ENHANCED GRAVITY RECOVERY OF BASE METAL AND INDUSTRIAL MINERALS

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ABSTRACT

Mineral separation by exploiting the differences in mineral or metal specific gravities (sg) has been used since antiquity. In the modern era, this is most commonly seen in the recovery of gold by the use of centrifugal concentrators and the separation of coal (low sg) from waste rock (high sg) using heavy media cyclones and jigs. Other metals, notably oxides of tin and tungsten, are successfully recovered using some combination of jigs, spirals and shaking tables. However, many conventional gravity separation systems are limited to fairly coarse (>1 mm) to medium (>100 micron) particle separations due to the limitations of the gravitational separation forces in conventional equipment.

Many of the high specific gravity minerals of interest are friable (e.g. cassiterite, wolframite, etc.) and excessive fines are generated in the grinding/comminution circuits which cannot be recovered with conventional equipment and may be lost directly to the tailings stream. Recent developments in centrifugal gravity separation equipment specifically designed for fine or ultra-fine particle separation and recovery have resulted in heavy mineral particle recoveries as fine as 10-20 microns. Ongoing research work has also identified the benefit of closed-circuit, multi-stage gravity recovery circuits using some combination of centrifugal concentrators and conventional equipment (tables, spirals, flotation, etc.) which can substantially increase overall plant recovery and final concentrate grade.

This paper will provide details of the evolution of non-fluidized bed gravity concentrators for high sg mineral recoveries, correlate laboratory scale development work with plant results to confirm scale-up, and show how recent flowsheet developments have contributed to significantly improved plant performance.

KEYWORDS

Centrifugal gravity concentration, Locked-cycle, Tin
INTRODUCTION

Gravity concentration is one of the oldest and most cost effective metal and/or mineral recovery systems, ranging from the classic hand panning of alluvial gold, through to the large scale production of a wide range of metals and minerals, including gold, silver, PGMs, black sands, coal and iron oxides. Conventional gravity recovery systems, comprised of some combination of sluices, spirals, jigs and shaking tables have limited application in fine particle (i.e. <100 microns) recovery, or where there are limited differences in particle specific gravities (sg), e.g. the separation of high sg, high value metal oxides (e.g. those of tin, tantalum or tungsten), from medium sg, lower value metal sulfides such as pyrite and pyrrhotite. These unit operations tend to have limited capacity, and while double and triple turn spirals and multi-deck tables have been developed, extensive floor space is often required in order to process the tonnages incorporated in the modern mineral processing plant.

Starting in the late 1970s, the development of high capacity, high G-force gravity separators (e.g. Falcon, Kelsey, Knelson & Mozley), stimulated a renewed interest in gravity recovery, particularly for the recovery of gold in base metals (copper, lead, zinc) flotation plants or gold & silver in cyanide leach plants. It was quickly recognized that the recovery of free milling gold, and to a lesser extent silver, in the primary grinding circuit resulted in measurable increases in overall plant gold recovery, primarily due to the avoidance of over-grinding of the gold & silver due to the high particle sg and the resultant preferential reporting to the cyclone underflow. Today, large diameter, centrifugal gravity concentrators can process feed rates up to 400 tons/hour per unit, and recover free gold particles as fine as 10 microns. Standard laboratory tests have been developed (Laplante, 1993) to determine the level of Gravity Recoverable Gold (GRG) in any given ore sample, and rarely does a new gold or base metals project go through metallurgical development without some consideration of GRG levels and the potential benefits of installing centrifugal concentrators in or around the grinding circuit.

The standard centrifugal concentrator (Falcon, Knelson) in a gold recovery operation functions by building an inventory of the gold concentrate in a series of riffles within a high rpm rotating cone while the machine is in the “load” mode. Pressurized fluidization water is introduced through a series of holes into the recessed riffles in the rotating cone in order to upgrade the retained concentrate and minimize the misplacement of non-gold particles in the riffles. After a pre-determined interval, normally in the range of 30-60 minutes, the concentrator feed is shut-off, the rotational speed of the cone reduced significantly, and the retained concentrate inventory in the cone is discharged from the slowly rotating cone. Once cleaned with rinse water, the rotational speed of the cone is increased back to normal operating levels, the feed to the machine is re-started, and the cycle repeated. The net result is that a small inventory (5-75 kg depending on the size and configuration of the machine) of high grade (tens, hundreds or thousands of ppm or gpt (grams/metric ton)) gold concentrate is discharged. While this may represent a significant fraction of the gold processed, i.e. 25-60% gold recovery, the mass is a very small fraction (0.01% - 0.10%) of the total mass of feed processed through the machine during the load cycle. Other key factors that impact the application and effective operation of centrifugal concentration units for gold recovery within grinding circuits have been previously discussed (Grewal, 2009). In summary, these semi-batch machines are excellent in gold recovery applications that benefit from low mass yields and high ratios of concentration.

The importance of the use of fluidization water in centrifugal gravity concentrators cannot be under-stated. In recognition of this requirement for fluidization water, these type of gravity concentrators are often referred to as fluidized bed centrifugal concentrators. Similarly, due to the need to stop and start the feed to the machine on a regular basis in order to discharge the retained inventory in the rotating cone, it is common to refer to the machine as a batch concentrator, or more commonly, a semi-batch concentrator, i.e. most of the time (90-95%) the machine is operating in the loading mode. As such, the full description of the machine would be a fluidized bed, semi-batch, centrifugal concentrator.

In parallel with the development of these high capacity machines for gold and/or PGMs, there has been a growing interest in the use of gravity separation systems for pre-concentration of high sg minerals ahead of comminution (Grewal, 2014) and the gravity recovery of non-precious metals, notably the
minerals of tin, tungsten, niobium, tantalum and chromium, with the latter being the focus of this paper. The minerals of interest (e.g. cassiterite, tantalite, chromite, etc.) tend to be somewhat brittle or friable relative to the host minerals, and the bulk of the losses in existing plants tend to be in the fine fraction, i.e. less than 100 microns, despite efforts to avoid over-grinding. A further challenge is that the sg difference between the “lights” and the “heavies” in these mineral assemblages may be only 3 or 4 specific gravities as opposed to the sg difference when separating metallic gold particles (sg ~ 19) from quartz (sg ~ 2.7). This has led to the development of higher g-force machines, with separating forces as high as 300-600 Gs, compared to the 150-200 Gs that are generally sufficient for optimal gold recovery. A third significant difference in these non-PM applications is that the minerals to be recovered can be present in much greater concentrations, measured in percentages, as opposed to most gold bearing streams in which the metal of value (gold) is measured in parts per million. A final consideration is that the gross value of the target product is usually measured in terms of a few hundred or a few thousand US dollars per metric ton, which is significantly less than the gross value of gold and PGMs which is measured in tens or hundreds of US dollars per troy ounce. This in turn dictates that the gravity separation systems need to have relatively low capital and operating costs, relative to the volume of product to be recovered.

In summary, the challenges in the gravity separation of these non-gold, non-PGM minerals relate to:

- the fine particle size range, i.e. <100 microns, of the valuable mineral,
- the minimal density or specific gravity difference between the “lights” and the “heavies”,
- the high mass pulls that are required to achieve acceptable recoveries, and,
- the low gross value of the recovered product relative to gold and the PGMs.

This has required a major re-think of the form and functionality of the centrifugal gravity concentrator, as the mass pull requirements, particularly in a rougher-scavenger type application, preclude building up an inventory within the rotating basket or cone. This has led to the development of non-fluidized centrifugal concentrators, with or without continuous discharge of the heavy fraction, that have been shown to be effective in recovering fine particles (< 100 microns) that simply cannot be recovered with conventional gravity concentration devices such as jigs, spirals and tables. The continuous discharge system allows for mass yields of 10-40% in a single pass, with the resultant recovery of 60-90% of the heavy fraction.

Machines can be configured in parallel to meet the mass and/or volumetric flow rate requirements of the stream to be processed. Similarly, machines (or groups of machines) can be configured in series, either in a rougher-scavenger role on the first stage tailings, or in a cleaner role (using flotation nomenclature) to upgrade the first stage concentrate, or both. Recent developments have also led to the recognition of the benefits of recycling specific streams back to a prior stage of the circuit, analogous to closed loops in flotation circuits. For example, the tailings from a second stage cleaner machine can be recycled back to the feed of the first stage machine. Similarly, the concentrate from a second stage scavenging machine can be recycled back to the feed stream of the roughing machine, while the tailings from the scavenging machine could be final tails, or sent to a downstream unit operation if this stream still contains sufficient recoverable minerals of value. These configurations have the advantage of building up a circulating load of heavies, that improves the competition of these heavies to the concentrate stream, which often results in the simultaneous improvement of both recovery and final product grade, which in effect moves the process to an improved grade-recovery curve.

The development of these high mass yield, un-fluidized, centrifugal concentrators has provided the opportunity to recover a wide range of minerals at significantly finer particle sizes when compared to the more traditional gravity devices. These concentrators provide additional benefits such as smaller unit footprint, ease of operation and high levels of automation. Until recently, the high mass yield machines had not been subject to the same level of research and modeling as the semi-batch, fluidized bed concentrators. In the last five years a significant volume of laboratory, pilot scale, and commercial scale test programs have been completed which has greatly increased the general understanding of the performance of these machines, particularly in the area of fine particle recovery, but perhaps more
importantly in the implications of closed-circuit performance. This new understanding is expected to move these machines beyond specific niche applications and into more general applications as the full potential of these units is significantly higher than previously recognized. Data from recent test programs at laboratory, pilot plant, and commercial scale is presented in the following sections as evidence of this potential with the ultimate objective being to develop the same level of understanding of separation fundamentals as has been achieved and successfully applied to fluidized bed semi-batch centrifugal concentrator technology.

PLANT SCALE PERFORMANCE

A number of operations that mine and process the ores of tin, tungsten and tantalum have incorporated high mass yield centrifugal concentrators into both gravity and flotation circuits. These units primarily target streams with fine particle size distributions in which the particles of interest simply cannot be recovered by conventional gravity machines such as tables, spirals and jigs. Other operations have successfully processed flotation concentrate streams to separate higher sg metal oxides such as cassiterite from lower sg metal sulfides such as pyrite, pyrrhotite and various base metal sulfides. The application and specification of centrifugal concentrators in these streams is discussed in more detail in the following sections.

Tantalum Recovery – TANCO Mine

One of the earliest sites to evaluate the high mass yield, un-fluidized centrifugal concentrator to recover fine, heavy, non-gold minerals was the TANCO tantalum-spodumene operation in Manitoba. TANCO successfully operated the Falcon Continuous C-Machines and Ultrafine UF-Machines for the multi-stage recovery and upgrading of fine tantalum. Extensive test work, comprised of approximately 75 separate tests, confirmed that the C-Machine was effective in recovering 70-80% of the tantalum in the -100 um fraction in the tailings from a conventional spirals circuit, with a mass yield of approximately 26% (Deveau, 2000). Continued test work then confirmed that 60% of the fine tantalum previously lost to the spiral tails could be recovered with a combination of the C-1000 operating in open circuit, with the concentrate upgraded with a smaller C-400, with the C-400 tailings recycled back to the feed stream of the C-1000. The combination of the two machines, one in open circuit, one in closed circuit, increased overall plant recovery by a substantial and significant 4%.

Based on this success with the high mass yield continuous machine, the UF-Machine was subsequently evaluated for the recovery of fine tantalite from a froth flotation concentrate in which 80% of the tantalite was finer than 20 microns (Deveau, 2006). Tantalum recoveries of 80-90% into a 30% mass yield were achieved with the machine operating at up to 600 Gs. A Falcon UF600 was permanently installed to upgrade TANCO’s flotation concentrates in April 2005. Site personnel subsequently reported on the high mechanical availability of both the C-Machines and UF-Machines and the low overall operating and maintenance costs (Deveau, personal communication).

Bluestone Mines Tasmania JV Pty Ltd. (Renison Tin Project)

The Bluestone Mines Renison Tin Project, located near the west coast of Tasmania, utilizes both flotation and gravity concentration to recover tin. The primary gravity concentration circuit consists of spirals, tables and Falcon C2000 Continuous units with the C-Machines processing the reground spiral and table tailings. The ultra-fines from the primary gravity circuit tails are upgraded via flotation followed by final upgrading with Falcon Ultrafine (UF) concentrators. In an effort to understand and compare the performance of the centrifugal concentrators to laboratory scale results, samples were collected from the streams around the centrifugal gravity units for lab scale testing.
Continuous Concentrators in Primary Gravity Circuit

Within the primary gravity concentration circuit, spirals and shaking tables are utilized for coarse liberated tin recovery. The tailings from the spiral and tabling circuit are reground to a P80 of 130 µm and processed through two Falcon C-2000 concentrators operating in parallel. It is important to note that while the 80% passing size of the Falcon feed is 130 µm, a size fraction assay of this feed stream showed that 90% of the tin is finer than 53 µm and 77% is finer than 38 µm.

During the sampling campaign, the feed to the centrifugal unit averaged 28 tph at a grade of 1.13% tin. Three sampling campaigns were carried out at settings that generated three different concentrate mass yields. The results from the balance around the centrifugal unit are presented in Table 1 below.

Table 1 – Plant operating conditions and tin recoveries for Falcon C machines in the primary gravity circuit

<table>
<thead>
<tr>
<th>Trial</th>
<th>Feed Flow Rate (tonne/hr)</th>
<th>Mass Flow to Conc. (tonne/hr)</th>
<th>Assayed Grade Sn (%)</th>
<th>Mass Yield (%)</th>
<th>Sn Rec. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.0</td>
<td>9.2</td>
<td>2.23</td>
<td>0.61</td>
<td>32.9</td>
</tr>
<tr>
<td>2</td>
<td>29.7</td>
<td>7.9</td>
<td>2.64</td>
<td>0.60</td>
<td>26.6</td>
</tr>
<tr>
<td>3</td>
<td>26.4</td>
<td>6.9</td>
<td>2.51</td>
<td>0.66</td>
<td>26.1</td>
</tr>
</tbody>
</table>

To evaluate amenability to high yield gravity recovery, a standard laboratory test protocol was used involving multiple passes through a laboratory scale Falcon concentrator known as an L40, with a UF bowl (in this case designating it as an Un-Fluidized bowl), in comparison with the fluidized L40 bowl used for conventional GRG work. After each pass the concentrate was recovered, dried, weighed and subsample taken and assayed. The tailings were re-processed through the same test unit multiple times to achieve the target mass yield. The tailings from the final pass though the L40 were also dried, weighed and assayed, with the data being used to generate conventional mass recovery curves (Figure 1). The results from the three plant trials are also plotted in the same chart. Two sizes of the un-fluidized bowl were tested, a standard and smaller version labelled as the “Mini UF” bowl to examine if one provided a better simulation of the plant scale centrifugal unit.
The results from both lab tests using the two different un-fluidized bowls provided very similar responses. Furthermore, the operational data from the plant-scale units correlated well with the lab results confirming that the laboratory scale test methodology provides a reasonable expectation of plant performance.

It is important to note that the lab methodology employs multiple passes through the lab scale concentrator to achieve the required mass yield and/or metal recovery. The full-scale Continuous Machine has an adjustable valving system to control concentrate mass yields. The multiple passes in the lab machine are used to get a first approximation of the target mass yield in the full-scale machine and does not imply that multiple plant-scale concentrators are required. Depending upon the rated feed capacity of the concentrator and the mass flow rate of the stream to be processed; a single concentrator can be utilized to achieve the target mass yield projected by the lab test work.

**Upgrading Flotation Concentrate with Ultrafine Concentrators**

The final tin flotation concentrate at the Renison Tin operation is upgraded in a circuit consisting of six Falcon Ultrafine (UF) concentrators in a rougher, scavenger, cleaner arrangement. Three UF units are deployed as roughers with the combined rougher concentrate reporting to a cleaner UF unit. The combined UF rougher tails report to two parallel scavenger units. The scavenger concentrate and cleaner tails are returned upstream and combined with the flotation concentrate to the rougher feed (see Figure 2). The particle size of the feed to this circuit is 98% passing 25 um.

![Figure 2 – Falcon UF Circuit Configuration for Treatment of Flotation Concentrate](image)

A balance around the circuit shows that the tin is upgraded from 14% in the flotation concentrate to 28% in the cleaner UF concentrate at recoveries in the range of 75%. The rougher concentrate was tested in the lab for comparison to the plant scale response. The test was done in a similar manner as described earlier using the mini un-fluidized bowl. The lab scale results are plotted in Figure 3. While only one data point was available from the plant, the results show that the lab scale results were similar to the plant unit even on this very fine feed stream.

The data and results from the test work indicate that the approach and equipment used at the lab scale provide results that are consistent with those obtained at plant scale. Tests done on individual streams provide data for the analysis of open circuit single pass performance. However, in many circuits,
there is a need to upgrade the mineral of interest using gravity concentration in cleaning stages where intermediate products are returned upstream. To this end, test work procedures were developed, not only to evaluate open circuit performance, but also to evaluate upgradeability using locked cycle testing in a manner similar to the locked cycle flotation tests. Two such case studies are presented in the following sections.

![Figure 3 – Comparison of lab results to plant data from UF circuit](image)

**LABORATORY SCALE TESTING**

**Recovery of Fine Tin from a Froth Flotation Concentrate (Kasbah)**

Samples of a froth flotation concentrate, provided by Kasbah Resources, grading slightly under 8% tin, with over 90% of the mass finer than 20 microns, were tested in an un-fluidized L40 lab concentrator. The test methodology was similar to the approach described in the previous sections.

Based on the curves below (Figure 4 and 5), one can see that the 1st pass recovered 50.9% of the tin into a concentrate grading 10.6% Sn, at a mass yield of 19.2%. After the 5th pass, 96% of the tin was recovered into 65% of the mass, at a cumulative grade of approximately 11.5% Sn, producing a final tail of 1.29% Sn.

![Figures 4 & 5 – Mass Recovery-Yield (left) and Grade-Recovery curves (right) respectively based on multiple passes through the L40 Laboratory Concentrator using the un-fluidized bowl](image)
As with all test work, bulk recovery is but the first step in the evaluation process, and addresses whether sufficient metal of value can be recovered to warrant further investigation. With the positive results reported above, the second stage involved designing a program to quantify the upgrading of the recovered material into a saleable product. A flowsheet consisting of three rougher and two scavenger stages followed by two stages of cleaning of the rougher concentrate was evaluated as per Figure 6.

![Flowsheet Diagram](image-url)

Figure 6 – Lab Falcon (L40) Rougher-Cleaner Flowsheet and Mass Balance utilizing the standard and mini un-fluidized bowl.

The cumulative rougher-scavenger recovery of 95.7% into a mass yield of 62.2% agrees very well with the results reported in Figures 4 & 5 above. After two stages of cleaning of the rougher concentrate, a final concentrate grading 32.8% Sn, at an overall circuit recovery of 41.9% was produced. While the final concentrate grade was deemed to be acceptable, i.e. the product was saleable, but with probable discounts due to the low grade, some additional effort was required to improve overall circuit recovery.

As has been well understood in the design of flotation circuits, the recirculation or recycling of key streams back upstream in the process can be beneficial from both a final product grade and an overall metal recovery perspective. Extensive work has indicated that this may be even more significant in the design of high mass yield gravity circuits. This is because recovery of a particle to the concentrate stream is a function of size and specific gravity, two characteristics that don’t change significantly as the individual particles move through or around the circuit. One could argue that there could be some particle attrition, but the impact of this is thought to be minimal.
This consistency of particle characteristics is in contrast to recycle loops in flotation circuits where over-dosing of reagents, deterioration of particle surface characteristics, and the risk of significantly over-loading the circuit can often limit the positive impacts of recirculating loads, and result in a net negative impact if the circuit is not adequately controlled.

In gravity circuits, recovery to the concentrate stream is probabilistic in nature and involves competition between particles, based on both specific gravity and size. As such, one would expect that as the relative flow rate of gravity recoverable particles increases, while the relative flow rate of the light fraction (i.e. the fraction that eventually reports to the tailings stream) decreases, then the overall probability of a heavy particle reporting to the concentrate stream would increase. This would manifest in equal or higher final concentrate grades at substantially improved recoveries. That is to say, the recycling of intermediate streams moves the overall circuit to a new, and better, grade-recovery curve.

For the tin project in question, a locked cycle flowsheet was developed as shown below in Figure 4, involving (i) the recycling of the rougher cleaner tails and scavenger cleaner concentrate to the front-end of the circuit, (ii) the recycling of the scavenger cleaner tails to the feed of the scavenger circuit, and, (iii) the recycling of the re-cleaner tails to the rougher concentrate/cleaner feed stream. The net effect is that there are only two exits from the circuit, one as the scavenger tails, the second as the final concentrate.

Simulation of this flowsheet in the laboratory, similar to flotation locked-cycle test work, requires multiple iterations until key parameters, in this case scavenger tailings grade and/or final concentrate grade, achieve some level of steady state. While the work is tedious, the results can often quantify significant
improvements in the circuit performance. In this project, after six iterations, an average tin recovery of 82.5% was achieved, as compared with the 41.9% tin recovery in the open circuit simulation. The average concentrate grade was 43.7% tin, up from 32.8% tin in the open circuit scenario, as summarized in Table 2 below. The final concentrate grade stabilized after only the 3rd cycle or iteration. During the test work, the circulating load increases with each iteration, and in this case, the final scavenger tailings tin grade steadily increased with each iteration, and had not stabilized after the 6th iteration. This simply reflects the overloading of the scavenger stages, and could be addressed by simply adding one more scavenger stage.

Table 2 – Summary of Results Quantifying the Impact of Locked Cycle Testing on Fine Flotation Concentrate

<table>
<thead>
<tr>
<th></th>
<th>Sn Grade (%)</th>
<th>Sn Rec. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Circuit Ro./Sc. Con.</td>
<td>11.9</td>
<td>95.7</td>
</tr>
<tr>
<td>Open Circuit - Cleaner Con.</td>
<td>32.8</td>
<td>41.9</td>
</tr>
<tr>
<td>Locked Cycle Cleaner Con.</td>
<td>43.7</td>
<td>82.5</td>
</tr>
</tbody>
</table>

In summary, while the preliminary open-circuit test work quantified the amenability of this tin-bearing material to gravity recovery of the tin, the extended locked-cycle test work resulted in a recovery improvement of just over 40% and the final product grade improvement of over 10% Sn, compared to the open-circuit test work, the combination of which significantly improved the overall project economics, i.e. higher recoveries and grades without a significant addition in processing equipment.

**Recovery of Fine Tin from a Tailings Sample**

A screened, -212 micron, fraction of a tailings stream, assaying 0.15% tin was evaluated in a process similar to that described above. The standard laboratory protocol comprised of seven passes through the UF L40 concluded that 79% of the tin could be recovered into a 16% mass yield. An open-circuit rougher-scavenger test was conducted; consisting of 3 rougher stages and 4 scavenger stages, with cleaner stages applied separately to the rougher and scavenger concentrates. The rougher and scavenger gravity passes recovered 55.1% and 22.5% of the tin respectively, for a combined tin recovery of 78.6%, which was in good agreement with the preliminary multi-stage rougher test. The 1.43% tin rougher concentrate was subjected to further cleaning and re-cleaning, achieving a final concentrate grade of 53.4% tin and a recovery of 14.4%.

Based on the results from the open circuit rougher cleaner test, a locked cycle flowsheet was designed, as shown in Figure 8 below. An additional rougher stage was added, with the Rougher Cleaner Tails and Scavenger Cleaner Tails recycled to the front end of the rougher circuit, i.e. a slightly different configuration from the previous example. The scavenger cleaner concentrate and the re-cleaner tails were recycled back to the Rougher Concentrate/Cleaner Feed Stream.

A tin recovery of 71.3% (compared to 14.4% recovery in the open-circuit flowsheet) was achieved after seven cycles with a final concentrate grade stabilizing at 45% Sn during the last 3 cycles. As per the previous example, the concentrate grade stabilized after only the 3rd cycle at a tin grade of approximately 45% Sn. Recalling that a cleaner concentrate grade of up to 53% tin was achieved in the open circuit test, there is potential to achieve >50% Sn grade if the concentrate product stream was cut more aggressively (smaller mass) during the table operation of the re-cleaner stage. The scavenger tailings grades were relatively stable, averaging 0.05% tin. Due to the additional rougher stage and the two additional scavenger stages, there was no upward trend in the tailings grade as reported in the previous example. It can also be shown, based on these results, that under operating plant conditions, the amount of tin contained in the recycling/circulating load streams as a percentage of the overall circuit will be almost negligible.

In summary, this -212 micron tin tailings sample responded well to locked-cycle centrifugal gravity concentration with the high mass yield, UF (un-fluidized) L40 bowl in the laboratory Falcon.
resulting in both high tin recovery and concentrate grade. Once again, the effects of recycle streams in the locked cycle mode are shown to be highly beneficial to overall circuit performance.

Table 3 – Summary of Results Quantifying the Impact of Locked Cycle Testing on Tin Tailings

<table>
<thead>
<tr>
<th></th>
<th>Sn Grade (%)</th>
<th>Sn Rec. (%)</th>
</tr>
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<tbody>
<tr>
<td>Open Circuit Ro./Sc. Con.</td>
<td>0.90</td>
<td>77.6</td>
</tr>
<tr>
<td>Open Circuit - Cleaner Con.</td>
<td>53.4</td>
<td>14.4</td>
</tr>
<tr>
<td>Locked Cycle Cleaner Con.</td>
<td>45.1</td>
<td>71.3</td>
</tr>
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</table>

**SUMMARY**

Fluidized bed, semi-batch centrifugal gravity concentrators are now commonplace in the industry. In conjunction with hydrocyclones which effectively act as rougher units, these machines can achieve both high concentration ratios and high recoveries of gold and PGMs in conventional grinding circuits. Considerable lab & plant scale testing and development has advanced the knowledge required to confidently apply laboratory results to the design and optimization of plant scale installations.

In parallel with the development of the fluidized bed concentrator, there has been a growing interest in the use of high g-force centrifugal gravity concentrators for the recovery of non-precious metals such as tin, tungsten, tantalum & chromite. The development of the high mass yield, un-fluidized, centrifugal concentrator has now provided the opportunity to recover a wide range of fine minerals (i.e. <100 microns) that previously could not be recovered by traditional gravity concentration devices such as tables and spirals.
Until recently, these high mass yield machines have not been subject to the same level of research and modeling as the semi-batch, fluidized bed concentrators. Two distinct lab-scale testing protocols have now been developed and verified against operating plant data. The first is a multi-stage open circuit test which confirms the amenability to gravity separation and quantifies the recovery-mass yield relationship for a specific sample. The second is a multiple iteration locked-cycle test, analogous to the well understood locked-cycle flotation test, which quantifies the upgradeability of the material and the ultimate recovery of the metal of interest into a saleable product. Extensive plant-scale test work has confirmed the correlation between plant performance and the laboratory scale results. This work has also confirmed that the high-mass yield, un-fluidized concentrator, operating either in a continuous mode or a semi-batch mode, in either open-circuit or closed-circuit can make effective separations on fine particles to well below 25 microns. Installation of these machines have been shown to significantly reduce fines losses to the tailings stream and substantially improve overall plant recovery of the metal or mineral of interest.

ACKNOWLEDGEMENTS

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