PAPER 31

Advances in Centrifugal Gravity Concentration – Beyond Low Mass Yield

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Key Words: Centrifugal Gravity Concentration

41st Annual Meeting of the
Canadian Mineral Processors

January 20 to 22, 2009
Ottawa, Ontario, Canada

ABSTRACT

Batch centrifugal gravity concentrators, which produce very high ratios of concentration, have become common place for recovering free gold within milling circuits. Their effectiveness has proven to be especially useful in recovering finer gold particles. The knowledge related to testing, modeling and scale-up of these systems has been well established over the recent decade mostly due to the efforts of the late Dr. Andre Laplante.

Gravity separation technologies such as jigs, spirals and shaking tables can provide the increased mass yields required for minerals that occur at higher concentrations than gold, however their effectiveness tends to diminish at finer particle sizes. The development of high mass yield centrifugal concentrators has provided the opportunity to be able to recover a wide range of minerals at finer particle size classes when compared to the more traditional gravity concentration devices. These concentrators also provide additional benefits such as smaller unit footprint and automated operation.

This paper discusses the background, current practices and future applications for high mass yield centrifugal concentrators in base metals, sulfides and industrial minerals. Bench scale, pilot scale and plant practice examples are also presented.

INTRODUCTION

Gravity concentration, one of the oldest mineral beneficiation processes, has evolved over the decades and continues to play an important role in modern mineral processing operations. The development and growth of froth flotation in the early part of the twentieth century led to a decline in the importance of gravity concentration. However, gravity concentration continued to be used for ores that are difficult to beneficiate using froth flotation; such as tin, tungsten, niobium/tantalum, iron, industrial minerals and oxidized coal. In recent decades, many operations have begun to employ a combination of both gravity concentration and froth flotation Since flotation relies on surface chemistry and gravity concentration relies on specific gravity differences, putting these techniques in series provides today's metallurgist with unprecedented opportunities to maximize grade and recovery of many of these minerals.

Gravity concentration has been the cornerstone for the recovery of gold for thousands of years but it also yielded to technological advances in areas such as flotation and cyanidation especially as the practice of mining complex gold ores grew. The advent of enhanced gravity technologies such as the Falcon, Kelsey, Knelson and MGS concentrators saw the resurgence of recovering some of the gold, silver and PGM species and minerals by gravity from plants that employ cyanide leaching and/or flotation.

Gravity concentration, where applicable and effective, has the lowest installed and operating costs when compared with other beneficiation technologies. It also tends to have the lowest environmental impact as gravity concentration does not require the use of chemicals and reagents. Hence, with the recent increases in energy, capital and operating costs as well as environmental concerns, many processors are re-evaluating the use of gravity concentration.

Finally, gravity concentration provides the versatility for treating a wide particle size range. Using pre-concentration as an example, devices such as jigs and spirals can be used for coarser particle size classes while proven enhanced gravity concentrators can be used for scavenging fine particles. Modern centrifugal concentrators are routinely effective down to 20 microns. Good performance to below 10 Microns has been demonstrated in some cases.

Centrifugal Concentrators and Gold Recovery

Most of the recent advances and increased use of gravity concentration has come with the development of centrifugal concentrators. Two units developed in Canada, the Falcon and the Knelson, have become popular for use within many grinding circuits where the presence of a reasonable amount of gravity recoverable gold has been identified in the ore. The units operate on a semi-continuous process requiring the units to be taken offline, usually on the order of every 20-60 minutes, to flush the concentrate.

The application and effective operation of centrifugal concentration units for gold recovery relies on some key factors of gold's behaviour within grinding circuits. The most important factor is that properly operating hydrocyclones retain almost all of the gravity recoverable gold (GRG) within the grinding circuit where a fraction of the circulating load can be bled out and treated with a gravity circuit (Banisi, Laplante and Marois, 1991). Gravity gold production is dependent on a dynamic interaction between the characteristics of the gravity recoverable gold (amount and size distribution), circulating load within the grinding circuit, the fraction treated by the gravity unit and the unit recovery of the gravity concentration device. The interaction of these variables has been extensively studied and reported (Laplante, Woodcock and Noaparast, 1995; Laplante and Xiao, 2001) to the point that it is now possible to model and predict gold recovery from within grinding circuits.

Figure 1 shows gold recovery from within a grinding circuit as a function of the fraction of cyclone underflow treated by gravity (based on a mathematical model) on material that is highly amenable to gravity concentration. The graph provides some interesting insight on the effective use of gravity concentration for gold recovery.
Key points to note from Figure 1 are:

- Gold recovery rises very rapidly (steep slope) up to treating about 10% of the cyclone underflow
- A transition stage occurs between ~10-25% where is there is a diminishing rate of recovery
- A plateau zone where each incremental fraction treated provides little additional increase in gravity recovery (i.e. slope is less than unity).

While the curve presented is based on a single set of parameters, performance from within grinding circuits (whether the feed is taken from cyclone underflow or feed) follows a curve of this general shape. A particular curve can be developed for any given ore, GRG content, gravity concentration effort and operating conditions of the gravity circuit located within the grinding circuit. Extensive modeling analyses reveal that it is rarely beneficial to treat much more than one third of the cyclone underflow or cyclone feed using gravity. An exception is where the *only* concentration technique is gravity.

Since hydrocyclones are efficient at retaining GRG within the grinding circuit, they act as rougher recovery units for subsequent upgrading in fluidized batch centrifugal concentrators. In fact, modeling of gold recovery from grinding circuits clearly indicates that the efficiency of the cyclone is the most important factor in the overall performance of the gravity circuit. Combining roughing with cleaning is well understood and applied in many mineral beneficiation circuits.

One final note about centrifugal concentrators for gold recovery is that they provide very low concentrate mass yields, often less than 0.05%, and consequently very large mass concentration ratios, exceeding 5000:1, for the largest units. Hence, these units are ideally suited for gold as it occurs at less than 20 g/t in most ore bodies.

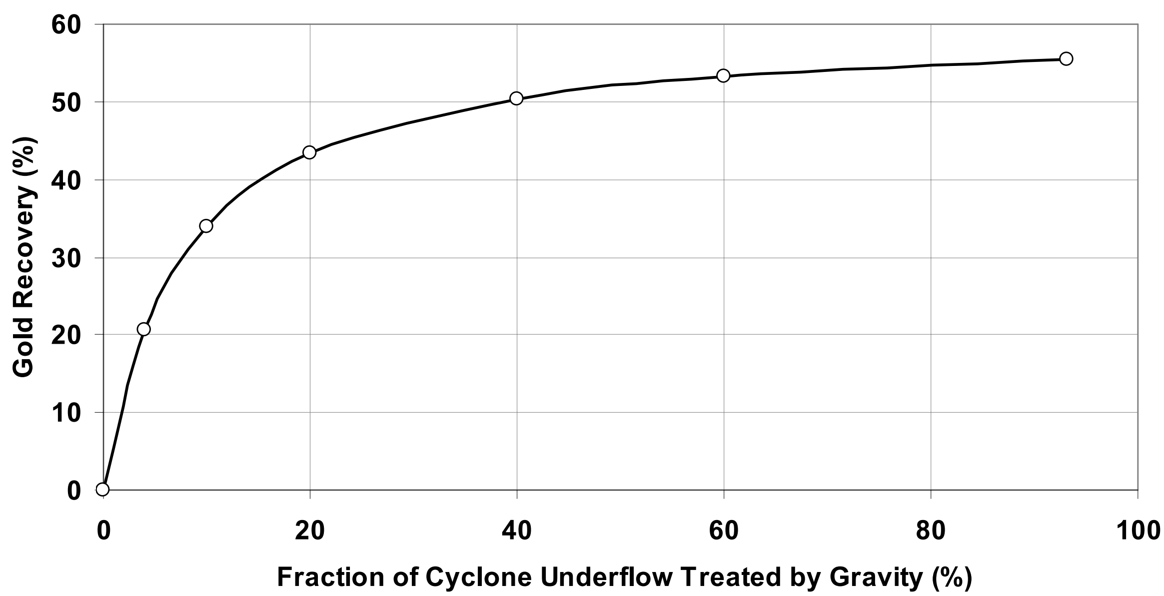

Figure 1: Gold recovery response for recovering gold from cyclone underflow (model parameter used were a ore GRG content of 60% and a grinding circuit circulating load of 250%).

As impressive as the historical results have been using conventional batch fluidized centrifugal concentrators, these concentrators are limited to <<1% mass yields in practice. It is now time to push the envelope by using modern high mass yield centrifugal concentrators for mineral systems and applications that have previously been out of reach using fluidized batch units.

Centrifugal Concentrators at Higher Mass Yields

Due to the high concentration ratios (and low mass yields) of batch-type or semi-continuous centrifugal concentrators, they are not suited for recovering or upgrading minerals that occur at levels exceeding a few hundred ppm. For example, a mineral which occurs at a grade of 1% would need a mass recovery of the same amount theoretically although in practice; the required mass recovery, at least in the rougher and scavenger stages, is considerably higher as few minerals are perfectly liberated. In addition, sharpness of separation is always obtained at the expense of recovery. Good mineral process engineering practice involves high recovery in a roughing stage in combination with cleaning for grade in a subsequent stage. Batch-type machines do not lend themselves to these applications in most cases.

Manufacturers of centrifugal concentrators have recognized the limitations of fluidized bed type batch technology. This recognition has led to development of centrifugal units capable of concentrate mass yields exceeding 40%. The leading centrifugal concentrators in this area are the Falcon C, Falcon UF (Ultra Fine), the Knelson CVD, the Kelsey Jig and the MGS. Strictly speaking, the Falcon UF is not a continuous unit, however it does operate in a manner which generates high mass yields and is capable of upgrading minerals that occur at concentrations exceeding 0.1%. The UF will be discussed in more detail in latter sections with examples and results from lab and pilot test work as well as plant practice.

Unlike batch fluidized bed units, high mass-yield units have not been subject to extensive research and modeling. Often, these technologies find niche applications only after some pilot or full scale plant trials as scale up information from laboratory data is scarce. Recently, new lab and pilot scale work is providing data showing that the potential of these units may be significantly higher than previously recognized. This potential is greatest for separation of minerals at finer particle size ranges where unit gravity devices, such as spirals, lose effectiveness. The higher g-forces (ranging as high as 600 g's) used in recent pilot and plant tests has further contributed to recognizing the potential of centrifugal gravity concentration in new applications.

Current research and testing is directed at improving our grasp on the potential of these technologies. Data from test programs at lab and pilot scale is presented in the following sections as evidence of this potential. The ultimate objective is to develop the same level of understanding of separation fundamentals as has been achieved and successfully applied to fluidized bed batch-type technology.

High Mass Yield Application – Example of Successful Implementation

The work at Tantalum Mining Corporation of Canada (TANCO) is one of the best examples where the use of centrifugal units for recovery in high mass yield applications has been applied successfully for recovery of fine tantalum minerals. The use of the Falcon "C" in the recovery of tantalum in the -100 um fraction was reported to be in the range of 70-80% with mass recoveries of approximately 26% (Deveau, 2000). The program consisted of approximately 75 tests. The overall conclusion from this work was that 60% of the fine-grained tantalum that was previously being lost by spirals is now being recovered with the installation of the Falcon "C" machines.

Further work was conducted on tantalite flotation concentrate using the Falcon's UF (Ultra Fine) technology. In this stream, 80% of the tantalum is finer than 20 um (Deveau, 2006). Tests with mass yields exceeding 30% provided tantalum recoveries in the range of 80-90% with units operating up to 600g's. A Model UF600 Falcon was permanently installed to upgrade Tanco's flotation concentrates in April 2005. Site personnel report high mechanical availability and low operating costs.

HIGH MASS YIELD LAB TEST WORK

Silver Ores

One area identified in a number of recent test campaigns has been the response of silver bearing ores to gravity concentration. While the specific gravity of silver is relatively high, it rarely occurs in its native form. More commonly, it is present as a mineral (often as sulfides). For example, acanthite and proustite, with specific gravities of 7.2 and 5.6 respectively, should be recoverable by gravity concentration methods. Since these minerals are present at higher concentrations (than typical gold ores) and that they may be locked with other sulfides, fluidized bed batch-type machines cannot produce the mass yields required for high recoveries.

A number of recent tests on silver ores from South America and Africa have indicated that some silver minerals become gravity recoverable' by increasing the mass yields beyond those attainable with production-scale batch units. (Laboratory batch units can produce these high mass yields. This can lead to confusion when selecting enhanced gravity technologies.)

Figure 2 and Figure 4 show the response of two samples, a ball mill discharge and flotation feed, from an existing silver operation. The silver distribution, plotted by particles size class, is also are presented in Figures 3 and 5 respectively for the 2 samples.

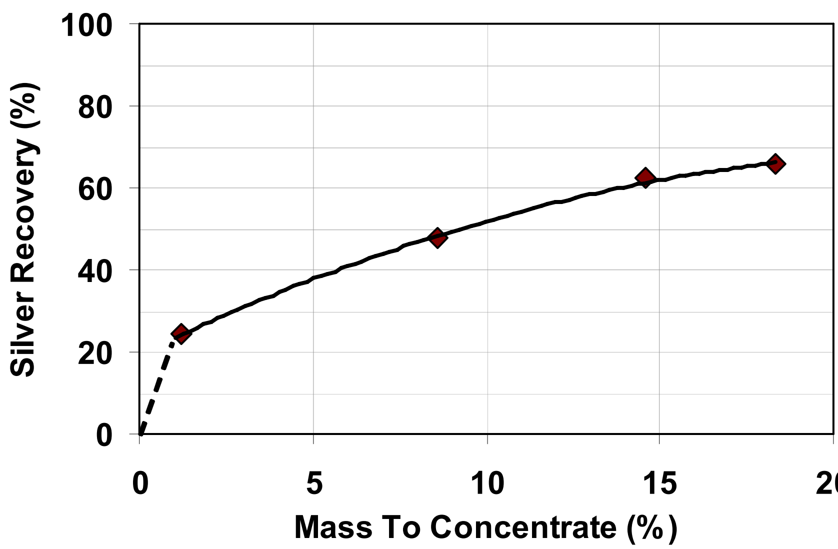

Figure 2: Centrifugal silver recovery response using a lab scale Falcon on a Ball Mill Discharge sample - silver head grade of 750 g/t and a particle size P80 of 417 um.

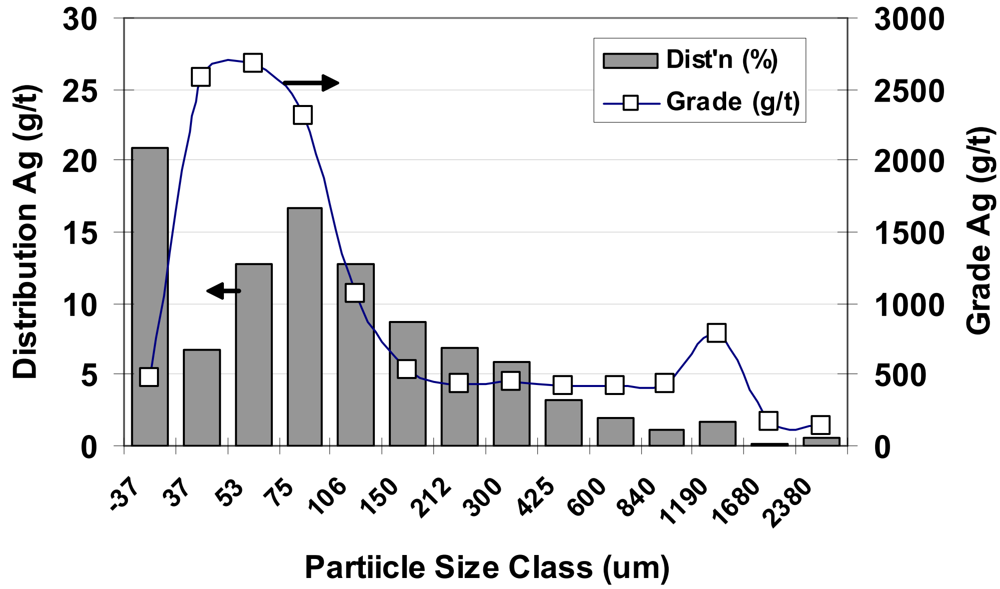

Figure 3: Silver distribution by particle size class for the ball mill discharge sample.

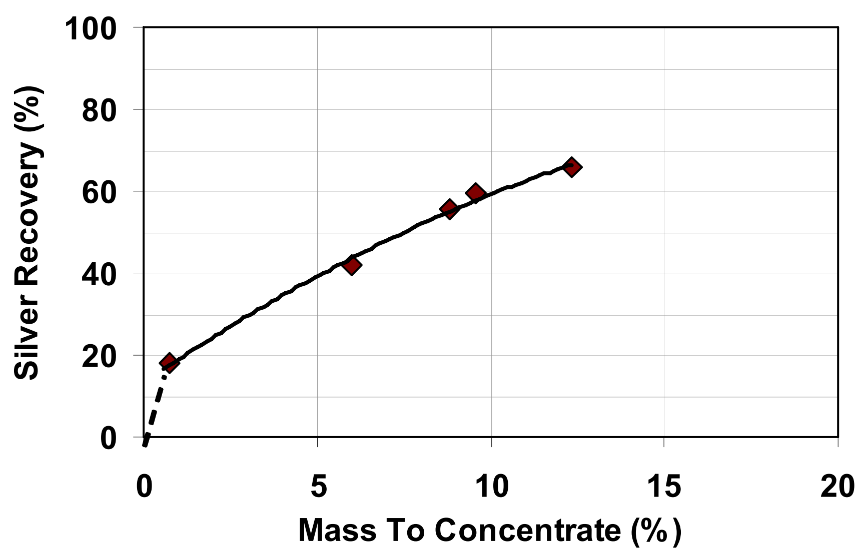

Figure 4: Centrifugal silver recovery response using a lab scale Falcon on a flotation feed sample - silver head grade was 413 g/t at a particle size P80 of 66 um.

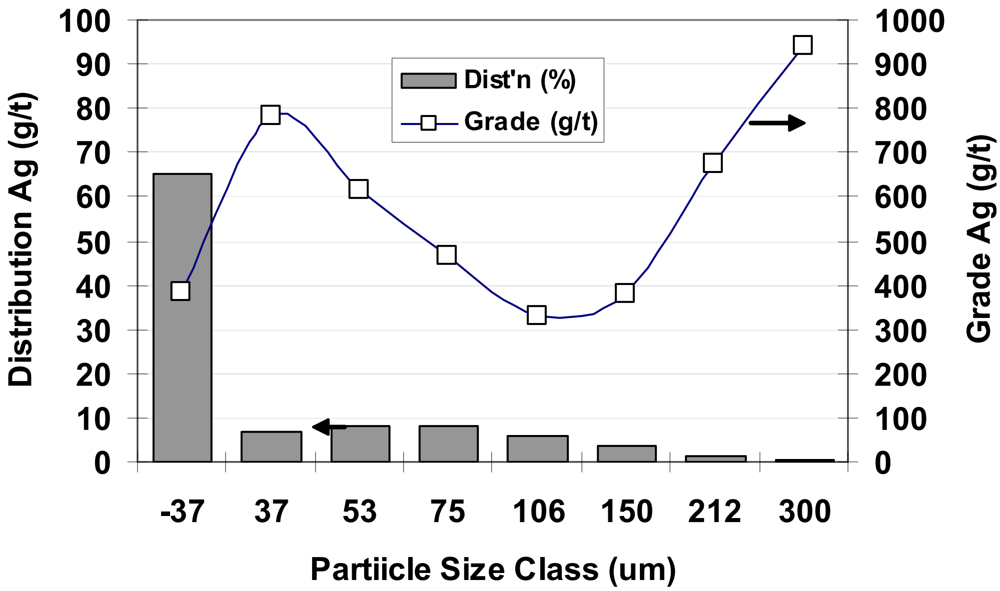

Figure 5: Silver distribution by particle size class for the flotation feed sample.

Silver recovery of 66% at a mass yield of 18% was achieved on the ball mill discharge sample. Since gravity concentrators operate most efficiently on narrow size fractions and the mill discharge contained a wide particle size distribution, these results are especially encouraging. The grade and distribution of the silver is significantly higher in the fine fractions within a coarse feed sample (i.e., feed P_{80} is 417 um).

Silver recovery from the flotation feed was the same at 66%, with a much lower mass yield, 12.4% as shown in Figure 4. It is interesting to note that the grade of the flotation feed is lower than the mill discharge as there is currently a conventional gravity device, a jig, operating within the circuit. Despite this, it is clear that there is still considerable gravity recoverable silver available in the flotation feed. The steepness of the slope at the 12.4% mass yield point suggests that additional silver recovery is possible with increased mass recovery.

This site is currently in the process of installing centrifugal units as a result of this study. Further test work will aim to correlate plant scale recovery with lab scale results.

Two silver mineral samples obtained from an exploration project in South America, were tested using a similar approach to that shown above for the African samples. The results, presented in Figure 6, again show that a significant fraction of the silver, from both the sulfide and oxide zones, is amenable to gravity concentration using a high mass yield centrifugal concentrator.

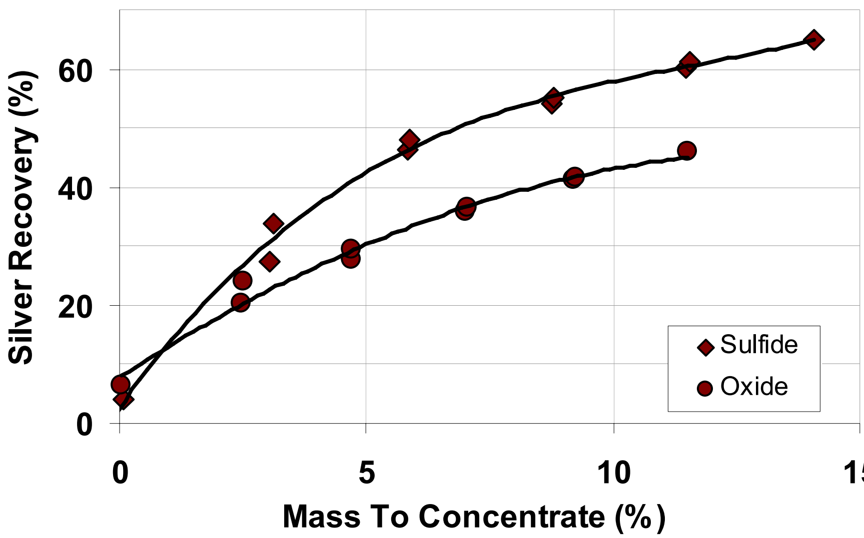

Figure 6: Centrifugal silver recovery response using a lab scale Falcon - silver head grades were 312 and 271 g/t for the oxide and sulfide samples respectively. The grind sizes were 84 and 73 um (P80) respectively.

Based on the results above, it appears that silver ores are amenable to gravity concentration. Like gold, the use of gravity may play an inportant part of the recovery process where the gravity is an intermediate process between the grinding circuit and downstream flotation and/or cyanidation. The economic benefit may not just be by the way of improved overall plant recoveries but also reduced reagent usage. This is certainly true in cyanide leach circuits as the residence time and cyanide consumption significantly higher for silver ores when compared to gold ores. An opportunity to concentrate part of the silver prior to leaching, possibly via regrinding the gravity concentrate, may provide improved kinetics.

Tungsten (Scheelite) Recovery from Tailings

A sample of scheelite tailings, with a particles size distribution D_{50} of 73 um, was tested using a lab scale Falcon Concentrator at a rotational speed to generate 300 times normal gravity (i.e. 300 g's) as per the flow sheet in Figure 7. The feed grade of the sample was 0.36% WO_3. The results are presented in Table 1 as well graphically in Figure 8.

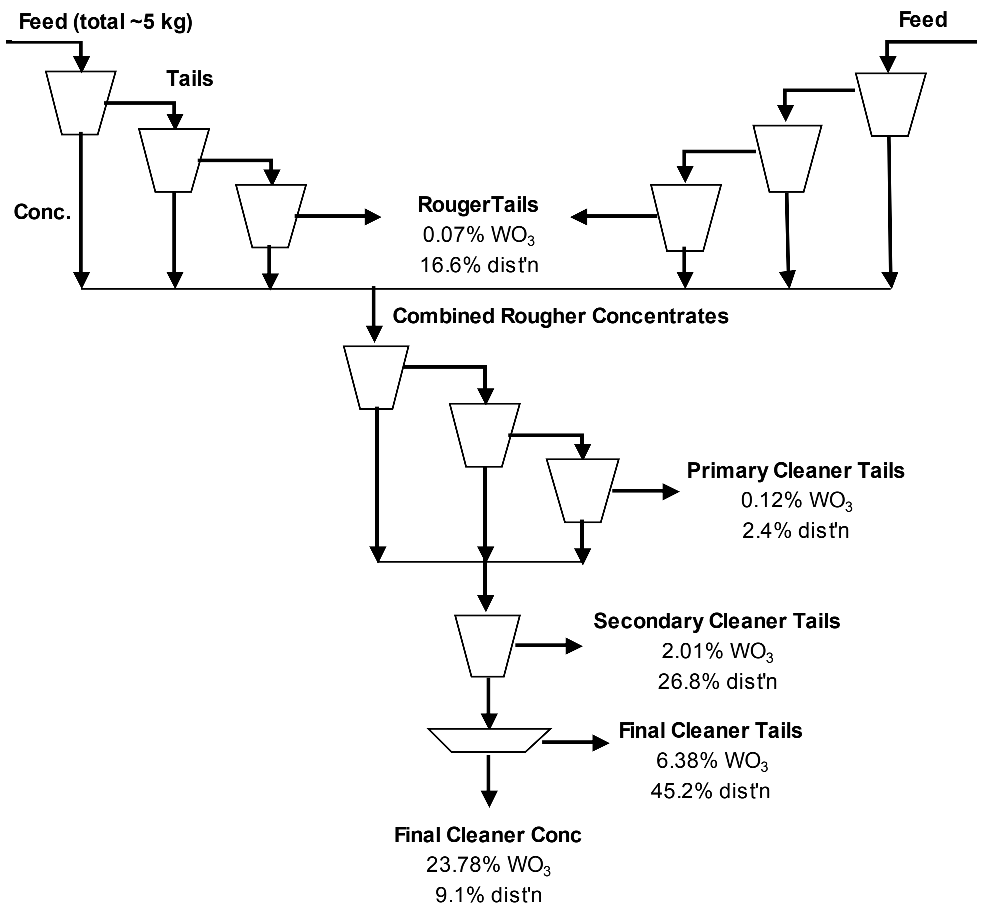

Figure 7: Test flow sheet for tungsten tailings samples using a lab scale Falcon operating at 300 g. Feed sample was split into 2 samples of ~2.5 kg each and processed as shown.

The results show that it was possible to upgrade the scheelite concentration by a factor of 20 in to the secondary cleaner concentrate with a recovery value of 54%. Further upgrading was evaluated by panning the secondary cleaner concentrate to a final grade of 23.8% WO3 representing a 66x upgrade. However, the recovery after this final upgrade was only 9.1%.

It must be noted that the test flow sheet represents a open circuit test and the grade-recovery response is expected to be significantly higher if the intermediate cleaner tailings products are recycled back upstream. Further test work using a locked cycle approach is recommended to determine the response of recycling intermediate streams.

Table 1: Results from tungsten recovery test as shown in Figure 7.

Products	Weight (%)	WO3 Grade (%)	WO3 Dist. (%)
Final Cleaner Conc.	0.14	23.78	9.1
Final Cleaner Tails	2.56	6.38	45.2
Secondary Cleaner Conc.	**2.70**	**7.27**	**54.3**
Secondary Cleaner Tails	4.82	2.01	26.8
Primary Cleaner Conc.	**7.51**	**3.90**	**81.1**
Primary Cleaner Tails	7.09	0.12	2.4
Rougher Conc.	**14.60**	**2.06**	**83.4**
Rougher Tails	85.40	0.07	16.6
Total	**100.0**	**0.36**	**100.0**

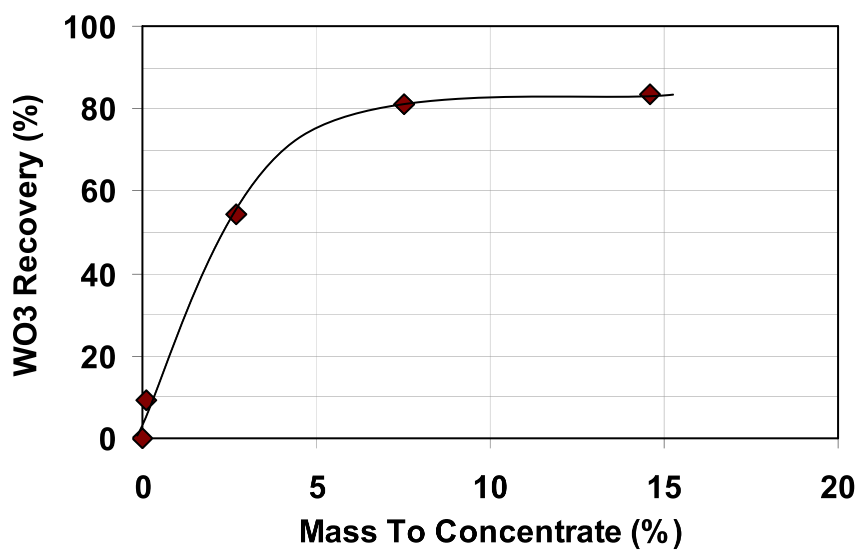

Figure 8: Centrifugal gravity recovery response using a lab scale Falcon, operating at 300g, on a scheelite tailings sample – WO3 head grade was 0.36% at a particle size D_{80} of 73 um.

Fine Cassiterite Tailings

A sample of fine tin bearing tailings, grading 6% tin, was tested using a lab scale Falcon UF concentrator. The objective of the test work was to achieve a target grade of 30%.

The particle size distribution and assay, provided in Table 2, shows that 76% of the mass and 86% of the tin occurs in the -37 micron particle size class. In order to maximize recovery and the product tin grade, coarse and/or dense particles that potentially interfere with gravity separation were removed by screening at 75 microns and froth flotation (to remove sulfides) prior to the gravity concentration stage.

Table 2: Particle Size Distribution of Tin Tailings

Particle Size (um)	Mass Dist. (%)	Tin Grade (%)	Tin Dist'n (%)	Sulfur Grade (%)	Sulfur Dist'n (%)
425	1.9	4.3	1.4	3.9	2.1
300	3.1	5.1	2.7	4.3	3.8
212	2.1	4.4	1.6	3.5	2.1
150	1.9	4.0	1.3	3.5	1.9
75	3.1	3.2	1.7	3.5	3.1
53	3.3	2.3	1.3	2.7	2.5
37	8.5	2.7	3.8	2.4	5.9
-37	76.1	6.8	86.4	3.6	78.5
		6.0		3.5	

The test procedure and results are presented in Figure 9. The overall recovery of tin in the primary cleaner concentrate was 59% at a concentrate grade of 27.3%. The UF cleaner concentrate was panned to examine its potential upgradeability. The panned concentrate assayed at 30.7% Sn however at a significant cost to recovery. Ideally, this re-cleaning stage would be conducted using a UF unit also due to the fine particle size of this material.

The cleaner scavenger tails contained only 5.4% of the tin at a grade of 2.1%. While the cleaner scavenger concentrates are considerably lower grade than the target grade of 30% tin, it is likely that the cleaner scavenger concentrate would likely be recycled back to cleaner feed circuit to maximize grade and recovery. Like the scheelite test work presented earlier, further testing using a locked cycle approach is recommended to determine the response of recycling intermediate streams.

The final tails (rougher gravity tails) contained only 14% of the tin at a grade of 1.8%.

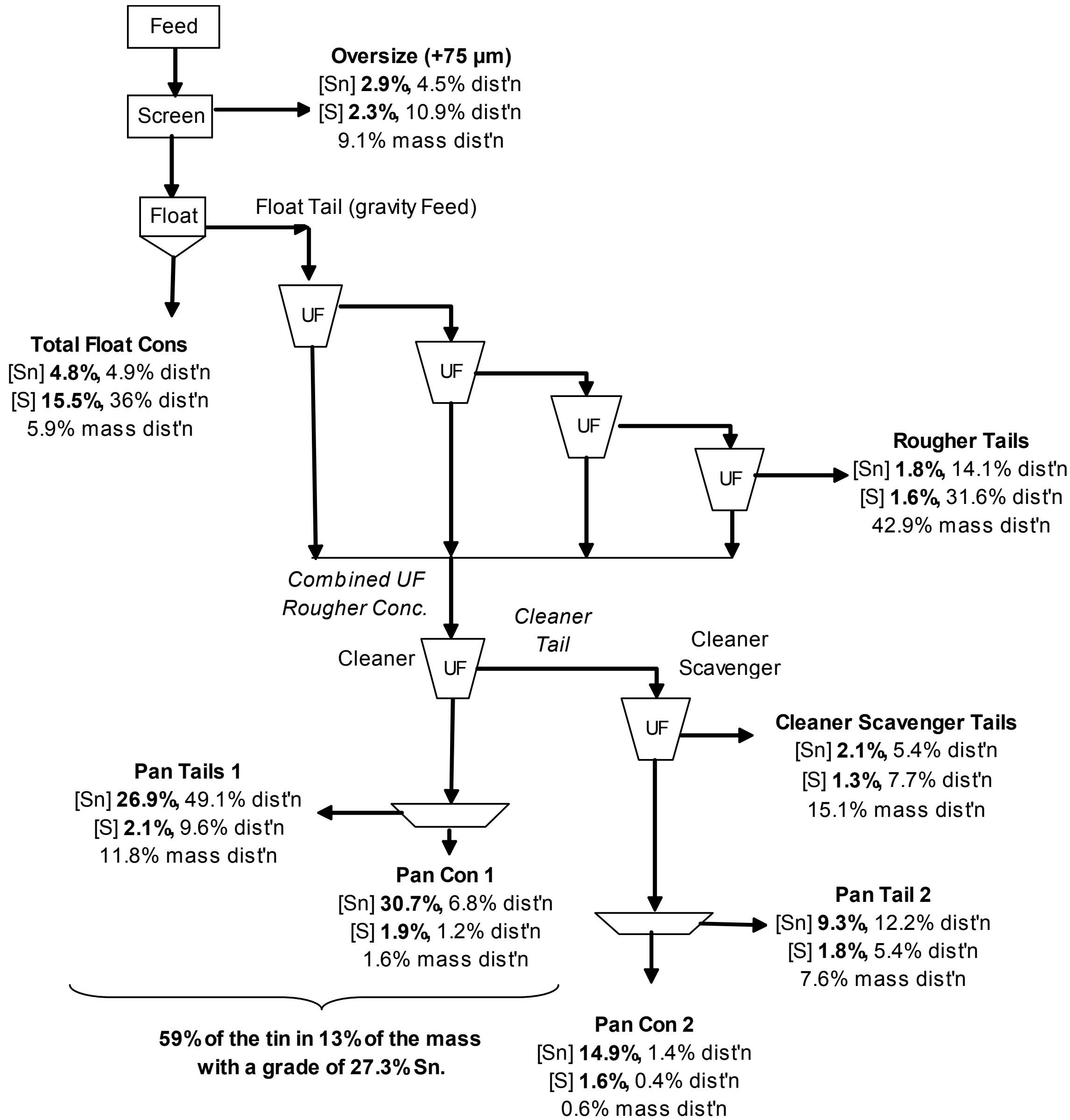

Figure 9: Process flow sheet and metallurgical results for Falcon UF test work on fine cassiterite tailings.

PILOT SCALE TEST WORK

Cassiterite Tailings

A short pilot test program was conducted on fine cassiterite tailings (nominally finer than 50 um) using a Falcon UF1500 unit operating at rotational speed corresponding to 600 g's. Two pilot tests, at feed rates of 33 and 39.7 kg/min, were conducted under conditions required to generate very high mass yields. The results from the roughing stages are presented in Table 3 below. The tailings Sn grade averaged 2.18% relative to an average feed grade of 9.4%. The concentrate grade averaged 13% at 92.3% tin recovery.

Table 3: Pilot test results using a Falcon UF on Cassiterite Tailings at 600 g's

Feed Rate (kg/min)	Assayed Feed Sn (%)	Tail Grade Sn(%)	Con. Mass (kg)	Tail Mass (kg)	Con. Grade Sn(%)	Mass Yield (%)	Sn Rec. (%)
33.0	9.52	2.05	48.2	19.9	12.6	70.8	93.7
39.7	9.34	2.30	48.0	27.7	13.4	63.4	91.0

Based on successful performance of a Model UF600 machine and the pilot work cited above, 3 x UF1500 machines that are scheduled go into service treating tin flotation concentrate in Q4 2008. Further on-site test work and operating surveys will provide comparative data between the pilot and full scale results.

Fine Iron Ore Tailings

Pilot studies on fine (final) iron ore tailings generated from a spiral circuit are currently underway at an iron ore operation using Falcon Continuous units. Current pilot work, which was scheduled based on the success of the initial work using the pilot scale C400 (rated to 4.5 t/h), is focused on integrating a Falcon C1000 (rated up to 27 t/h) with spirals in open and closed circuit configurations. A summary of the overall results from the current Falcon-spiral work were not available as of writing of this paper hence the results from the first phase of the pilot program, which employed only a Falcon C400 in open circuit, are presented herein.

Although the feed particle size to the pilot plant varied during operation, the typical feed particle size distribution was 200 um (P80) whereas the corresponding iron distribution was slightly finer at a P80 of ~140 microns.

The feed grade of the iron averaged 10.7% for these tests indicating it was possible to upgrade the iron under various operating and mass yield conditions. The mass-recovery and grade-recovery responses are presented in Figures 10 and 11. Current testing is aimed at closed circuit testing to improve product grade.

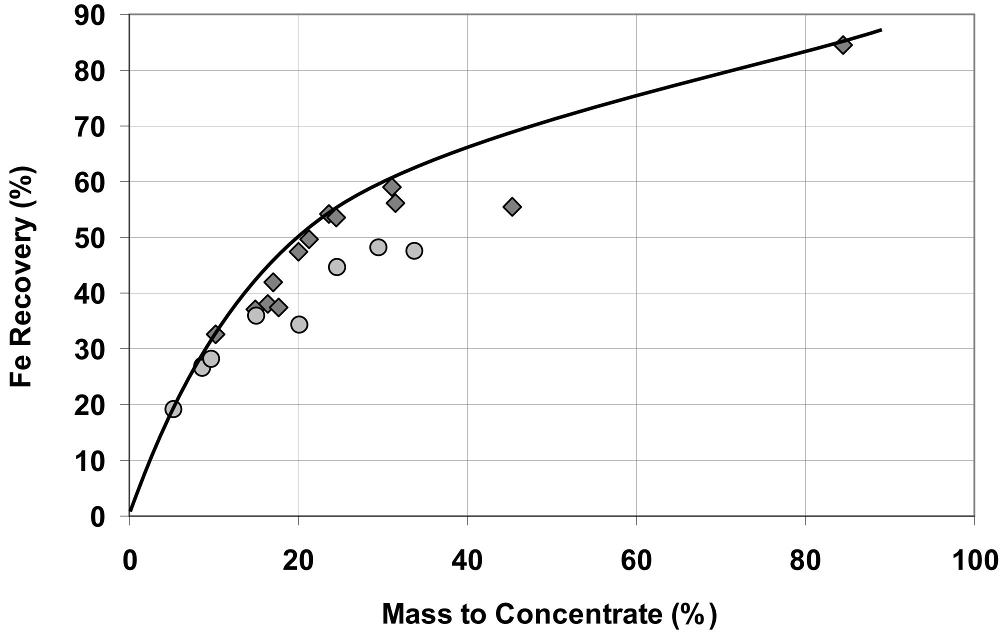

Figure 10: Iron recovery with a pilot Falcon C400 continuous centrifugal concentrator operating in open circuit. The various points represent different operating conditions and tonnages. The diamonds and circles represent results from feed rates of 2.6-3.3 t/h and 5.8-6.1 t/h respectively.

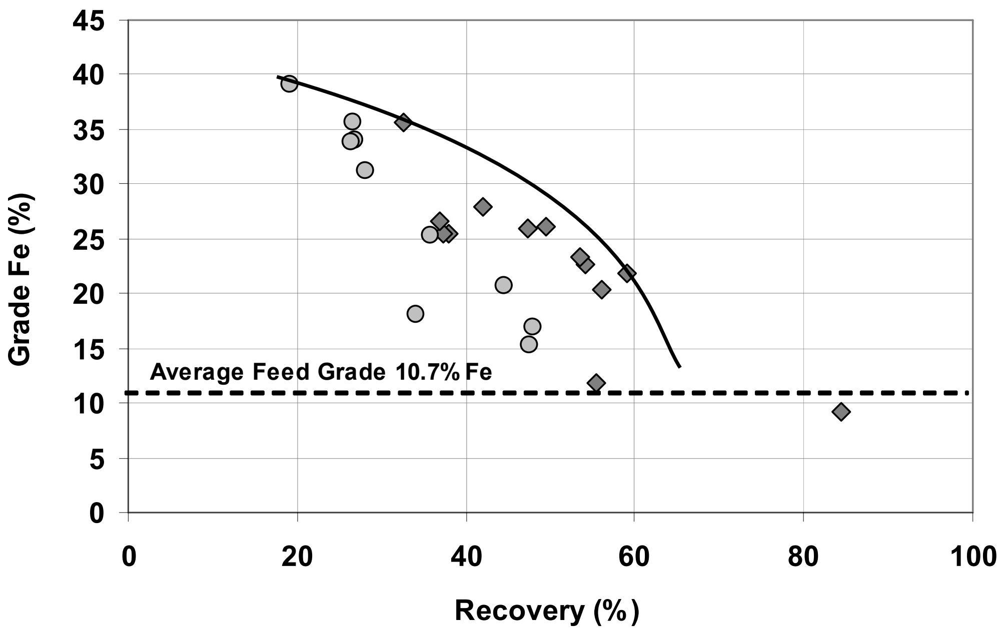

Figure 11: Iron grade-recovery response with a pilot Falcon C400 continuous centrifugal concentrator operating in open circuit. The various points represent different operating conditions and tonnages. The diamonds and circles represent results from feed rates of 2.6-3.3 t/h and 5.8-6.1 t/h respectively.

SUMMARY

The use of fluidized batch concentrators which produce very high ratios of concentration, have become common place for recovering free gold within milling circuits. These units capitalize on the ability of hydrocyclones to act as rougher units and retain gravity recoverable gold (GRG) within the grinding circuit. This allows the low mass yield batch centrifugal gravity units to achieve both high concentration ratios and high recoveries. Considerable research and understanding of gold's behaviour within grinding circuits and recovery using fluidized batch centrifugal concentrators has advanced the knowledge required to predict and scale-up from laboratory results.

The industry needs similar understanding and advancement of high mass yield centrifugal concentrators since they:

- have the lowest capital and operating cost of any mineral beneficiation method,
- are environmentally friendly and do not require addition of any chemicals and reagents making it easier to obtain permits,
- significantly widen the particle size range amenable to gravity concentration

Research is also required to understand the interaction of various gravity concentration technologies especially when flow sheets are configured with roughing, scavenging and cleaning stages as is done in froth flotation.

This paper presented results from various lab and pilot scale studies to demonstrate the potential that modern high mass yield centrifugal concentrators provide in recovering and concentrating a variety of minerals based on specific gravity differences. Lab, pilot and plant test results presented herein have demonstrated that these units are now able to make effective separations on fine particles, down to well below 40 microns, when compared to traditional unit gravity devices such as jigs and spirals.

In the next few months, a number of new installations utilizing various high mass yield units are expected to be in long term pilot scale test programs as well as in full plant scale operation. These operations will provide an opportunity to conduct further research and analysis of these systems for eventual presentation to the industry in future publications.

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