

Ultra Fine Grinding - A Practical Alternative to Oxidative Treatment of Refractory Gold Ores

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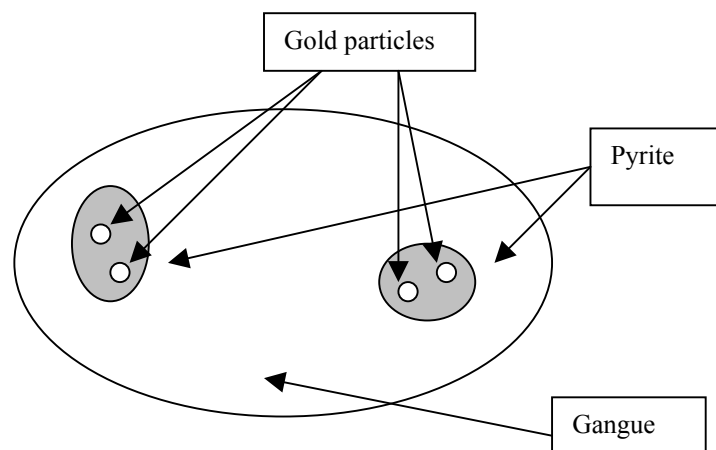
Abstract

Since early 2001, Kalgoorlie Consolidated Gold Mines (KCGM) has successfully operated an ultra fine grinding (UFG) circuit to supplement its roaster capacity for the treatment of the refractory gold flotation concentrate. A second UFG mill was installed in 2002 taking the total UFG capacity to over 20tph while grinding to 11-12 microns and achieving over 90% gold recovery. A development program in 2002/3 involving plant trials, pilot plants and laboratory testwork resulted in process improvements and a better understanding of the milling and gold leach processes that assisted in narrowing the gap between UFG and roasting . This paper details the operation of the ultra fine grinding process at KCGM as a non oxidative treatment for the extraction of gold from a refractory ores.

Introduction

The refractory nature of gold ores is often associated with gold finely disseminated in sulphide minerals, such as pyrite, at conventional grind sizes. Conventional milling can liberate the pyrite from the gangue allowing a low mass pyritic concentrate to be produced by a process such as flotation. However, direct leaching of the concentrate results in poor gold extractions as the cyanide lixiviant is unable to contact the gold locked or included within the pyrite (Figure 1).

Figure 1 Pyrite Locked Gold Within an Ore



The traditional approach for such refractory material has been to liberate the locked gold by chemically destroying the pyrite through oxidation. Roasting, pressure oxidation, and bacterial oxidation all employ various degrees of temperature, pressure and catalysis to react the pyrite with oxygen to produce an iron oxide and sulphur by-products. This method efficiently liberates finely disseminated gold or gold in solid solution.

Whilst such oxidative reactions are metallurgically sound and are capable of achieving high metal recoveries, the environmental aspects of treating the reaction products can alter the economics of the process.

For example, capture and disposal of sulphur dioxide from the roasting of sulphides or the neutralisation of the acidic liquors from pressure oxidation, may add significant additional costs to the process. In certain cases, these additional costs may make an alternative process route more economically attractive.

Fine Grinding

An alternative, applicable to the liberation of disseminated gold from the host mineral, is to continue the grinding process to further reduce the particle size of the host mineral thereby exposing a part of the gold surface for contact with cyanide solution. A benefit of this technique is that the host mineral is not destroyed in an oxidative chemical reaction with the resultant problems of treatment of the reaction products. Such fine grinding, however, has proven to be increasingly energy intensive with each size reduction step. In pit blasting, primary crushing, secondary crushing, SAG and ball milling are all able to exploit natural fracture planes in the ore allowing breakage along these features. As progressive size reduction occurs, the naturally occurring minerals are liberated and a point reached where the crystal structure of the mineral has to be broken for further size reduction to be achieved. This may present a significant barrier to further breakage with higher power intensities required to achieve a breakage event.

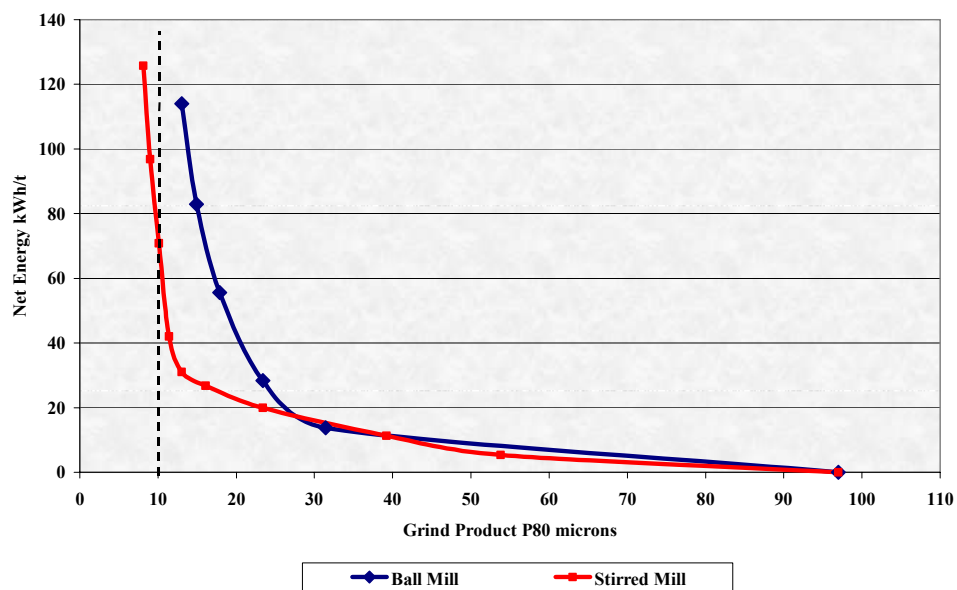
In the past, inefficiencies associated with conventional milling have made fine grinding unattractive to the mineral processing industry. The desired grinds for the harder minerals could only be achieved by prolonged milling with resultant low throughput and high power consumption. The use of smaller media in closed circuit can assist tumbling mills to achieve fine grinds but remain fundamentally limited in the manner in which they impart kinetic energy to the media as well as having large "dead zones" where little media movement occurs (Kalra, 1999). As finer media is used, the kinetic energy imparted to the media lessens thus significantly reducing the available energy transfer in a media/particle contact event.

Ultra Fine Grinding

UFG mills overcome these limitations by the use of rotating stirrers inside a stationary mill shell. Ultra fine grinding mills have been in use for many years in a large number of every day applications such as pharmaceuticals, dyes, clays, paint and pigments before being used in the mineral processing industry. They usually fine grind in a range of 1 μm to 10 μm , and impart a significantly increased surface area as well as other potentially desirable properties such as colour, ease of absorption into the blood stream and increased chemical reactivity.

Figure 2 compares the power consumption of a laboratory ball mill to a UFG mill in grinding KCGM concentrate.

Figure 2 Comparison of Grind Product Sizes



The use of UFG grinding in the minerals processing industry is a relatively new development being based on the smaller low mass, batch UFG mills being used by other industries for high value products.

The chief requirement of the minerals processing industry was a mill that could process quantities in the order of several tonnes per hour in continuous operation whilst maintaining cost efficiency in power and media usage.

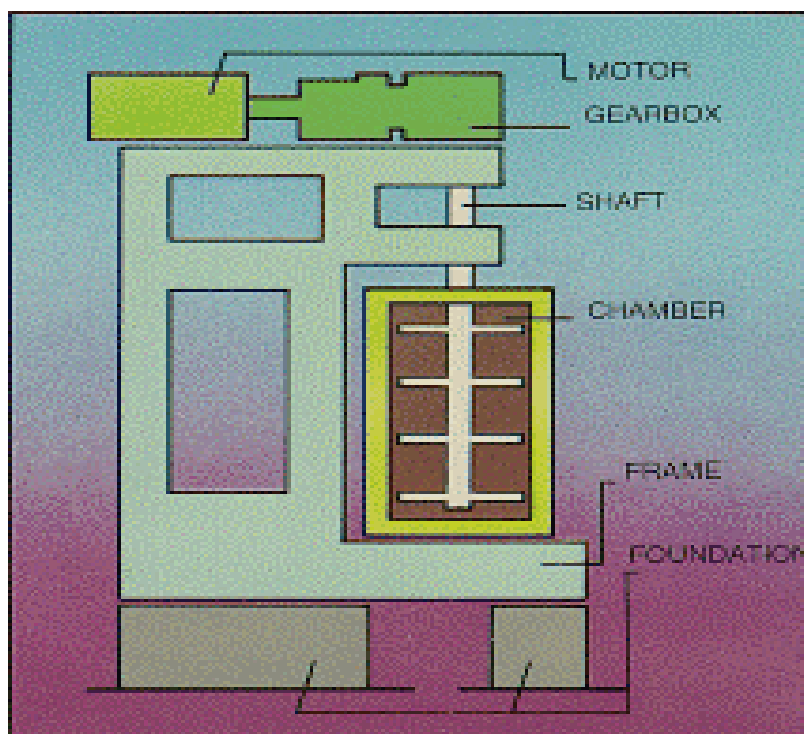
In achieving finer grinds, UFG mills use a finer media size (2-3 mm) than conventional milling (12-100mm) with a much higher installed power per mill unit volume (Table 1).

Table 1. Typical Mill Grinds and Power Intensities

Type of Mill	Typical Lower Grind Size P80 μm	Power Intensity kW/m^3
Ball Mill	75	20
Tower Mill	20	40
UFG Mill	5	280

Two basic types of UFG mills are available, the vertical stirred mill and the horizontal stirred mill. Both use rotating stirrers within a stationary mill shell to impart kinetic energy to a fine media charge (usually sand). The breakage mechanism is the same for the two mills, the differences being related to stirrer speed, method of media retention, and size of currently available mills.

Figure 3. Arrangement for a Vertical UFG Mill



Breakage and Particle Reactivity

As well as the resultant increase in the degree of liberation of the mill products, UFG also increases the surface area of the products enhancing the rate of downstream chemical reactions. The application of intensive non breakage stress events is believed to distort the mineral crystal lattice creating new defect sites which have high localised electron densities. These high electron densities facilitate the transfer of electrons to an oxidant thereby significantly increasing the rate of chemical reactions (Hourne and Halbe, 1999). This can result in a lowering of the activation energy for chemical reactions of the mill products and allow the reaction to proceed at lower temperatures and pressures than for the unmilled material.

This increase reactivity is demonstrated by the very high oxygen demand observed for pyrite after it is subjected to UFG .

The Activox and Albion processes make use of this phenomenon in their leach steps to achieve sulphide dissolution at reduced temperature and pressures to conventional pressure oxidation. However, for gold recovery, this increased rate of chemical reaction of the pyrite presents unwanted side reactions that can result in increased cyanide and lime consumptions.

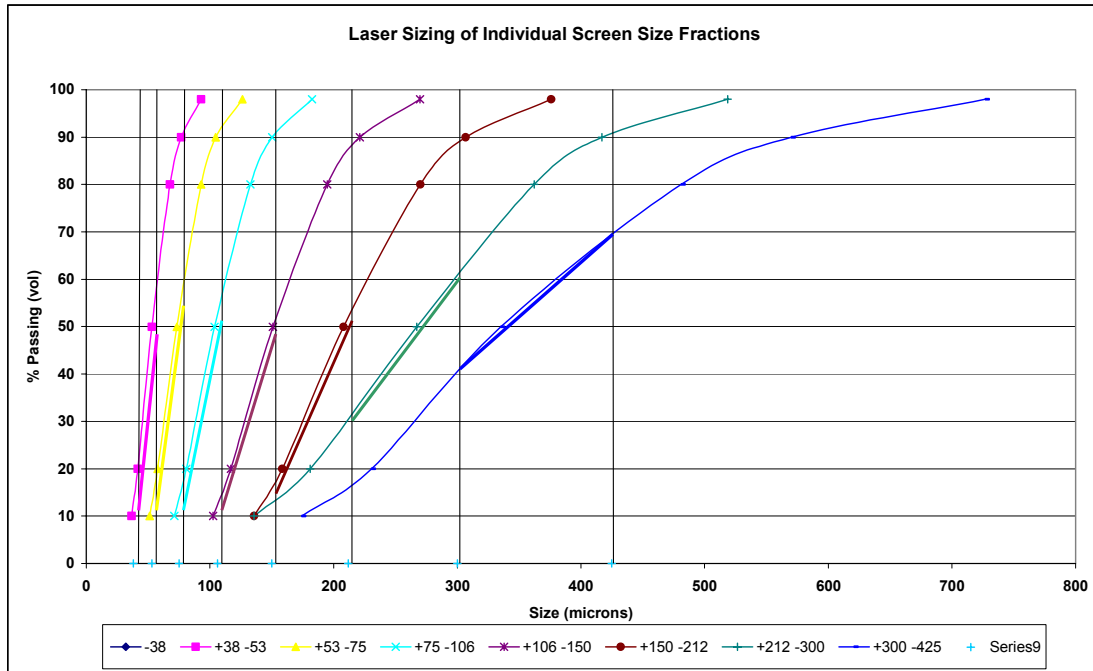
Sizing Measurements of the Product

Over time, laser sizing has gained popularity and has now become the de facto standard for fine particle size measurement. Limitations with the earlier laser machines have been overcome with the development of sufficient on board computing power to use the Mie Equation relating light scattering characteristics to particle size. The laser measures an average particle volume and converts this data to an average particle diameter. The laser method is fundamentally different from a screen sizing which measures the diameter of a particle that can pass through a screen aperture.

Testwork conducted at KCGM (Turton-White, 2003) showed that the source of the greatest error in carrying out a laser sizing measurement was the sub-sampling of the bulk sample to the very small sample presented to the machine. It was shown that samples of greater than 50 μ m required an additional sub-sampling step to ensure a reproducible measurement.

Caution should be exercised with the practice of screen sizing out the coarse particles and laser sizing the screen undersize and combining both sets of results. Figure 4 highlights the different results than can be obtained when size fractions from a dry screening are analysed by the laser.

Figure 4. KCGM Comparison of Laser and Screen Sizings



Method of Breakage

Stress Intensity has been examined as a critical determinant of the kinetic energy contained by the media in motion (Becker, 1997) and can be described in terms of the media diameter d , the stirrer tip speed v , and the media density ρ .

$$\text{Stress Intensity (Nm)} = d^3 \times v^2 \times \rho \quad \text{Equation 1}$$

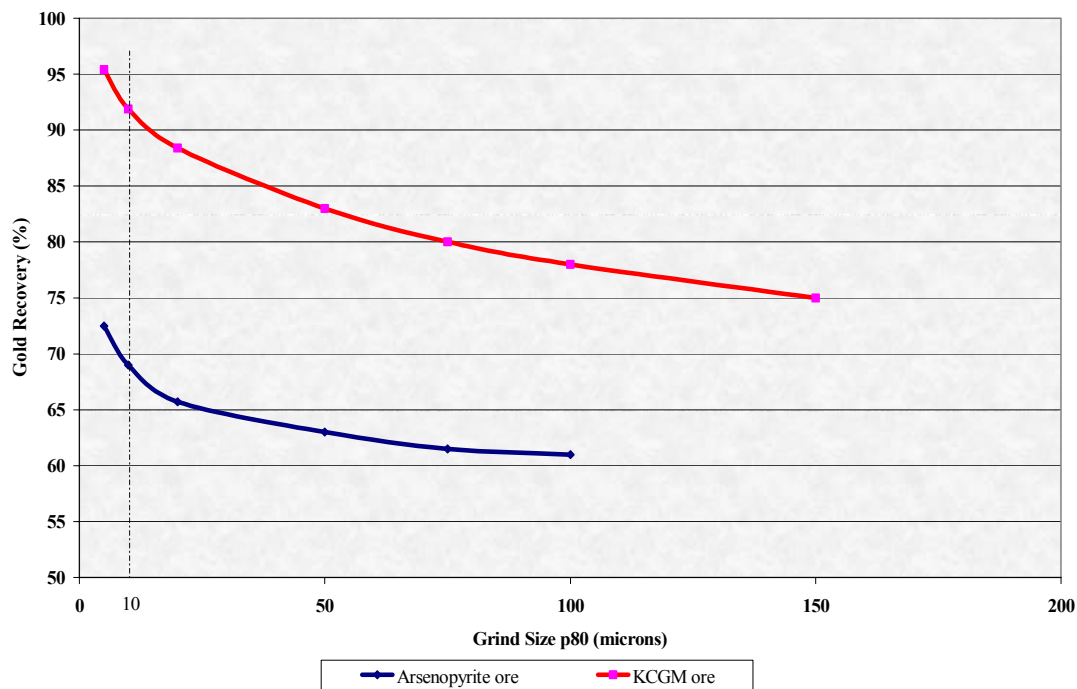
As shown in Equation 1, the Stress Intensity is related to the cube of the diameter of the media. For the same media type and mill speed, the Stress Intensity is increased by a factor of eight if the media size is increased from 3mm to 6mm. This highlights the importance of the inter-relationship between the top size of the mill feed, the selection of media size, and the wear on mill internals.

Kwade (1999) concluded that impact breakage rather than attrition was the main breakage mechanism in stirred mills for particles larger than 1 μ m. Recently Yue and Klein (2003) have examined breakage in successive grinding cycles and have found that a grinding limit exists where increasing grind time no longer results in particle breakage. They have postulated that this grinding limit is a function of the applied stress intensity and have noted that as this limit is reached, attrition rather than fracture becomes the chief breakage mechanism.

Sample Testwork

Not all refractory gold ores give a large recovery improvement after fine milling. Gold locked in arsenopyrite for example does not achieve the same gold recovery as gold disseminated in pyrite due to the smaller gold particle size of the locked gold (Figure 5).

Figure 5. Gold Recovery of Arsenopyrite and Pyrite Ores



Preliminary metallurgical testwork can be readily undertaken to determine the leach response to UFG. This involves the milling of a samples to a variety of nominated grind sizes and the leaching of the milled product. This not only determines the potential recovery but also gives a first pass economic assessment of the main economic drivers - power consumption, reagent costs, and gold recovery. Such preliminary data allows a comparison to be made with other processing routes.

Along with the determination of the grind/recovery curve, a mineralogical assessment of the gold deportment and particle size may provide additional information. Mineralogical scans such as QEMScan and MLA are able to give good data as to the mineral liberation and particle size of gold down to about 5µm. Below this size, an alternative method such as secondary ion mass spectrometry (SIMS) should be used.

Ultra Fine Grinding at KCGM

KCGM examined many concentrate treatment options that could provide an alternative to the roasting process in use. Chief among these were pressure oxidation, bacterial oxidation, and ultra fine grinding. An economic study carried out in 1997, determined that UFG had the superior Net Present Value return of the alternative options examined but was still a higher cost option than roasting as conducted at KCGM's Gidji site.

To progress UFG to the detailed engineering stage, further testwork was undertaken to define the flowsheet. A full pilot plant trial of the milling and leach process was carried out by Amdel (Adelaide) in 1999 which confirmed the recovery and power consumption indicated by laboratory scale testwork. The grinding of KCGM concentrate was amongst the highest energy consumers when compared to other UFG applications (Table 2); demonstrating that power consumption is very case specific.

Table 2. IsaMill Comparative Milling Data for Various Mineral Concentrates

Type of Ore	Lead Rougher Concentrate (PbS)	Zinc Rougher Concentrate (ZnS)	Lead/Zinc Rougher Concentrate	Copper Concentrate (CuFeS)	KCGM Gold Concentrate (FeS ₂)
Feed F80 micron	25	30	65	120	120
Product P80 micron	10	10	10	10	10
Net Energy kWh/t	10	20	30	100	80
Throughput t/h	96	48	32	9.6	12.0

The work demonstrated that the recovery of gold from KCGM concentrate could be increased from 75% to 92% by grinding to 10µm.

Mill Selection

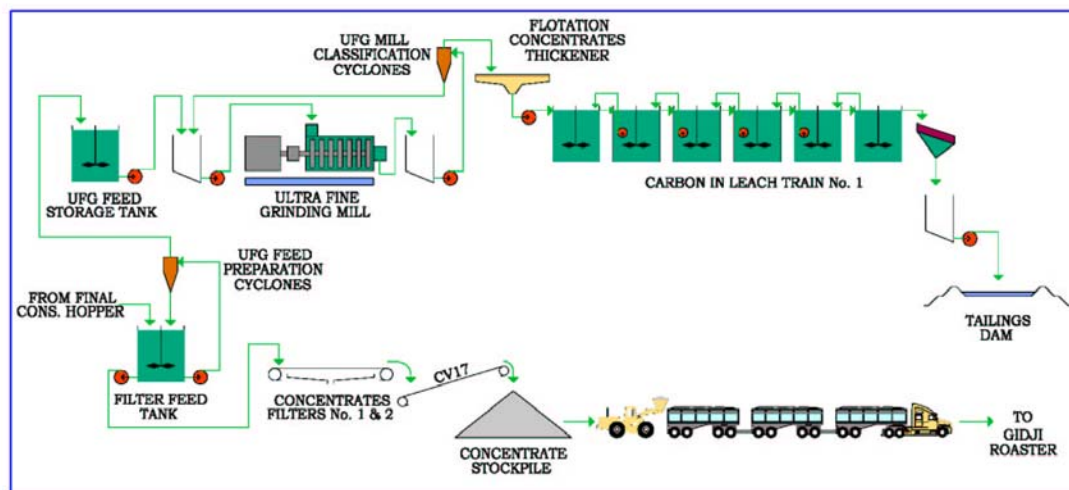
In the first instance equivalent samples of final concentrate were sent to all major mill suppliers for assessment. Results highlighted the lack of uniformity in the test methods and in the methods of sizing. No useful comparison could be made between results.

Site visits were useful in ascertaining the maintenance requirements of the mills, and general impressions of operators but with the variety ore types, hardness, and feed size to the mill any difference in metallurgical performance was difficult to gauge. From the preliminary assessment, the choice of mill was narrowed to the Detritor and the IsaMill. To discriminate between these mills, a pilot scale comparison was made by bring both the 18.5 kW pilot Detritor and the 55kW pilot IsaMill to site. The two mills performed similarly with no measurable difference in product quality or in power consumption under equivalent conditions. Given that no significant difference in metallurgical performance was apparent, KCGM opted for the IsaMill based on its mill size, low maintenance requirements, and its proven performance.

KCGM Flowsheet

For KCGM the main process risk lay with the unproven cyanide leaching of 10 μ m pyritic ore with acceptable reagent consumptions. In order to minimise this risk and to reduce capital costs associated with the process, KCGM determined to use single stage milling acknowledging that some inefficiency in power consumption and general mill and cyclone operation would result from the large size reduction step. To minimise the impact of the large feed size, a pre-treatment cyclone step was used to lower the feed size to the UFG mill by rejecting the coarser material to the cyclone underflow. The underflow was directed to the roasters for processing where the size was not of major significance. Whilst this approach assisted in reducing the feed size to the mill, it was subject to variations driven by the limited amount of suitably sized material in the concentrate. A further disadvantage lay in the pre-treatment cyclones directing an increased quantity of fine gangue material to the mill. The final flowsheet for the KCGM process is shown in Figure 6.

Figure 6. KCGM Flowsheet



The key design criteria for the process is shown in Table 3.

Table 3. UFG Key Design Criteria

Item	Design
Concentrate Processing Rate	10 t/h
Deslimed Concentrate Solids Size Distribution (F80)	120 microns
UFG Feed Prep Product Solids Size Distribution (P80)	50 microns
Initial Concentrate Gold Grade	40 to 50 g/t
UFG Feed Prep Product Solids Concentration	45 % to 55% w/w
UFG Product Solids Size Distribution (P80)	10 microns
Gold Recovery	92 %

Media Selection

The media size selected for the duty was based on the top size of the feed likely to be introduced to the mill. Pilot plant experience had shown that running too little media or too small a media size could result in a build up of unbroken feed top size in the mill. This build up in feed material within the mill led to a locking and centrifuging of the charge with a marked drop off in power draw. To ensure that the feed top size was adequately broken under all conditions, 6mm top size sand media was selected for the duty. Silica sand was selected due to its relatively low cost with initial supplies sourced from Northern New South Wales. Despite Australia wide searches for alternative supplies, only a few locations have been identified as having sand media of sufficient competency to achieve acceptable media consumption rates. Steel, smelter slag and ceramic medias were tested but rejected on the ground of cost, high consumption rates, and/or the introduction of deleterious materials (iron) to the leach process.

The use of a large media size (6mm) whilst ensuring top size particle breakage, resulted in severe wear on the mill internal components. Typically, wear associated with the leading mill disc, necessitated a mill stoppage every ten days compared to several months at other IsaMill installations running with 3mm media.

Media size is a critical determinant of the kinetic energy imparted to the media and is related to the cube of the diameter of the media. For the same media type and mill speed, the energy is increased by a factor of eight if the media size is increased from 3mm to 6mm. This highlights the importance of the inter-relationship between the top size of the mill feed, the selection of media size, and the wear on the mill internals.

Cyclones

Testwork had shown that closed circuit grinding with classification cyclones could significantly improve the mill throughput rate over open circuit. This was particularly apparent with the broad feed size distribution being presented to the mill as new feed. A key aspect of the KCGM flowsheet was the ability to provide a suitably sized product to the leach process for gold extraction whilst maintaining a suitable mill feed density (55%) with good fines rejection to overflow.

Closed circuit was also beneficial to the downstream gold leaching process in that the pyrite mineral carrying the gold have high SG's which preferentially reports to the cyclone underflow over an equivalent sized particle of a lower SG. This natural preference for high SG particles to report to the underflow, results in a further passage through the mill until such time as the reduced size counters the differential SG and allows passage out of the cyclone overflow and then to leach at a finer grind size.

KCGM selected 68mm cyclones for the classification duty on mill discharge. These cyclones have been essential in achieving a 10 μ m P80 product to leach but have presented a number of operational problems in spigots blockages and high wear rates.

With 10mm spigots, blockages were a constant problem with trash, scale, and sand media all contributing to blockages. Such blockages allowed a direct bypassing of mill discharge to leach with the resultant drop off in recovery. Significantly fewer spigot blockages have occurred since a vibrating screen was installed between the mill discharge and the cyclone feed hopper to remove this material. The main source of blockage nowadays is bridging of the spigot if the cyclone underflow becomes too high resulting in roping.

Thickening

The low pulp density of the cyclone overflow (8%) necessitated a thickening step to achieve the targeted 50% leach density. Testwork showed that the 10 μ m product would flocculate and settle rapidly at around 0.4 t/m²/hr using the standard non-ionic polyacrylamide flocculant in use at a dosage rate of 140g/t. Plant experience confirmed these figures with thickener underflow densities of up to 55% being readily achieved.

Leaching

The leaching of sulphidic ores is often problematic with a number of side reactions likely to occur that can lead to high reagent consumption and poor gold recovery (Deschenes, 2001). The KCGM concentrate to be leached not only contained a high percentage of pyrite milled to a very fine particle size but also cyanide soluble copper (0.15%) as chalcopyrite. The presence of telluride gold (calaverite) also added to the leach complexity requiring specialised leach conditions.

In the laboratory testwork and early plant practice, a very high oxygen demand and slow leach kinetics were noted. Typical gold recovery of around 90% was achieved at a cyanide consumption rate of 15 kg/t. A leach development program was conducted in 2002 where intensive laboratory and pilot leach tests were carried out to improve gold recovery and lower reagent consumptions. The testwork resulted in a revised leaching regime where pre-oxidation was abandoned, lead nitrate was introduced at the start of the

leach, and low dissolved oxygen levels (3ppm) maintained in the leach. It was also found that a high lime environment (30 kg/t) and use of carbon in leach (CIL) assisted the leaching of the gold tellurides.

By the use of these new leach conditions, the leach residence time was reduced from 72 hours to 24 hours, the cyanide consumption reduced from 15 kg/t to 8 kg/t, and average gold recovery increased by 2%. These improvements are shown in Figures 7, 8, and 9.

Figure 7. Improved Gold Recovery

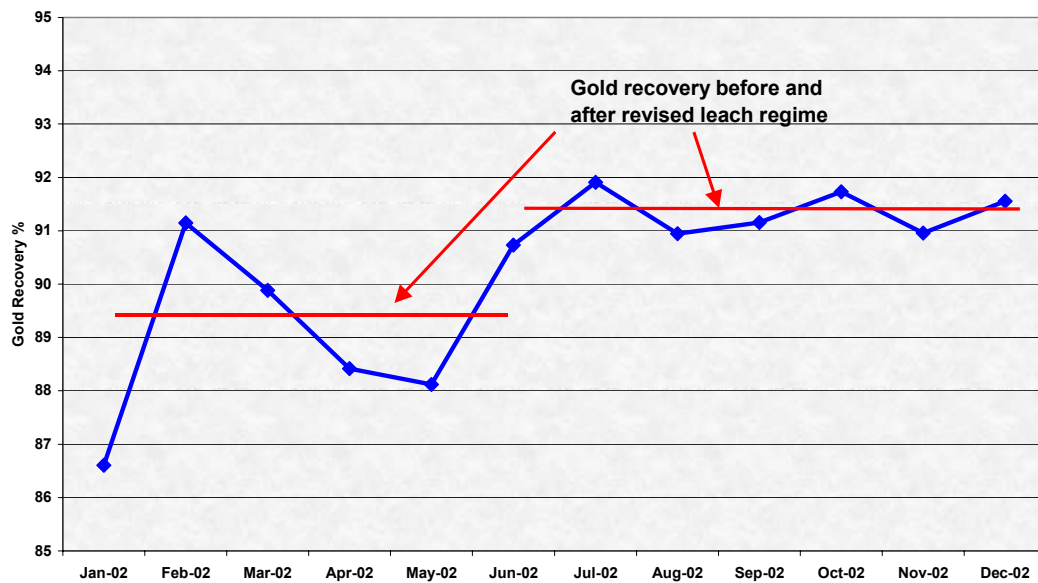


Figure 8. Reduced Cyanide Consumption

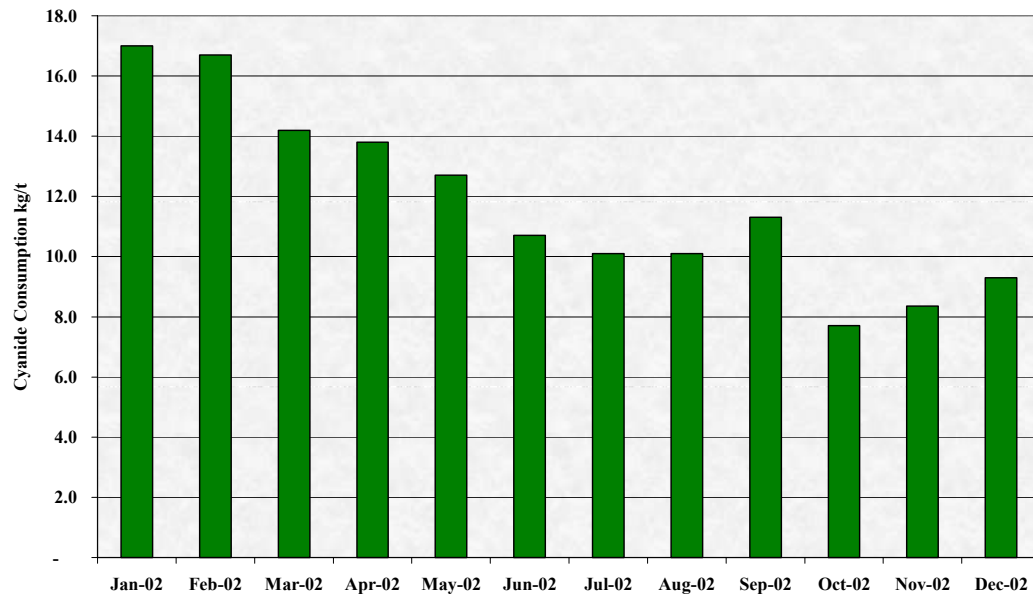
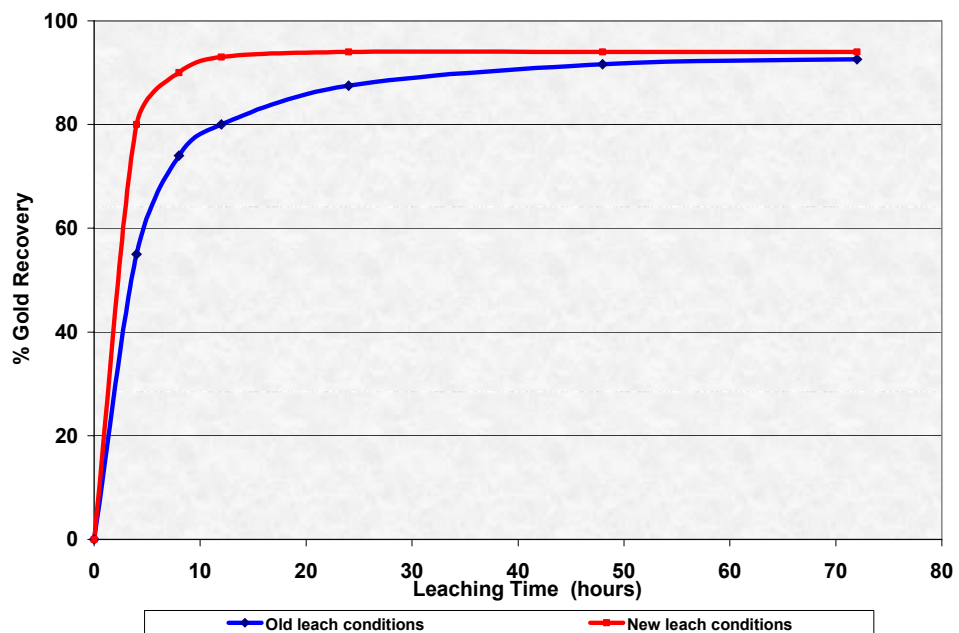


Figure 9. Improved Leach Kinetics



Despite the presence of an amount of sub 10µm material in the leach, no issue with the loss of carbon activity due to fine particles blocking pores in activated carbon has been apparent.

Costs

The capital cost of each of the KCGM UFG milling installation was \$4.5 million. With ancillary equipment for the leach process the total project costs (including EPCM, owners management costs, and contingency) were around \$6 million for each circuit.

Operational costs with a breakdown to the respective activity are shown in Figures 10 and 11.

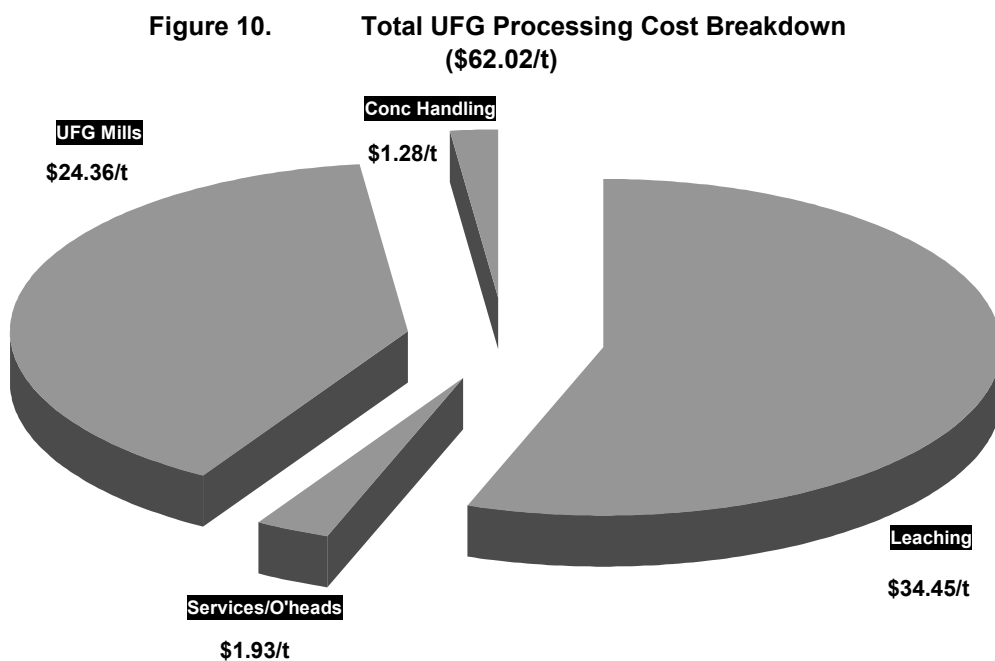
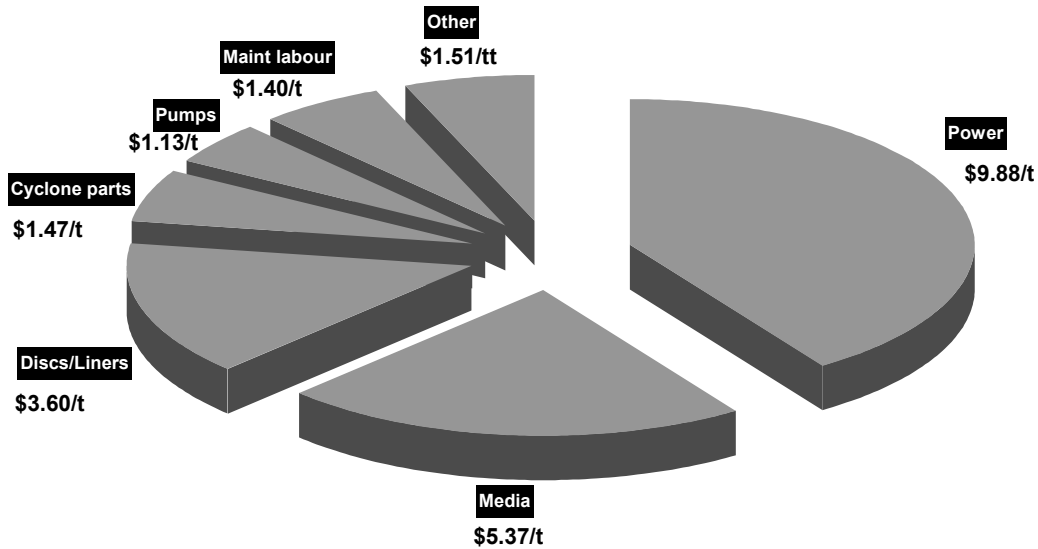


Figure 11. UFG Milling Cost Breakdown (\$24.36/t)



The Future

With UFG being in operation for over two years at KCGM and having successfully proven the concept of economic gold extraction from refractory sulphide ore, albeit with lower gold recovery than roasting, the challenge is to further reduce process operating costs. The developmental work carried out has highlighted a number of areas where further improvements may be possible. Further work is in progress to quantify the benefits of introducing a primary milling stage. It is believed that a significant reduction in mill and cyclone wear components would result if a finer mill feed was produced as this would allow the use of a smaller media size thereby bringing wear rates in line with other similar mill users. Some improvement in power efficiency may also result from such an approach as well as some further improvement in gold recovery resulting from improved cyclone classification of a finer mill product.

The cost efficiency of ceramic media is likely to improve considerably in the future due to recent improvements in the quality and a lowering of the unit price with an increasing

market size. As the number of UFG mills increases, the availability of sand of sufficient size and quality may be limited.

The application of ultra fine grinding to refractory gold ores has proven to offer a viable alternative to conventional oxidative processes in particular cases. Its application to a hydrometallurgical extraction route for other metals beyond gold is open and likely to lead to alternative process routes for these metals also.

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