyrite-bornite and chalcopyrite composites originally contained significant amounts of fluorine at ~3300 g/tonne. Fluorine content in the final concentrate was reduced as the regrind discharge particle size was reduced corresponding to the improvement in copper metallurgical performance for these composites. The chalcocite-bornite composite contained much less fluorine and regrinding had no measurable effect on reducing the amount in the final concentrate.

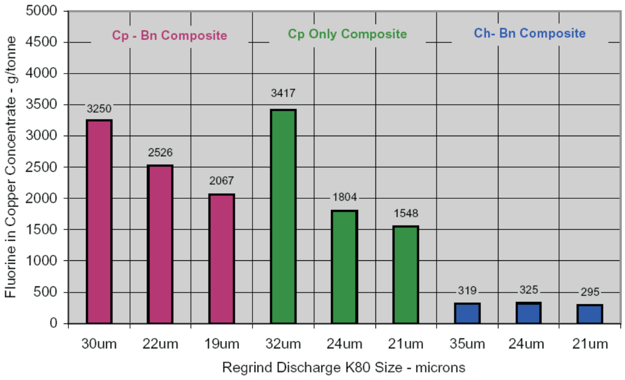


FIG 3 - Effect of regrinding on fluorine content of copper concentrate.

The metallurgical results for copper are shown as a series of grade-recovery curves in Figure 4. As shown, decreasing the regrind discharge to less than 24 µm $P_{80}$ from about 30 µm $P_{80}$ had a beneficial effect on metallurgical performance for the chalcopyrite and chalcopyrite-bornite composites. Conversely, no measurable change in the grade-recovery profile was observed for the chalcocite-bornite composite.

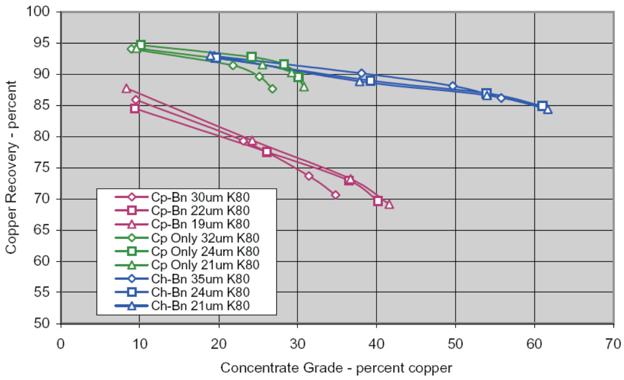


FIG 4 - Results from batch cleaner tests – copper grade recovery curves.

These results are consistent with those from previous test work which showed finer regrinding improved metallurgy for the chalcopyrite-pyrite and bornite-chalcopyrite domains. The net improvement in copper (and gold) metallurgical performance justified the additional regrinding and cleaning capacity exclusive of the fluorine and uranium issue.

Hence the decision was taken to specify:

- regrind sizing $P_{80}$ of 20 µm; and
- additional cleaning capacity, preferably in a washed froth device.

These concepts were relatively novel in the copper industry. However, some members of the metallurgical development team had considerable previous experience with equipment developed to meet much more onerous liberation and separation duties for the treatment of the refractory zinc-lead-silver ores of the Carpentaria-Mount Isa Mineral Province.

## ISAMILL™ FOR REGRINDING

The IsaMill™ was developed by Mount Isa Mines (now Xstrata) and Netzsch-Feinmahltechnik GmbH to meet the need to grind the fine grained Macarthur River orebody to 80 per cent - 7 µm to produce a saleable concentrate. Grinding below 20 - 25 µm with conventional grinding technology (ball mills and tower mills) was considered uneconomical due to low energy efficiency and high media consumptions. Additionally the high ferrous media consumptions changed mineral surfaces and pulp chemistry which was detrimental to subsequent flotation performance of the fine particles.

The first 1.1 MW M3000 IsaMill™ installed in Mount Isa in 1994 was followed by a further seven over the next five years in the Mt Isa zinc-lead circuit (Young and Gao, 2000; Young, Pease and Fisher, 2000; Pease *et al*, 2006). The result was a step change in metallurgical performance with no overall change in operating costs (despite the addition of 6 MW of grinding power).

Since these early installations in the 1990s IsaMill™ development has moved in two directions. Firstly the features that allowed the IsaMill™ to address the inefficiencies in conventional technology when grinding to very fine sizes were found to be equally applicable to coarser sizes. The high energy efficiency and intensity as a result of the IsaMill™'s ability to use fine media as well as the increased efficiency from using ceramics such as Magotteaux's Keramax MT1 could be transferred to grinding coarser material. Today there are more IsaMill™s used in typical regrind and mainstream applications than there are in fine and ultrafine duties which has expanded the operating base of the technology improving reliability and availability. Secondly the scale up of the IsaMill™ to the 3 MW M10 000 model (Curry, Clark and Rule, 2005) has meant that the IsaMill™ is now of a large enough capacity that a single unit can be used resulting in a smaller plant footprint, lower capital costs and a simpler flow sheet than if alternative technologies had been selected.

Once the need to regrind the Prominent Hill rougher concentrate down to 20 - 25 µm had been identified, a large IsaMill™ was an attractive option for this duty because:

- a single unit could perform the duty,
- it uses inert ceramic media avoiding 'fouling' of mineral surfaces with debris from ferrous grinding media (high intensity conditioning is a by-product of the IsaMill™), and
- it is proven 'mainstream' technology in sulfide mineral concentrators.

### The Prominent Hill IsaMill™

The Prominent Hill IsaMill™ was designed based on test work completed in early 2006 on a composite of rougher concentrate produced in the pilot plant. The IsaMill™ is renowned for its accurate and direct scale up from M4 Laboratory test work to full scale mill operation. The direct scale up method has proven accurate for all large scale IsaMill™s. The feed size of the sample as received was $P_{80}$ of 144 µm. The sample was treated with multiple passes through the 4 litre M4 IsaMill™ to produce the signature plot as shown in Figure 5. The signature plot allows direct correlation of product size with energy requirement for a given feed size. All sizings were done using a Malvern Laser sizer.

From the signature plot in Figure 5 it was determined that the M10 000 IsaMill™ at full capacity could grind 138 t/h of rougher concentrate to a $P_{80}$ of 23 µm.

## JAMESON CELL

### Additional flotation cleaning capacity

The flotation test work clearly showed the need to maximise the copper concentrate grade by reducing the recovered amount of non-sulfide gangue.

Mineralurgy Pty Ltd suggested that the concentrator have an additional stage of washed froth cleaning in a Jameson Cell

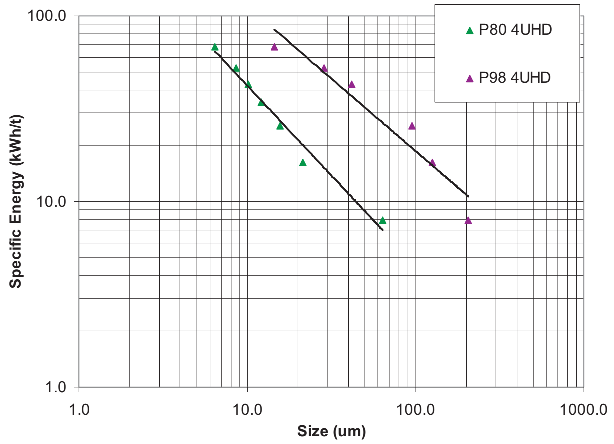


FIG 5 - Prominent Hill IsaMill™ signature plot.

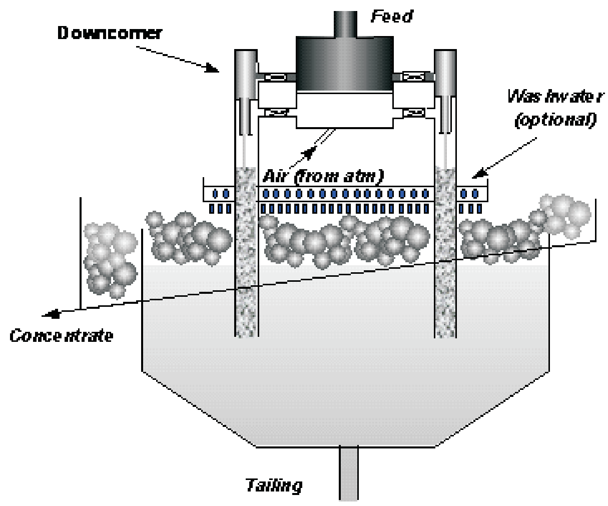


FIG 6 - The Jameson Cell.

ahead of the three stages of cleaning in conventional cells. The Jameson Cell operating at a constant feed volume could make ~50 per cent of the final concentrate with froth washing reducing non-sulfide gangue recovery by entrainment. Jameson Cell tailings would go to the three stages of cleaning in conventional cells which produce the remaining ~50 per cent of the final concentrate. Removal of a significant amount of mass as final concentrate in the Jameson Cell allows the conventional cells to operate at lower pulp densities. The ability to add more water to the conventional cleaner cells, via the Jameson Cell tailing, will also help reduce the entrainment of non-sulfide gangue into the copper concentrate and could reduce the fluorine content by 30 - 50 per cent. The Jameson Cell used as a scalper in the lead cleaner section of the lead/zinc concentrator at Mount Isa Mines Limited combined with the resulting changed mode of operation of the three stages of conventional cleaning achieved a 45 per cent reduction in silica recovery and a 30 per cent reduction in non-sulfide gangue recovery (Young, 2006).

## Principles of operation

Xstrata Technology estimated that a Jameson Cell of size J5400/18 (5.4 m diameter with 18 × downcomers) would make 20 - 25 t/h of final copper concentrate or ~150 000 t/y.

As discussed by Young *et al* (2006) the Jameson Cell combines a novel method for air and slurry contact where a plunging jet naturally entrains air, achieving high voidage, fine bubbles and intimate bubble particle contact (Figure 6). Small bubbles (0.3 - 0.5 mm) are consistently produced, and intense bubble-particle contact occurs in a short time (six to ten seconds) in the downcomer. Thus the Jameson Cell is a high intensity device producing fast mineral flotation rates. Bubble/particle contact occurs in the downcomer, the purpose of the 'cell' is simply for bubble-pulp separation, and therefore cell volume is very small compared with alternative technologies. The high flotation rates resulting from the intense aeration mean a high productivity per surface area, making froth washing attractive to increase concentrate grade. Power consumption is lower than the equivalent mechanical or column flotation cells (with only the feed pump, and no blower or compressor) and the maintenance is minimal (with no rotor, the only wearing part is the slurry lens). The fundamentals of Jameson Cell operation have been described by numerous authors (Clayton, Jameson and Manlapig, 1991).

The first production Jameson Cells as lead cleaner cells at Mt Isa (Jameson and Manlapig, 1991), gave vast improvements in flotation kinetic rates over mechanical cells and flotation columns in a smaller and cheaper installation. These early units also showed that Jameson Cells were ideally suited to producing high concentrate grades (from a single pass) at moderate recoveries (Jameson, Harbort and Riches, 1991). To obtain high overall circuit recovery they needed to be operated in closed circuit with other flotation banks. Later work highlighted the fact that a single pass Jameson Cell could produce final concentrate grade from rougher feed at 60 - 70 per cent recoveries, which was significantly better than mechanical cell test work.

While Jameson Cells have taken longer to be accepted into base metals circuits they quickly achieved success in coal fines flotation and SX-EW organic removal (Jameson, Goffinet and Hughes, 1991; Dawson and Jackson, 1995) as a result of high single pass recoveries and small installation footprints. Fundamentally base metals flotation has slower differential kinetics and higher upgrading ratios than coal. This difference requires the base metals Jameson Cell be operated in closed circuit with other flotation units (mechanical or Jameson Cells) to achieve high overall recovery.

As discussed by Young *et al* (2006) two key issues were addressed to allow the Jameson Cell to 'move' into base metals flotation:

1. A tailings recycle system was established at the cell feed to allow a constant volume and pressure to be fed to the downcomers in spite of the normal fluctuations in operating plants. Typically 40 per cent of the feed gets a 'second chance' in the downcomer and increases first pass recovery.
2. Applying Jameson Cells in base metal flotation accounting for low single-pass recovery, while taking advantage of the fast flotation rates and high concentrate grades can result in an overall low cost circuit. This requires recognition of the Jameson Cell as a 'high grade machine' that required additional recycle to maximise recovery. While the high intensity and small bubble size in Jameson Cells mean they are good at recovering fast floating material, the lower intensity and greater residence times in conventional flotation banks make them better at recovering slower floating material. These fundamental differences between conventional and Jameson Cells mean that the flow sheet needs to be designed to maximise the inherent strengths of the respective cells and to optimise the response of the ore based on kinetics and upgrade ability.

When designing a base metals flotation circuit it is essential that the correct flotation machine gets chosen to meet the task requirements. The key feature of the Jameson Cell, its ability to produce a high grade concentrate at a moderate recovery while utilising froth washing to minimise entrainment, needs to be recognised.

An appropriate place to install a Jameson Cell is in a 'cleaner scalper' duty which is ideal for both new plants and expansions and retrofits, where a conventional cleaner circuit already exists and extra capacity is required. The 'hybrid' circuit takes advantage of the best features of both technologies with Jameson Cells collecting fast floating material to produce a high grade and tonnage concentrate and the conventional cells achieving final recovery. Additionally froth washing increases concentrate grade by reducing entrainment. By producing a high tonnage in a small footprint, the Jameson Cell allows froth washing to be applied economically to a significant part of the concentrate while reducing the feed solids to the subsequent conventional cleaners means these operate at lower density and lower froth rates, reducing entrainment. A relatively small area of froth washing can significantly reduce the total entrainment in this 'hybrid' circuit. It is this circuit which is used at Prominent Hill.

For more details on the concentrator at Prominent Hill the reader is referred to the paper by Colbert, Munro and Yeowart (2009) also in this volume.

### Prominent Hill Jameson Cell design

Due to limited availability of sample no Jameson Cell test work was conducted for this design. This may seem surprising but it should be noted that flotation columns are selected for cleaning duties in new copper concentrators in the Americas on the basis of flow sheets developed from standard laboratory tests with conventional machines. Usually no specific pilot scale testing is done on columns. Data analysis by the axiom of size-by-size mineral particle behaviour by liberation class gave confidence that this separation technology developed to treat the fine particles encountered in refractory zinc-lead-silver ores of the Carpentaria-Mount Isa Inlier could be successfully applied to Prominent Hill. Great weight was given to the wealth of experience in Jameson Cell operation at Xstrata Technology. The Jameson Cell was designed based on the cleaner block feed of 138 t/h at 17 per cent w/w solids. A J5400/18 cell was selected with 44 mm slurry lenses to give a recycle of approximately 50 per cent.

To ensure adequate lip length and so maximise potential concentrate recovery, six radial cross launders were installed in addition to the existing launders. The wash water system was designed for sufficient flow to create a positive bias of >1.

## FLOTATION CIRCUIT PERFORMANCE SINCE COMMISSIONING

Milling of low-grade ore commenced on 9 February 2009 and the flotation circuit was initially commissioned and run without the IsaMill™ and the Jameson Cell. This resulted in high levels of non-sulfide gangue in the initial concentrates produced. With the IsaMill™ and the Jameson Cell in circuit the non-sulfide gangue was reduced to design levels.

Due to delayed commissioning of some equipment, the processing plant was handed over to the operating team on 31 March 2009. True plant ramp-up performance should be gauged from that date.

In April 2009 the concentrator milled 584 813 tonnes of ore at a head grade of 1.82 per cent Cu making 12 756 tonnes of copper concentrate at 58 per cent Cu grade at 70 per cent recovery. Fluorine levels were ~700 ppm F and compare favourably to the internal target of 800 ppm F. By mid-May 2009 the month-to-date copper recovery was up to 85 per cent for a concentrate grade over 55 per cent Cu. This meets the performance prediction for the chalcocite-bornite ore type from the metallurgical test work.

## CONCLUSIONS

The mineralogically-based approach of domaining metallurgical ore types combined with the axiom of size-by-size mineral particle behaviour by liberation class gave a clear understanding of the liberation and separation issues involved in the processing of Prominent Hill ore.

Technologies developed to meet much more onerous liberation and separation duties for the treatment of the refractory zinc-lead-silver ores of the Carpentaria-Mount Isa Mineral Province were successfully used to improve concentrate quality by rejecting fluorine- and uranium-bearing minerals. The equipment used was the IsaMill™ for regrinding down to ~20 μm and the Jameson Cell for additional cleaning capacity.

Plant performance since commissioning has justified the approach for metallurgical test work and equipment choices for the flotation circuit.

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