GRAVITY RECOVERYOF GOLD FROM WITHIN GRINDING CIRCUITS

Ish Grewal, M.A.Sc. P.Eng.[1], Mark Van Kleek, B.A.Sc. MBA[2], and Steven McAlister, P. Eng.[2]

[1] Met-Solve Laboratories Inc., 8515 Eastlake Drive, Burnaby, BC, Canada
[2] Falcon Concentrators, 9663 199A Street, Langley, BC, Canada

ABSTRACT

Gravity recovery of gold from within grinding circuits has become common in many operations around the world. Effective gravity concentration effort is a function of numerous factors including the quantity and size distribution of the Gravity-Recoverable-Gold (GRG) present, downstream processes, water balance and gravity section operating costs. This paper describes test work protocols, mathematical modeling techniques and the practical considerations that lead to the 'right' gravity circuit being installed in a given grinding circuit. The right gravity concentration effort is that which produces the best economic outcome for the operator.

INTRODUCTION

Gold recovery using batch-type centrifugal concentrators (BCC's) from within grinding circuits is a well established practice in many operations where the presence of gravity-recoverable-gold has been identified to be present in the ore. The benefits of including gravity concentration to supplement cyanidation and flotation are well understood and accepted by the industry. Considerable research and fundamental work (Banisi, Laplante and Marois, 1991) in understanding the behaviour of gold within grinding circuits has contributed to the development of mathematical models and testing requirements for predicting gravity gold recovery. Installation practices, on the other hand, vary widely. In addition to describing effective test and mathematical modeling procedures, economic benefit calculation parameters and best installation practices are presented based on the authors' extensive operating experience.

MODELING GRAVITY GOLD RECOVERY

Batch centrifugal gravity concentrators, which produce very high concentration ratios, have become the devices of choice for recovering gold from within grinding circuits. These are usually installed in the mill discharge, cyclone feed or the cyclone underflow streams where a fraction, typically 10-40%, of the stream is treated by the gravity circuit. The key factors affecting gravity recovery of gold from within grinding circuits are:

- the gravity-recoverable-gold (GRG) content of the ore
- the size distribution of the GRG
- the recovery efficiency of the gravity concentration circuit
- cyclone efficiency (as defined by the partition curve of GRG)
- the fraction of the circulating load treated by the gravity concentrator
- the amount of GRG converted to non-GRG in the grinding mill (grinding behaviour of the gold)
- Gravity Section availability
- gold room efficiency

A population balance model can incorporate each of these key factors. The power of the model not only helps to predict gravity gold recovery but can also assist in trouble shooting existing circuits.

The GRG Test (Ore Characterization)

The gravity-recoverable-gold content of an ore, as obtained via a GRG test, provides a quantitative theoretical limit of gold that can be recovered using a BCC. The test itself consists of a sequential liberation via grinding followed by gravity concentration using a lab scale BCC (see Figure 1). The concentrates and the final tails products are screened and analyzed for gold by particle size class. The progressive grind approach limits the smearing of gold particles and allows for the recovery of GRG as it is liberated. The results from the test are presented as a cumulative GRG distribution as ell as GRG distribution by particle size class as shown In Figure 2.
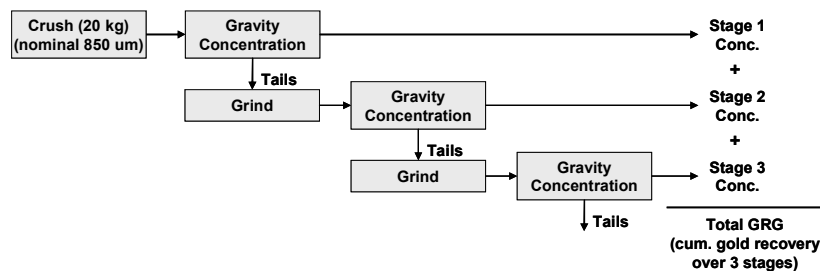

Figure 1. Standard procedure for a GRG test using a centrifugal gravity concentrator.
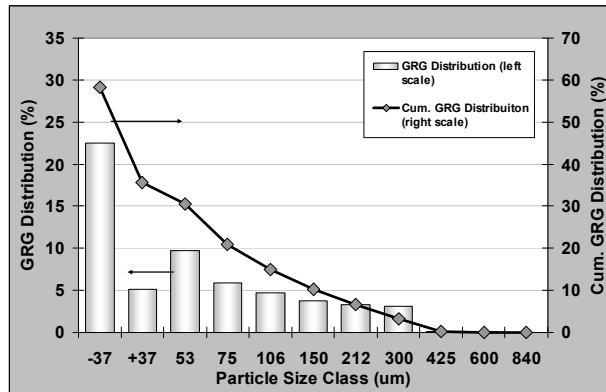
Figure 2. Results from a GRG Test –Cumulative distribution as well as by individual particle size class.

Cyclone Efficiency and Grinding Behaviour of Gold

Previous studies of the behaviour of gold in grinding circuits have shown that cyclones are very effective at retaining gravity recoverable gold within the grinding circuit resulting in high circulating loads of gold (Banisi, Laplante and Marois, 1991). The retention of GRG within the grinding circuit allows for effective gravity recovery of gold from within the grinding circuit. A typical partition curve for both the ore and GRG, presented in Figure 3, illustrates the significant difference in the partition behaviour of the gold relative to the ore.

The cyclone partition curve for GRG can be generated from sampling the cyclone streams and measuring the GRG content of the cyclone overflow and underflow using lab scale BCC.
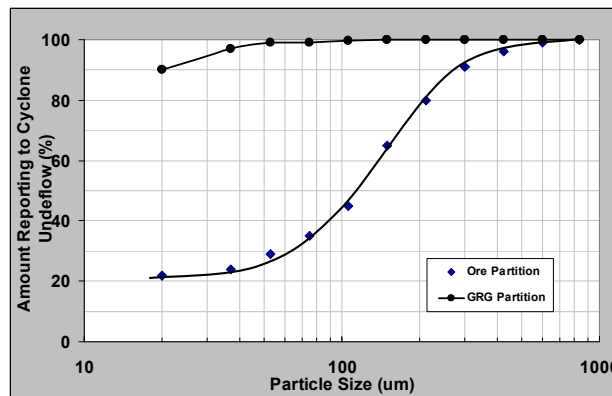

Figure 3. Typical partition curves for ore and GRG

Gold not only grinds six to twenty times slower than most minerals, it can even flatten and report to coarser size fractions. The long residence time of the gold within the grinding circuit can cause some of the GRG to become non-gravity recoverable due to smearing on to grinding media, mill liners and gangue minerals. This effect is minor as more than 98% of the GRG entering the ball mill remains gravity recoverable after grinding (LaPlante, 2000).

Concentrator Efficiency and Concentrate Upgrading (Gold room efficiency)

Batch centrifugal concentrator's provide high concentration ratios, >1000:1 typically, but operate with relatively low stage recoveries of 20-40%. They rely on the efficiency of the cyclones to retain GRG within the grinding circuit to be effective.

The concentrate produced by the primary BCC is often upgraded using a shaking table. Recently; intensive cyanide leaching of the concentrates has also become common. Specialized intensive leach units have been developed to treat concentrates generated by centrifugal gravity concentrators.

Modeling of gravity gold recovery includes the characteristic efficiency of the primary BCC and the concentrate processing method used. The data for the model inputs can be obtained from site surveys or from the manufacturers of the respective technologies.

Modeling – incorporating tonnage treated by gravity

A basic approach to the model incorporates the bulk GRG value or the un-weighted average of the result from the GRG test, cyclone efficiency and stage recoveries of the various centrifugal gravity concentration models. A more

sophisticated approach incorporates the GRG results and the cyclone efficiency on a particle size class basis. A typical milling circuit incorporating gravity in the cyclone underflow presented in Figure 4.

A sensitivity analysis from modeling provides a few important insights about the effect of various parameters on gold recovery. The single most important variable in effective recovery of gold is the efficiency of the cyclone to for retaining gold within the grinding circuit. Poor partition behaviour of the cyclone combined with upsets in the cyclone feed stream ~~can~~ is the most significant cause of reduced gravity gold recovery. This impact of cyclone inefficiency is illustrated in Figure 5 where a drop of 2% in the efficiency of the cyclone significantly reduces gravity gold recovery. It is important to note that the slope of the gravity recovery line is significantly steeper at the higher cyclone efficiency values. When minor fractions of the circulating load are treated, high recovery of gravity gold is only possible when cycloning is extremely efficient. The actual amount of the circulating load treated is dictated not only by metallurgical requirements but also economic and practical considerations discussed in the following sections.
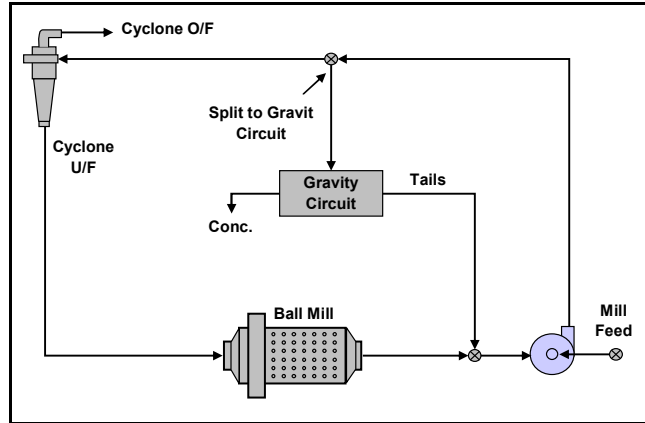

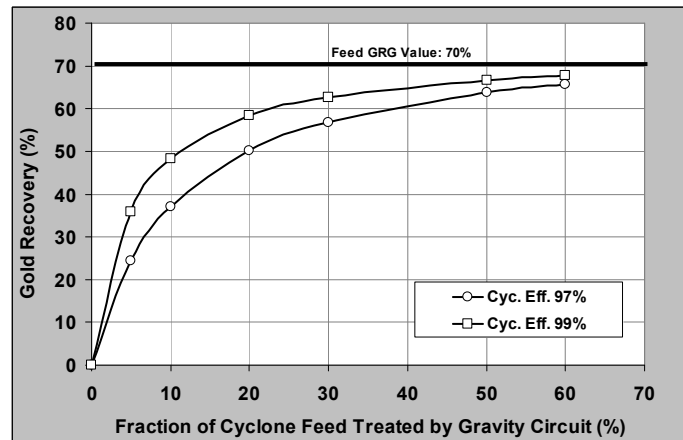**Figure 4. Typical grinding circuit incorporating gravity concentration**

Figure 5. Modeling result for gold recovery as a function of the fraction of the cyclone feed; assuming 1% loss of GRG in the ball mil, 70% feed GRG and 250% circulating load and BCC stage recovery of 40%. No upgrading of the primary gravity concentration is considered in this analysis.

ECONOMIC ANALYSIS

Gravity concentration has undergone a transformation in recent decades due to rapid advancements in technology. As technology has changed, so too has the definition of where gravity technology can be economically applied. The economic benefits of integrating BCC's into the grinding circuit ahead of flotation or cyanidation is are sometimes difficult to measure. The difficulty has never arisen from the calculations themselves, which are relatively straightforward, but rather with the understanding of gold's behavior in mills and in obtaining accurate plant data. With the advent of modern circuit modeling techniques for gravity, the understanding of gold's behavior in milling circuits has improved significantly, however obtaining accurate circuit data is still problematic and can render the calculations meaningless in some cases.

In cases where a gravity circuit accounts for a very large change in overall gold recovery, the error in the measured quantities used in the calculations is negligible when compared to the benefit achieved and therefore of limited concern. Conversely, when the change in overall recovery attributable to gravity is small, extremely accurate circuit measurements are required in order to quantify a statistically significant economic benefit. Even in cases when the overall efficiency increase attributed to gravity is very small (a fraction of a percent), the addition of a gravity circuit can still have a surprisingly large benefit due to the low cost associated with the installation and operation of a gravity circuit. It is because of the potential for a high benefit given a very small efficiency change that the need for increasingly accurate benefit quantification has arisen.

In the case of a Greenfield project or any other project where both capital and operating costs need to be considered, the Rate of Return (ROR) or Net Present Value (NPV) methods can be used. In some cases where the capital costs have been fully depreciated, an even simpler calculation consisting of subtracting the costs from the revenue per time period can be used although in this case NPV is equally usable and perhaps a more sophisticated approach .

Economics of Various Circuit Types

Gravity Only Circuit

The simplest economic case is the "Gravity Only Circuit". Historically, this was the only method of gold extraction (along with mercury) until the introduction of chemical alternatives (cyanidation, flotation) in the last century. In this case, gravity technology is the only technology applied, and thus the economic calculation is a simple NPV calculation in the case of a Greenfield project or, in older operations where the capital costs have been fully depreciated, it is simply the revenue minus the costs for a given time period. This type of circuit was largely replaced by flotation and cyanidation recovery methods although environmental pressure against chemical systems has resulted in a resurgence of interest in these types of "environmentally friendly" circuits.

Flotation plus Gravity

In circuits that utilize flotation plus gravity, the economics of the gravity portion of the circuit are generally very strong. According to Dr. André Laplante (Laplante, 2005) the benefit for every 10% of recovery by gravity usually falls in the range of +0.5-5% of additional overall gold recovery. This rule of thumb is based on a large database of mills from around the world and indicates an extremely strong economic incentive for the use of gravity in flotation mills.

While the number provided by Laplante is an interesting start, one can calculate the gravity circuit benefit in far more detail. When calculating economics in flotation mills, one generally takes a flotation-only circuit as a base case, and then utilizes laboratory or pilot scale gravity test work to consider the effect of adding gravity recovery in various locations. Not all of the gold recovered to a gravity concentrate is gold that would have been lost to final tails. The gold recovered to a gravity concentrate will be a mixture of gold that would have reported to tails, and gold that would have reported to the various final concentrate products.

Gold contained in final tailings results in zero benefit and thus any gold shown to be recovered from that stream and into a gravity concentrate can be factored 100% as revenue gain. For the other product streams, any gold removed into a gravity concentrate will generally not be a 100% revenue gain. Most smelter contracts for flotation concentrate will pay a certain percentage for the gold contained therein, subject to various conditions and penalties. Each smelter contract will vary widely and have a significant effect on the overall economics of a gravity circuit. The smelter contract should be examined in detail even prior to initial test work or pilot work in order to determine higher value gravity recovery targets. Some products, such as zinc concentrates, may pay as little as zero for contained gold whereas gold in copper concentrates can pay well over 90%. When calculating the economic benefit in relocating gold from flotation concentrates to gravity concentrates, we must calculate the total value of gold recovered in the gravity concentrate and subtract the value that would have been paid for the gold by the smelter purchasing the flotation concentrate. This residual is the gravity benefit and must be calculated for each flotation product.

The final benefit consideration is associated with the speed with which payment is received for the gold product. Payment for gold in a flotation concentrate will take a number of weeks or even months depending on the distance to the smelter and the contract terms. Payment for gold as a gravity concentrate will be much faster, resulting in a gain that can be calculated using the appropriate capital discount rate for the project in question. Once the benefit for each stream has been calculated, including the speed with which the revenue will be received, one can again apply ROR or NPV methods to calculate overall benefit.

When choosing the placement of gravity equipment in a flotation mill there are a number of options. These options are not necessarily mutually exclusive and each potential circuit will have its own economic calculation. These circuits should be examined in the same order as presented here to ensure downstream effects are factored in.

- Primary Milling Circuit – In high grade mills this can be a good target, however it is much less likely to be economic in the large lower grade mills (<0.3 g/t). A gravity installation in the primary milling circuit will reduce the amount of gold in any downstream recovery circuit; therefore, this must be taken into account when performing downstream economic calculations.
- Flotation Concentrate Regrind Milling Circuit – If the primary milling circuit proves to be economic for a gravity circuit, the regrind circuit will almost always show an even stronger economic incentive, even when factoring in the gold removed by the primary circuit. This location will almost always have the highest return of any installation option. In fact, this location is generally among the most lucrative of any gravity circuits in any type of mill. If gravity is not viable in this location, it is very unlikely to be viable anywhere else in a flotation circuit, although there are exceptions depending on mineral associations and the deportment of gold in differential flotation circuits.
- Scalping gold from concentrate products – Placing gravity recovery in a single pass scalping application (not within a grinding circuit) can sometimes be very economic. Any gold removed previously by gravity in the primary or regrind milling circuits will affect the content and nature of gold in the final concentrate products; therefore care should be taken to reflect this in any laboratory or pilot testing. Generally, this type of application is only pursued after the possibilities in the milling circuits have been exhausted.

Cyanidation plus Gravity

In circuits that utilize cyanidation plus gravity, the economics of the gravity portion of the circuit can often be very strong. According to Laplante (Laplante 2005) the benefit for every 10% of recovery by gravity usually falls in the range of +0.2-1.0% of additional overall gold recovery. Like the previous rule of thumb for flotation, these numbers are based on a large database of mills from around the world and although the percentage benefit average is slightly less than in flotation mills, grades are generally higher in cyanide operations (cyanide operations are generally pure gold mines whereas in flotation mills gold is often a by product) and therefore the cash incentive may be even greater. In cases where the ore has a preg-robbing component, the gravity benefit can be far higher than the rule of thumb.

There are additional incentives in a cyanide circuit that do not occur in a flotation circuit. A gravity circuit in a mill utilizing cyanide can see benefits from lower carbon costs, lower gold inventory, lower reagent costs and reduced carbon stripping frequency. In Greenfield projects there can be huge capital cost savings where the leach residence time can be reduced with the inclusion of a gravity circuit.

In cyanide circuits there are generally only two placement options for gravity recovery. The most common is the standard batch concentrator installation within the milling circuit. A second option, usually in addition to the batch concentrator in the milling circuit and generally only in refractory ores, is the installation of a continuous concentrator in the cyclone overflow. In either case, as with flotation, one uses the standard cyanide only circuit as the base case and then, utilizing laboratory or pilot plant data; one calculates the effect of adding the gravity recovery units. As with other circuits, one can then use NPV or ROR methods to calculate the final benefit.

PRACTICAL CONSIDERATIONS

Once the decision to install a gravity section within a gold grinding circuit is taken, there are many practical issues that must be considered in the actual placement of the BCC within the grinding circuit.

Location within the Milling Circuit

Given the elevated grade, most of the early BCC installations were placed in the cyclone underflow, however further research has shown that cyclone feed or mill discharge is often the best placement option. While the higher grade in cyclone underflow is an advantage, this is outweighed by the high density of the cyclone underflow. As with other gravity devices, higher feed densities will lower the unit efficiency of the device. In the case of BCC's the best efficiency point is less than 55% solids with the optimum being in the 45%-50% range. When considering the need for lower density feed and the constraints of the mill water balance, mill discharge or cyclone feed is usually the best economic option as far more feed can be treated without compromising the circuit water balance. The benefits associated with proper feed density increase with decreasing gold particle size.

Other Placement Considerations

Prior to the advent of BCC's, it was usual to treat mill discharge with a mineral jig for gravity recovery. There are other considerations that lead to treating cyclone feed:

Plant Height. Unless cyclone underflow is pumped (**not** recommended), overall plant height can be reduced by treating cyclone feed. One saving for reduced height is lower capital costs. Where the plant is inside a cladded building, this height saving can be large.

Pumping Costs. Cyclone feed pumps must work against lower physical and friction heads if the plant is shorter. These lower heads result in lower pumping costs, another advantage of reduced height.

Grade Difference. As shown in Figure 6, cyclone feed grade is only slightly lower than cyclone underflow in most grinding situations. However, this grade deficit is more than compensated for since efficiencies are higher when treating cyclone feed.

In evaluating grade differences between cyclone feed and underflow, it is important to remember that the CUF/COF ratios as shown in Figure 6 will shift left when a gravity section starts operating in a given circuit. This shift will continue until a new steady state is achieved that reduces the difference between CUF and cyclone feed grades, adding further weight to the cyclone feed argument.

Efficiency. VSMA guidelines dictate that both cyclone feed and underflow should be diluted for optimum screening efficiency. As produced, screening efficiency will be higher with cyclone feed. Optimum solids concentration for BCC's is ~45% by weight. Although BCC's can process high percentage solids slurries, the natural pulp density of screened cyclone feed is closer to optimum than that of cyclone underflow. The increase in efficiency gained by treating cyclone feed more than compensates for the deficit in grade.

| CIRC. LOAD (%)	CUF/COF RATIO							
	1	2	3	4	5	10	15	20
100	100	75	67	63	60	55	53	53
150	100	80	73	70	68	64	63	62
200	100	83	78	75	73	70	69	68
250	100	86	81	79	77	74	73	73
300	100	88	83	81	80	78	77	76
350	100	89	85	83	82	80	79	79
400	100	90	87	85	84	82	81	81
450	100	91	88	86	85	84	83	83
500	100	92	89	88	87	85	84	84

CYCLONE FEED GRADE AS A PERCENTAGE OF CYCLONE UNDERFLOW GRADE

Figure 6. Cyclone Feed Grade as a Percentage of Cyclone Underflow Grade for Various Circulating Loads

Screening and G-force

World practice is converging on the use of slotted 2 mm apertures for preparation of BCC feed in gold grinding circuits rather than the coarser screens used in the past. Larger openings significantly increase BCC operating costs on account of increased wear rates while smaller apertures require significant increases in screen area and tend to blind. The reason for the modern tendency towards finer screening is twofold. Firstly, finer screening in front of a BCC has been shown to increase the unit efficiency. Secondly, the newest generation of BCC's maximize recovery by utilizing variable frequency drives to operate at g-forces of up to 200g. To operate at high g-force the maximum particle size should be minimized to reduce wear on the BCC. In most applications, the cost of screening down to 2mm will be outweighed by the increased benefit due to high g-force. If extremely coarse gold is present, screening coarser may be warranted, but BCC operating costs will be higher than for 2 mm. If substantial amounts of free gold are known to be less than 53 um (270 mesh) higher g-forces are certainly required and screening at 2 mm (or even finer in some applications) will show a very large economic benefit.

Screens should be offset from the centerline of the concentrator so as to allow overhead crane access to the BCC. Please refer to Figure 7.
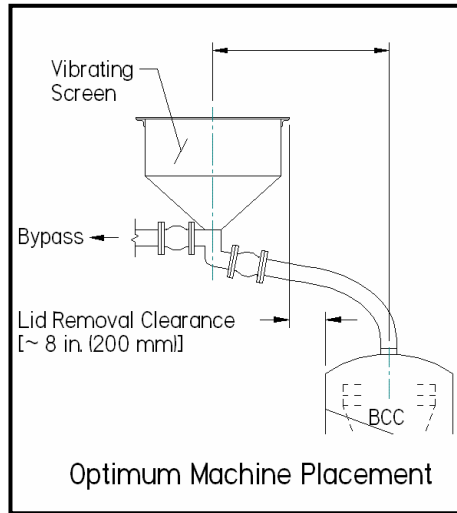
Figure 7. BCC placement relative to sizing screen.

Bypassing

BCC's require a bypass that is utilized when concentrate is periodically rinsed from the concentrating bowl. Bypass frequency is typically every ~30 minutes in a grinding circuit application. Based on 8,000 operating hours per year, feed to the BCC will bypass ~16,000 times annually. Since the BCC is not concentrating while bypassing, it is important to minimize the time spent rinsing. Off line time required for rinsing depends to some extent on the design of the bypass. Here are some guidelines:

1. Keep the bypass as close as practical to the entrance of the concentrator, certainly downstream of the sizing screen. This minimizes delays required for clearing the feed system of incoming slurry.
2. Offset valves from the centerline of the concentrator and support them independently. This reduces down time when servicing concentrator internals.
3. Make certain that the bypass is easy to access by maintenance personnel. Consider how the various wear components such as sleeves and solenoids will be replaced.
4. Avoid creation of gold traps that will force coarse gold to bypass, as opposed to going through the concentrator. Please refer to Figure 8.
5. Cause the feed to bypass the BCC in the event of a power failure.
6. Use fast-acting valves (pinch or dart) with adequately sized compressed air supply lines. Use large solenoid valves to minimize fill and exhaust times.
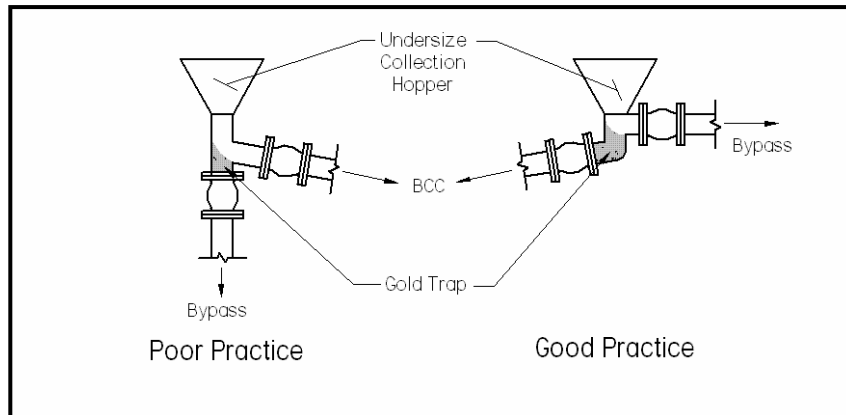
Figure 8. Preferred Bypass Details

Rinsing

The time taken to rinse concentrate out is an important consideration when designing BCC circuits since it is non-productive time. For example, if Concentrator 'A' uses a Variable Frequency Drive equipped with dynamic braking when rinsing, and Concentrator 'B' coasts to rest, the difference in rinsing time can be 2 minutes or more on each cycle. Using a delta of 2 minutes in a continuous duty application with 16,000 rinses annually translates to an advantage for the VFD-equipped machine of approximately 11 extra operating days or ~7% better concentration availability on account of reduced rinsing time alone. VFD's are recommended for minimizing rinsing time.

The quantity of water associated with each rinse needs to be considered carefully especially if the following process is intensive leaching. Provision needs to be made for receiving dilute slurry without losing fine gold. Rinse water quantity varies widely with machine size and manufacturer.

Pumping

BCC concentrate is notoriously difficult to pump on account of high S.G. solids, relatively large top size and lack of fines. Pumping BCC concentrates should be avoided wherever possible. It is preferable to use a gravity flow system. Pumping of cyclone underflows should also be avoided for the same reason.

Fluidization Water Quality

Fluidization water injection hole maintenance can be a significant source of downtime and maintenance labor in BCC circuits. These holes require periodic cleaning. The frequency of this operation is dependent on the design of the holes (Each manufacturer has it own approach.) and also the quality of the fluidizing water. 'High' quality fluidizing water has few, if any, suspended solids and little dissolved solids. It is difficult to provide a water quality specification since the equipment will operate for albeit short intervals when suspended solids are present. Bearing in mind that BCC's can operate outside the following limits, here are some quantitative guidelines for what constitutes 'good' fluidization water.

Total Suspended Solids (TSS) : <1,000 mg/l
Total Dissolved Solids (TDS) : <1,000mg/l
P100:   ~ 20 Microns

Anti-scalants and Dispersants are available for higher concentrations. Chemical composition and dosage are highly dependent on variables such as pH and temperature gradient. Reagent vendors should be consulted for these situations."

Summary

Recovering gold from grinding circuits using batch centrifugal gravity concentrators is now a well-established, powerful tool in the mineral processing engineer's toolbox. The general approach used to model and predict gravity gold recovery using BCC's from within the grinding circuit was presented. The approach utilizes results from a laboratory test for measuring the gravity-recoverable-gold content of an ore combined with the characteristic behaviour of gold with grinding circuits. While the modeling results may show that gold can be recovered from within grinding circuits, the economic case may require a full understanding of the influence of gravity gold on the overall gold recovery when downstream processes are considered. An increase in overall gold recovery may not be the only important factor as net impacts on smelter returns also need to be considered. The various factors influencing the economic justification for gravity gold recovery were discussed as well as the many practical considerations necessary for a successful installation.

REFERENCES

Banisi, S., Laplante, A.R. and Marois, J., 1991, The behaviour of gold in Hemlo Mines Ltd. Grinding Circuit, CIM Bulletin, 84(955), 72-78

Laplante, A.R., Woodcock, F. and Noaparast, M., 1995, Predicting gravity separation gold recoveries, Minerals and Metallurgical Processing, 74-79

Laplante, A.R. ., 2000, Testing requirements and insight for gravity gold circuit design, Randol Gold and Silver Forum, Vancouver

Laplante, A.R., 2005, Gravity Gold Recovery - Introductory presentation, AJ Parker Cooperative Research Centre for Hydrometallurgy Gravity Gold Workshop, Perth, Western Australia.