

Bench-scale & Pilot Plant Testwork For Gravity Concentration Circuit Design

André R. Laplante¹ and D. Erik Spiller²

ABSTRACT

Successful gravity concentration is founded in adequate liberation, informed selection of unit operations, and finally the proper presentation of feed to those units. As with all physical separation, effective circuit design and equipment selection require representative samples of adequate size. Characterizing the mineralogical nature of both value and waste components is critical. This paper presents testing methods used to establish amenability including selection of appropriate unit operations, bench- and pilot- scale testing and their limitations, and scale-up for effective commercial circuit design. All manner of commercial devices are considered with particular attention to recently introduced centrifugal machines.

INTRODUCTION

Gravity Separation – A Versatile Technology

Gravity concentration, once the stalwart technology for mineral beneficiation, has evolved and entrenched in the last 30 years to regain and maintain its commercial importance to the recovery of various mineral based resources. Precious metals, ferrous and non-ferrous metals, energy minerals (in particular coal) and numerous industrial minerals are processed all over the world using gravity separation technology. Particles as coarse as 200mm (nominally 8 inches) to as fine as 10 μ m are successfully beneficiated using gravity separation equipment. There are dry gravity separation systems and equipment, although the vast majority of commercial gravity concentration is performed wet. The past 20 years of technology development has been most dramatic in the application of centrifuge-based equipment for fine particle separations and for recovery of very high specific gravity particles occurring in low concentration, i.e., liberated gold in a grind circuit stream.

The single most important factor in successful gravity concentration is liberation of the heavy and light components. Liberation in natural mineral systems occurs along a continuum from an essentially homogeneous state to complete physical liberation. The necessary degree of liberation coupled with correct equipment selection is fundamental to successful and cost effective gravity concentration circuits.

Readers are directed to reference the chapter titled “Process Design, Scale-up and Plant Design for Gravity Concentration” in *Mineral Processing Plant Design, 2nd Edition*, 1980. This reference contains considerable relevant information on the subject.

Virtually all gravity-concentrating machines tend, at times, to confuse gravity concentration with size classification so it follows that the most effective gravity separations are accomplished on narrowly size classified feeds. Of course, there is an economic and practical limit as to how much equipment and process energy is justified for size classification during the feed preparation process. This limit should be established during the design-engineering phase of study after the necessary bench and pilot studies are completed.

¹ McGill University, Montréal, Quebec Canada

² OUTOKUMPU TECHNOLOGY INC. Physical Separation Division, Jacksonville, Florida USA

Advantages of Gravity Separation in Process applications

There are a number of advantages to applying gravity concentration techniques to mineral systems. Among the most obvious are:

- Relatively simple equipment translates to low cost (capital and operating)
- Little or no reagents required (cost advantage and environmental advantage)
- No reaction products (no chemical change) minimizes energy cost and results in environmental advantage
- Can be effected at relatively coarse sizes (assuming adequate liberation of either value or gangue components) to extremely fine size materials

Gravity separation, when it works, is usually the most cost effective beneficiation technology. Importantly, even in instances where complete separation cannot be achieved by gravity techniques, it is often desirable to produce a gravity pre-concentrate. This pre-concentrate product (now with less mass) can then be further concentrated or processed by more expensive, perhaps environmentally sensitive, techniques to produce the final desired product.

Definition of Testwork Scale (Bench vs. Pilot vs. Demonstration)

In general terms, testing for gravity concentration amenability and application can be considered at three levels; bench, pilot, and demonstration. The bench-scale (often done more for characterization than process testing) is typically conducted on samples from 1 to 20 kg, whereas pilot-scale testing can require samples of 100 kg upwards to several tonnes. Demonstration scale testing is essentially operating the equipment at full commercial feed rates over extended time periods.

Gravity concentration equipment cannot be readily miniaturized for bench-scale testing. The mechanics of the separations simply require more area/space, higher flow rates, and more incremental time than can be accommodated by bench top units operating on small samples. For this reason bench-scale testing is often focused on characterization of the feed and desired products with an emphasis on liberation.

Pilot-scale testwork for gravity concentration is commonly done on commercial equipment, albeit when possible on the smallest version of the commercial equipment. When possible, testing is done continuously in open circuit; prepared feed is presented to the test unit and timed product samples are taken at steady state. However, at commercial rates or even rates approaching commercial processes rates, feed is consumed very quickly and large quantities of concentrate and tailing products must be handled. Therefore, a modified open circuit test (commonly referred to as a batch test) is often employed wherein feed is introduced to a sump/pump arrangement from which feed to the test unit is withdrawn and presented to the concentrator unit. Products from the unit are returned to the feed sump, remixed and pumped again to the unit. When all conditions of operation are set, i.e., feed rate, feed pulp density and concentrate/tailing cut points, timed samples of all the products are taken. This procedure minimizes the need for large feed samples and the cost of preparing the product samples for analyses. Multiple tests at different conditions can often be done on one batch of prepared feed because only the amount of sample cut for the test is removed from the system.

Further evolution of the batch test is the semi-continuous batch test. The objective of the semi-continuous version is to minimize the sample requirements while providing adequate product for subsequent (cleaner or scavenger) stage testing. Here the batch test is initiated, and at proper conditions the concentrate and tailing products are diverted and collected until the desired amount is produced or until the feed being presented to the unit/machine is no longer valid. This procedure can be repeated as necessary with the introduction of new feed to sump and alternate collection of products. The resulting products from semi-continuous testing can then be further tested as necessary in cleaner or scavenger stage application.

Demonstration (commercial scale) testwork is very common for gravity concentration. Often gravity equipment is niched into an existing operation or added onto a commercial process as a scavenging or subsequent step at the end of the flowsheet. In these circumstances, industrial, or near-industrial scale machine units are installed in the operating plant and tested for metallurgy. In this manner the equipment is not only evaluated and optimized for metallurgical performance, but also with respect to its robustness and operating cost over an extended time period. Demonstration testwork can extend for months or even longer.

Conventional and Centrifugal Based Unit Operations

Centrifugal (or “enhanced” gravity) separators became a common occurrence in mineral processing plants in the eighties, when the Knelson Concentrator became the unit of choice for the recovery of gold from grinding circuits, replacing mostly spirals and jigs. The low grades of the material treated, typically between 1 and 500 g/t, make it possible to operate the unit in semi-batch mode (i.e. a tailing stream is continuously produced, but the unit must be stopped to harvest the concentrate). Soon after, other semi-batch centrifuge units became commercially available for gold recovery, the best known being Falcon’s SB Concentrator. Knelson and Falcon have also developed continuous centrifuge units, but these do not enjoy the degree of acceptance of the semi-batch units, and will only be discussed briefly. Two other continuous centrifuge units will also be discussed, Mozley’s MeGaSep/MGS and the Kelsey Jig of Mineral Technologies (now a subsidiary of Roche Mining). The four continuous units are based on four very different concentration mechanisms also used in non-centrifuge units, and are generally best suited for very different applications. Further, they may be used synergistically either with each other or with conventional gravity equipment. For each centrifuge mechanism, a sole commercial unit is available, a stark contrast to flotation units or even conventional gravity units.

This presentation will discuss all centrifuge units aforementioned, with emphasis on Knelson Concentrators, to reflect their much wider use. Both semi-batch and continuous concentrators require unique bench-scale testing which are atypical for other separators. The semi-batch units are generally used to process all or part of the circulating load of a grinding circuit, an application that is almost impossible to replicate at bench-scale and can be difficult to mimic at pilot-scale. The continuous separators are also difficult to test at bench-scale, because typically no bench-scale *batch* unit can reproduce their main concentration mechanism. For preliminary testing, typically the low-capacity version of the continuous unit is used. Feed material may be difficult to generate at the design stage, since often the unit feed is not the ground ore but rather a relatively small stream. As a result, most applications of continuous centrifuges have been retrofits in existing circuits with the bulk of the test work performed on site. Typical testing programs will be discussed in the centrifuge section.

FEED CHARACTERIZATION AND EQUIPMENT (UNIT) SELECTION

Characterization of the feed material is the first step in developing a successful gravity concentration flowsheet and leads directly to selecting the most effective separating equipment.

Objectives of Characterization

The basic objective of feed characterization is to understand the mineralogy of the ore. Once understood, especially as related to liberated particle size, then selection of the appropriate separating equipment can proceed. For purposes of developing a successful gravity concentration process, the mineralogical analysis is best focused on the “nature-of-occurrence” of both the valuable and gangue components. Determining the genesis of each mineral in the matrix is of secondary importance and is often expensive. This paper will not attempt to cover the techniques used to do a mineralogical analyses of feed ores, but rather point out the practical aspects of such analyses and what resulting information is desired.

Spending money on feed characterization is equally important with all other steps in flowsheet development, and it can be argued that without a proper understanding of the feed it may be impossible, excepting luck, to end up with a successful process. Understanding the nature of occurrence also prevents unnecessary testwork and the loss of precious time. A good mineralogical characterization of the feed ore will result in knowing as much about the following as time and budget will allow.

- The minerals of value, their chemical composition, and their specific gravity
- The gangue minerals, their chemical composition, and their specific gravity
- The grain size range of both the value and gangue minerals, including information on intergrowth occurrence in both

Sampling and Sample Requirements

In a perfect world, the mineral processing engineer would have access to as much sample material as desired and the samples would be perfectly representative both individually and as a blend of all the variation (ore types) in the resource. This is rarely the situation. Furthermore, statistically valid samples based on sampling theory are also usually out of the question due to their size and to the cost of procuring multiple large samples which often require extensive drilling, adit construction, trenching, deployment of personnel, and required sample transportation in remote areas. Finally, the specific mineral resource commodity being considered also plays a role in the amount of sample required to do a complete job of characterization and testing; for example, spotty gold ores require more sample material than does coal from a continuous seam.

As a practical approach, the following guidelines should be followed.

- Communicate with the geologist about the nature and variation of the resource.
- Obtain samples representing the average and reasonable extremes of the resource.
- Obtain samples representing a mine plan, i.e., for example, what the process plant will see the first year, the third year, and subsequent years through the economic life of the resource.
- Think ahead; ensure the integrity of any sample materials (splits) left behind for future requirements.
- Samples for bench-scale studies, including feed characterization samples, should generally be from 1 to 20 kg in size. This assumes, based on particle size and preparation procedures, a sample of such a small size can be considered valid for the purpose of the work.
- Pilot-scale studies require from 100 kg of material upwards depending on the mineral commodity being studied, the equipment being considered, and the amount of resultant data required.
- Demonstration scale studies are conducted at commercial rates most always in a commercial plant setting where there is no limit to the amount of feed sample available (either as an integral part of a flowsheet or when operated on a bleed stream in the plant).

Characterization of Feed Resource

There are a number of different approaches to developing characterization data. First, is a simple microscopic examination, second is the use of sink/float analyses, and third is the use of scanning electron microscope technology. An additional way of estimating the likelihood that gravity concentration could be successful is the concentration criterion calculation. There are numerous descriptions of each of these techniques in the literature.

The same techniques of characterization can be used on intermediate (inter-stage) product streams to determine where they should report in a flowsheet, or if they should be rejected. They can also be used to differentiate between true middlings and particles that report to a middling stream because of mechanical misplacement.

Microscopic Analyses. Simply looking at crushed, ground and size-classified samples of the resource under a microscope can be enlightening. More sophisticated analyses are entire subjects to themselves and include such techniques as polish and thin section analyses and grain counting. On occasion, magnetic fractionation, such as with a Frantz Isodynamic Separator or other device, is a useful tool to identify specific minerals in the resource.

Sink/float Analyses. This technique is used without exception for investigating coal and mineral sand resources, and is of value in all potential gravity separation applications. Safety issues surrounding the use of organic heavy liquids mandates strict containment procedures and thus in the past discouraged their use. However, there are now commercial and user friendly substitutes for the organic liquids in the form of sodium polytungstate solutions and other similar substitutes. These solutions can produce sink/float separations up to 3.1 g/cm³ density. Therefore, these non-toxic solutions are useful to both the coal and mineral sands industries, and directly substitute for analyses previously done in tetrabromethane.

For procedures and data interpretation techniques you are referred to the many references on this subject (Mills, 1980).

Scanning Electron Microscope (SEM) Based Analyses. There are commercial liberation analyzers that are based on SEM technology with various software packages attached. These units (commercially known as the QEMScan and JKMRC/Phillips Mineral liberation Analyzer-MLA) are capable of producing an enormous amount of information on mineral liberation, grain size, and intergrowth of mineral species. This information, especially if coupled with sink float analysis, will provide very useful information to the investigator regarding the suitability of the feed ore to gravity concentration. Of equal value is the information it provides relative to problems encountered in gravity concentration circuitry.

Concentration Criterion. Assuming that the particle size effect is eliminated or minimized, and that the value and gangue components are liberated, the remaining task is to ensure there is sufficient specific gravity differential to effect a commercial gravity based separation. Fundamentally, there must be a marked difference in the specific gravity of the liberated value and gangue components. Applying the concentration criterion (does not apply to dense medium separations) is a convenient mathematical means for determining if the specific gravity differential is sufficient. Use:

$$CC = (D_h - D_f) / (D_l - D_f)$$

Where:

CC = concentration criterion

and:

D_h = specific gravity of the heavy component

D_l = specific gravity of the light component

D_f = specific gravity of the fluid (usually water at 1.0)

When the absolute value of:

CC > 2.5, it is likely that some form of gravity concentration will be possible

CC < 1.25, gravity concentration will be virtually impossible using commercial methods

2.5 > CC > 1.25, gravity concentration will be difficult but may be possible to some extent on narrowly sized feed and with slow and careful feed presentation

Using the guidelines offered by the concentration criterion, one can speculate about the possibility of using gravity concentration successfully on any given mineral resource system. Of course, additional criteria must be met in a gravity concentration circuit to ensure success. For instance, feed preparation and presentation are important to varying degrees depending on the equipment and minerals being beneficiated. In general, finer particle sizes require larger concentration criterion values to indicate the possibility of successful gravity concentration.

CONVENTIONAL GRAVITY SEPARATION SYSTEMS (UNIT OPERATIONS)

There is an amazing array of mechanical devices that have been conceived, built, and marketed to separate minerals based on particle specific gravity differences. The guidelines presented in this paper cover gravity separation via the classical system definitions of stratification, flowing film, and shaking (see Kelly and Spottiswood 1982); density systems, i.e., dense medium separations (DSM) are not included. Added of course to these systems are the centrifugal based separating machines that have become common over the past 20 years.

Conventional Equipment Alternatives and Considerations

Over the years there have been a number of graphs and charts developed to aid in selecting the most suitable gravity processing equipment for a specific application. The effective feed particle size range and capacity of the various concentrating units differ substantially. Presented herein are two of the more common summaries that provide indications of equipment/feed compatibility. Of course the information presented in the figures are generalized and reflect both experience and prejudice of the authors. Considerations of the ore's mineralogy, i.e., liberation characteristics, and (assuming a favorable concentration criterion) coupled with the information in the summary tables will indicate if gravity concentration is probable.

Figure 1 is a graphical presentation of the size range applicability of commercial gravity separation equipment. Presented in Table 1 are again the various types of commercial gravity concentrators with information about their relative water requirements and capacity.

Hindered settlers, operated as density separators via control of the teeter bed within the unit, are now common to gravity circuit design. Properly used, the units facilitate and complement gravity separation. Other authors will deal with hindered settlers in the context of gravity separation. The hindered settler is included as a gravity concentration device in Table 1.

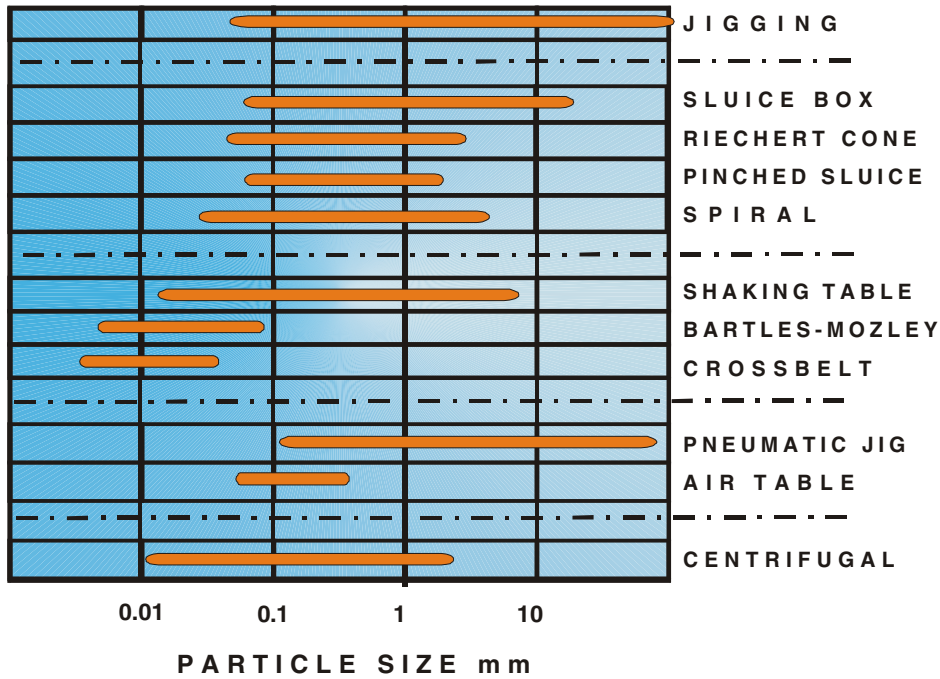


Figure 1 Size Range Applicability of commercial Gravity Separation Equipment

Table 1 Characteristics of Gravity Concentration Machines³

Type ⁴	Machine	Operating Size Range (mm)	Water Requirements ⁵	Capacity ⁶
Stratification	Jigs-Conventional	0.10 → 100	High	medium
	Jigs-Circular	0.05 → 100	high	high
	Jigs-Centrifugal	0.02 → 2.0	high	medium
Flowing Film	Sluice Box	0.15 → 10.0	high	medium
	Reichert Cone	0.05 → 1.5	low	high
	Pinched Sluice	0.05 → 1.5	low	medium
	Strake	0.15 → 2.0	high	low
	Spiral	0.03 → 2.0	medium	medium
Shaking	Shaking Table	0.02 → 2.0	medium	medium
	Orbital	0.01 → 0.07	high	low
	Crossbelt	0.01 → 0.03	high	low
Centrifugal	Spinning Bowls	0.01 → 1.7	very high	high
Hindered Settler	Density Separator	0.07 → 0.60	medium	high
Air Dry	Pneumatic Jig	0.15 → 25	none	medium
	Air Table	0.25 → 6	none	low

³ Spiller, 2000; Generalized; specific machine operating on site-specific materials may or may not perform to these characteristics

⁴ Kelly and Spottswood, 1982

⁵ Relative

⁶ Relative per unit; multiple units always equate to high capacity

Projecting Data to Commercial Application, and Limitations Thereof

In general, data developed in the laboratory and pilot plant can be used directly to select equipment and predict performance at commercial scale. This of course assumes that the samples tested represent the eventual feed to the plant or gravity concentration circuit. Care should be taken to understand the nature of recirculated middling streams in complex circuitry. For example, product middlings that are liberated and are simply mechanically mixed components will eventually respond to separation and exit the circuit as concentrate or tailing products. However, unliberated middlings will build up in the circuit and choke performance if they are recycled upstream without additional liberation. Further difficulty arises when the gravity concentrator is treating a small portion of a larger stream in the plant, i.e., a recirculating load in a grinding circuit. A discussion of this situation is presented under centrifuge based unit operations elsewhere in this paper.

Proper feed preparation and presentation is essential in gravity concentration. In fact, certain machines such as shaking tables demand a very consistent feed rate. Other considerations in feed preparation are desliming and sizing to reject coarse tramp oversize.

CENTRIFUGE BASED SEPARATION SYSTEMS (UNIT OPERATIONS)

Objectives of Bench and Pilot-scale Test Work

Semi-batch Centrifuges for Gold. The difficulties of trying to replicate at bench-scale the performance of a centrifuge semi-batch unit, processing all or a bleed of the circulating load of a grinding circuit, has already been alluded to in the introduction. Additional hurdles challenge this process, namely the inability to achieve, at bench-scale, the very high concentrate grades full-scale circuits will typically achieve, the sampling difficulties normally associated with gravity recoverable gold (GRG⁷), and the wide range of recovery efforts⁸ used in full scale circuits. The typical gold gravity circuit is also unusual in that it usually works in tandem with a flotation or cyanidation circuit. Thus, most of the gold it recovers would be eventually recovered even in the absence of a gravity circuit. As a result, the optimum *economic* recovery can be highly variable. Where the ore is simple and the downstream circuit very effective, the net contribution of gravity recovery could be as little as 0 to 0.5% of the gold values. Contrast this with highly preg-robbing ores where the impact of gravity recovery has been measured at more than 10%, or even mills that rely entirely on gravity recovery (“extreme” gravity recovery; Van Kleek, 2001). The extent of the gravity recovery effort will therefore vary from as little as 1% of the gold in the circulating load to in excess of 20% for extreme gravity recovery. To address these issues, the objectives of bench-scale testing have to be clearly understood and test design chosen accordingly. Broadly speaking, testing objectives are two-fold.

Firstly, bench-scale tests will seek to generate a gravity tailing that most closely resemble the feed that the downstream cyanidation or flotation circuit would process, for bench-scale testing of flotation and cyanidation. The focus of these tests will be to generate the correct gravity tailing, with emphasis on the recovery of coarse gold that would not normally report to cyclone overflows and be directed to downstream recovery circuits. Most bench-scale tests would be of this type.

Secondly, bench-scale tests should aim to generate the data needed to design, size, and predict the performance of the intended gravity circuit. Such test work should not attempt to mimic the full-scale gravity circuit, but rather to characterize the GRG content in the ore. Typically, these tests are far more detailed than the first type, but few are required. A number of ores have been characterized with a single test, from which a gravity circuit has been successfully designed. This cost-effective approach is particularly appropriate when the economic impact of gravity recovery is low, the mineralogy of the ore is simple, and the scope of the project is limited. As the size or complexity of the project or the role of gravity recovery increase, so does the number of tests required, but very rarely should it exceed three or four. Typically, two tests would be needed to characterize the effect of head grade on the GRG content.

⁷ GRG: gold present in particles in concentrations such that the behavior of the particle in gravity units is significantly affected (Laplante et al, 2001)

⁸ Recovery effort: overall gravity recovery expressed as a percent of the gold in the circulating load of the grinding circuit (Laplante and Xiao, 2001).

The two objectives of bench-scale work are not easily reconciled, but both may not be needed. Most of the test work should address the first objective. Typically, this is achieved by treating a 5-kg or 10-kg batch of ore at final grind with a laboratory centrifuge, either a Knelson Concentrator 3MD (3-inch unit) or a Falcon SB50 (4-inch unit). The concentrate is then cleaned to a small mass, 1 to 10 grams, by hand panning, superpanner or Mozley laboratory table. The rougher and cleaner tailings are combined and used as feed for flotation or cyanidation test work. The procedure is repeated on as many head samples as deemed necessary to assess issues of ore variability, optimum grind size, and cyanidation or flotation conditions. This typically requires many tests and may in fact represent the bulk of the gravity test work. Some semi-batch centrifuge representatives claim that actual plant performance often sits between the cleaner and rougher recoveries (Peacocke, 2002). This lends credence to the ability of this experimental protocol to produce a gravity tailing that is similar to the grinding circuit product. In essence, for this type of testing gravity recovery services cyanidation or flotation test work, much in the same way that full-scale gravity circuits service downstream cyanidation or flotation circuits.

As effective as the above procedure is in producing a suitable feedstock for cyanidation or flotation test work, it does not provide the information needed for optimum design of the gravity circuit and prediction of how much it will recover. This additional information can be generated only from a test specifically designed to do so. This test should have the characteristics outlined in Table 2.

Table 2 Test Requirements for Gold Gravity Circuit Design

Objective	Action
Eliminate the nugget effect associated with GRG	Perform test work on representative sample size adequate as defined by sampling theory
Recover only GRG	Use large feed mass to keep weight recovery low and examine concentrate to determine degree of GRG liberation (Laplante, 2000)
Determine screening requirements and best possible recovery unit	Generate size-by-size information; recover gold as soon as liberated to avoid over-grinding by staged comminution and recovery
Eliminate the risk of gold traps	Slurry the feed directly above the separation unit
Predict gravity recovery	Difficult to achieve at bench-scale – use model to predict performance

A test that fulfills the objectives of Table 2 will be described in the next section. An important observation is that the interaction of grinding, classification and recovery units would be extremely difficult to reproduce at bench-scale but is now reasonably well understood and described. It is therefore more expedient to model this behavior mathematically, using the information generated by a test that satisfies the requirements of Table 2.

Piloting semi-batch centrifuge units in grinding circuits is advantageous in achieving the interaction between grinding, classification, and recovery units that defines how much gold will be recovered at full scale. Typically, the objective of such piloting is to generate a higher degree of confidence in predicted metallurgical performance, when warranted by the scale or complexity of the project. This is not often the case for typical gravity and CIP flowsheets. In some cases, piloting is used to assess head grade more accurately by processing a large representative sample of ore. Should piloting be warranted, gravity recovery can still be over-predicted if the recovery effort used is larger than what will be used at full scale. This is often the case, even when the gravity unit used in the piloting exercise is rather crude (e.g. a strake or blanket). It is essential to measure the gravity recovery effort when piloting, to either design the full circuit to use the same recovery effort, if economically justified, or downgrade pilot performance when scaling up the performance of gravity. Ideally, the pilot recovery effort should be set at that which will be used by the full-scale circuit.

The usual pitfalls of bench testing with semi batch centrifuges are:

- using too many samples that are too small to be statistically meaningful, or samples that are not representative of the ore body
- testing many operating conditions that generate unusable information,
- failing to generate size-by-size information about the natural size distribution of the GRG and
- producing very low grade concentrates that contain too much gold that is not gravity recoverable.

The approach described above is appropriate except when testing for recovery from flash flotation concentrates. Direct test work can then yield an accurate estimate of full-scale recovery, provided the plant unit is fed at a very conservative feed rate (Laplante and Dunne, 2002). When gravity recovery is the sole recovery method, its economic impact is increased at least tenfold, and the test program becomes similar in scope and magnitude to those used for other recovery circuits.

Continuous Units: Continuous centrifuge units are typically add-ons to existing circuits. Further, unlike semi-batch centrifuges, the number of units actually used in commercial applications is low and these units are still perceived as being largely developmental. Existing applications reflect this perception, as the units are typically retrofits shoehorned into existing circuits. Typically, test work consists of a limited program of exploratory test work using a “bench-scale” continuous unit followed by a trial period with a rental unit. Table 3 shows examples of which units are typically used at bench/continuous and piloting/demonstration scale.

Table 3 Examples of Continuous Centrifuge Retrofits

Unit/Manufacturer	Preliminary Work	Examples of Demonstration/Piloting
Geologics’ Kelsey Jig	J200	With J1800 at Labrador City for Iron of Canada (hematite), Granny Smith for Placer Dome Pacific (gold and gold carriers)
Falcon’s C (continuous) series	C400Falcon Concentrator	With C4000 at New Celebration
Mozley’s MeGaSep	MGS	MGS C902 or MeGaSep
Knelson CVD	CDV6 (6’’)	CVD32 (32’’) Luzenac’s Penhorwood

The objective of the preliminary test work is essentially to generate results that warrant the demonstration/piloting test work on site with rental units. The test work on site is often performed with full-scale or near full-scale units, and consists generally of identifying optimum operating conditions and performance, assess the mechanical reliability and ease of operation of the unit, determine the effect of feed variability (grade, mineralogy) and generate concentrate for further test work. Typically, a two-month program is needed, although in some cases more than 6 months of test work have been necessary.

Data Development and Expectations

Semi-batch Centrifuges. When a bench-scale centrifuge unit is used to generate a feed for downstream processing, simple metallurgical balancing (i.e. how much gold reports to the final gravity concentrate) is adequate. Often the final gravity concentrate will be fully fire-assayed. The cleaner gravity tailing may or may not be sampled for its gold content prior to recombining with the rougher tailing product. Emphasis is placed, as it should, on downstream metallurgical performance. Processing a sample to characterize its gravity recoverable gold content is clearly different: the size distribution of gravity recoverable gold must be characterized, as well as the grind at which it is liberated.

The McGill GRG test is a release analysis that uses a laboratory centrifuge, a Knelson Concentrator MD3 (Woodcock and Laplante, 1993; Laplante et al, 2001). Well over 100 samples have thus been characterized, many from ore bodies being processed in part by gravity recovery. The test methodology, illustrated in Figure 2, is as follows. A representative sample of 40 to 100 kg is crushed to 100% minus 850 μm for a first recovery attempt. A first concentrate of about 100 g is produced and screened from 600 μm down to 20 μm . The five coarsest size classes are further upgraded with a hydrosizer and examined with an optical microscope. The tailing is split and a 27-kg sample is ground to 50-55% minus 75 μm for a second recovery with the same centrifuge, but at a lower fluidization flow and feed rate to recover finer GRG more effectively. The tailing is processed at a final grind of 80% minus 75 μm . Except for small masses kept for mineralogical examination, the concentrates of all three stages are screened from 20 μm to top size, and the fractions are assayed to extinction. A 600-g sample of each of the three tailings is screened from 20 μm to top size for fire assaying (up to 30 g or one assay ton per fraction).

Because of the redundancy of the three stages and the fractional assays, the test is remarkably resilient to typical assaying problems (e.g. broken crucibles and cupolas). Trends in concentrate and tailing assays can be used to replace failed assays and gain insight into the behavior of both GRG and non-GRG. The high initial weight for all stages minimize the problems associated with statistical representativity and the recovery of gold in gold carriers (as sulphide recovery is typically only 3 to 5%). The microscopic examination of the coarser fractions of stage 1 provides valuable insight into GRG associations and potential liberation problems.

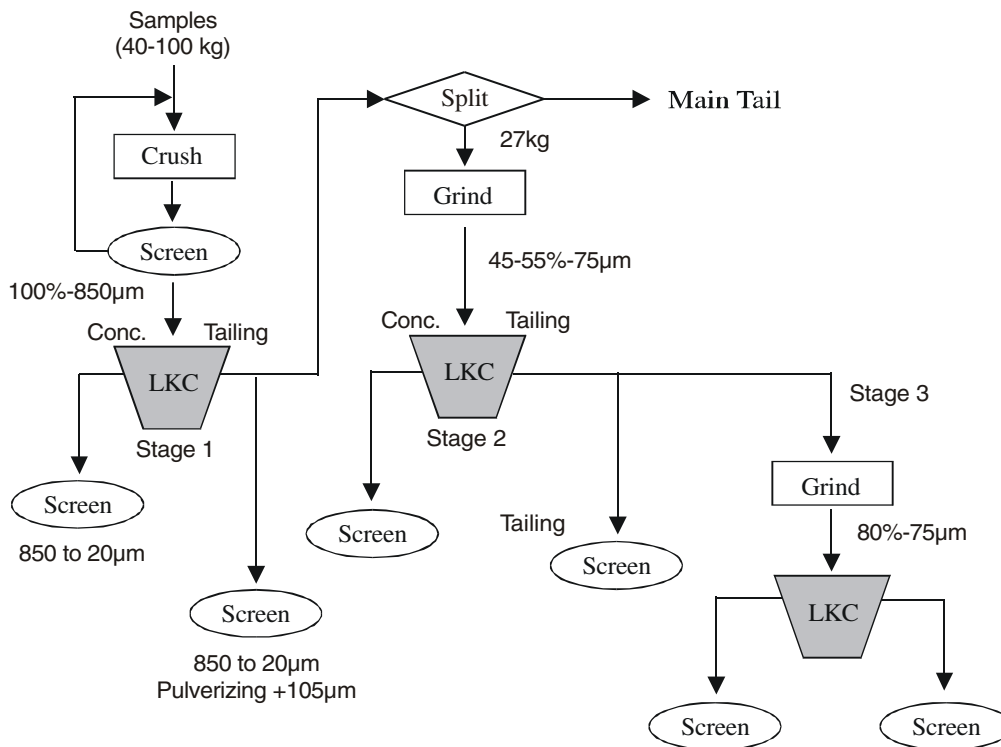


Figure 2 Procedure for Measuring GRG Content with a Knelson Concentrator MD3 (from Xiao, 2001)

The most informative way of reporting data is a graphical representation of the cumulative retained GRG content. Figure 3 shows three typical responses. The “High-Coarse” curve represents a highly responsive ore that can generate high gravity recoveries (more than 50%), and can be processed equally well with centrifuge and non-centrifuge units. The average response is typical of free-milling ores where gravity recoveries of 30 to 45% can be achieved. The “Low Fine” curve represents unresponsive ores where gravity recovery would be seldom used, but flash flotation can assist both GRG and base metal recovery. The flash flotation concentrate would then have a high GRG content, which can be recovered in part with semi-batch centrifuge units (Putz et al, 1993; Laplante and Dunne, 2002).

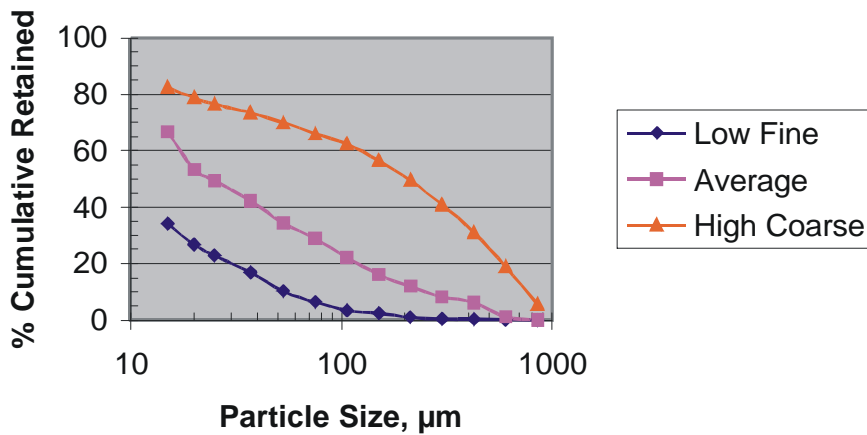


Figure 3 Typical responses of the GRG Test

When generating the response of the GRG test or any other tests performed at bench-scale to design and predict the performance of a gravity circuit, it is critical to generate size-by-size information, as full-scale units cannot recover fine heavies as effectively as bench-scale units do. Bench-scale performance must therefore be de-rated when the amount of fine GRG recovered is high (Laplante, 2002).

Continuous Units. Typically, promising results at bench-scale with any of the four units discussed here will lead to a pilot or demonstration program at mine site. Thus, the emphasis on data reliability and completeness is shifted to this second phase of the work. The typical precautions associated with piloting apply:

The program should be of adequate duration to optimize unit operation, cover normal variations in ore type, and assess unit mechanical reliability and ease of operation. Data generated should mass-balanced using a least-square algorithm to assess and improve reliability.

Enough samples of the feed, concentrate and tailing streams should be extracted for further studies, in particular size-by-size performance and cleaning/scavenging at bench-scale

Projecting Data to Commercial Application, and Limitation Thereof

Semi-batch Centrifuges. When gold is recovered by gravity from a grinding circuit, typically a portion of the circulating (as low as 5%) is screened and fed to the centrifuge unit, which may recover as little as 10% of the GRG in its feed. Reasonable recoveries are achieved only because of the high GRG circulating loads that arise from its slow grinding kinetics and high recovery to cyclone underflows. Consequently, the projection of bench-scale data to the recovery of a semi-batch centrifuge operating in a grinding circuit must take into consideration not only the GRG content, but also the dynamic interaction between grinding, classification and recovery units. Population balance modeling (PBM) has been used with some success in the past (Laplante et al, 1995). Recently, a simple regression equation has been developed to predict how much GRG can be recovered as a function of its size distribution, the recovery effort, and two parameters representing grinding and classification behavior, respectively (Laplante and Xiao, 2001). The

effect of classification is extremely important, because GRG finer than 106 μm is unlikely to be ground into finer particles that are not gravity recoverable on account of its very slow grinding kinetics (Banisi et al, 1990). It thus, either exits the grinding circuit via the cyclone overflow or is recovered by gravity. The probability of reporting to the cyclone overflow and thus not be recovered by gravity is the mirror image of the GRG partition curve. Figure 4 shows that this probability is highly dependent on grind size, and is either much lower than or comparable to typical GRG recoveries at fine size for semi-batch centrifuge units (from 10 to 30%). Generally, full-scale recovery will be as low as 20% of the GRG content of the ore for difficult applications or poorly designed circuits, to more than 80% of the GRG content for very efficient circuits. Circuits fail to perform as predicted for reasons outlined in Table 4. Note that if some problems can be corrected, there is no correction for unrealistic expectations. Factors affecting gravity circuit performance are discussed in more detail in Laplante (2000b). The advent of commercial intensive cyanidation units to treat centrifuge unit concentrates (Gray and Katsikaros, 1999; Lethlean and Smith, 2000) is seen as very positive, as these units achieve GRG recoveries in excess of 97%, as opposed to the conventional tabling approach which can achieve GRG recoveries as low as 40 to 50%. Not only can overall gravity recovery be significantly improved, but also the uncertainty of gold room performance is eliminated.

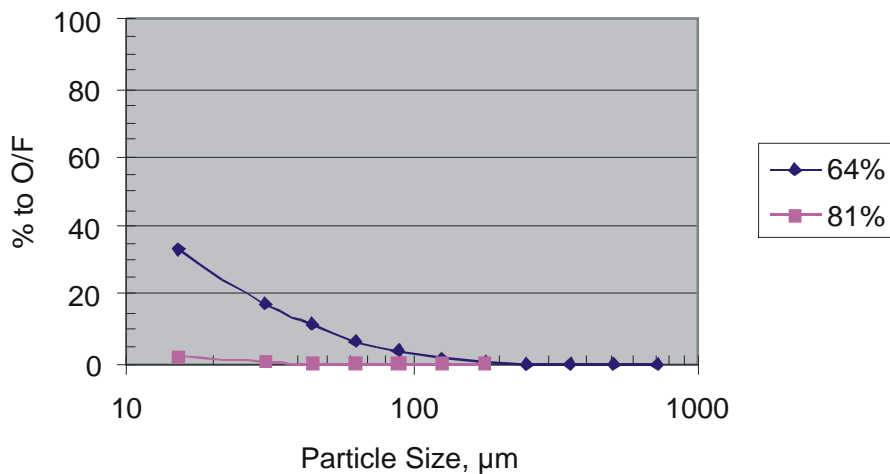


Figure 4 Proportion of the GRG Reporting to Cyclone Overflow for Coarse (64% minus 75 mm) and Fine (81% minus 75 mm) Classification

Table 4 Common Causes of Poor Performance for Gold Gravity Circuit

Problem	Solution
The GRG content is based on a non-representative sample	Follow an accepted sampling protocol; do not selectively choose a high-grade sample for testwork
It is assumed that all the GRG content will be recovered	Generally, between one third and two-thirds of the GRG is recovered. GRG recovery can be estimated from gravity circuit design and grind size
The wrong stream is bled for gravity recovery	Always choose primary cyclone underflow or the corresponding ball mill discharge
Too little of the circulating load is bled to the primary recovery circuit, or the primary recovery unit fails to perform because its feed is too coarse or too dense (i.e. massive sulphides)	Design screening ahead of primary recovery carefully. Use horizontal vibrating screen of adequate surface area
The primary gravity concentrate is processed in a poorly designed gold room	Using intensive cyanidation whenever possible. If not, apply the guide-lines of Laplante (1999)
Classification is too coarse and fails to keep GRG below 106 μm in the grinding circuit	Problem can be alleviated by increasing the recovery effort.
Flash flotation used in the same grinding circuit decreases gravity recovery	Recover GRG from the flash flotation concentrate using a semi-batch centrifuge (Laplante and Dunn, 2002)

Continuous Units. Because continuous units are relatively unproven, they are likely to be extensively tested before a final decision is made to proceed. The final test program is likely to be performed with either the full-scale unit or one only slightly smaller. As a result, data projection to the commercial application is less likely to prove disappointing. The major risks pertain to mechanical issues; a recent application of a continuous centrifuge unit was recently discontinued, despite a significant initial investment, because of wear and maintenance costs.

Examples of Successful Testwork, Design, and Commercialization

Semi-batch centrifuges. There are many examples of applications of semi-batch centrifuge units (Laplante et al, 1989; Darnton et al, 1993; Putz et al, 1993; Gregory et al, 1996; Hewitt, 1996; Folinsbee and Hewitt, 1997; Ritson and Tyreman, 2001; Choquenaira Bombilla and Muñoz, 2002). A number of these replaced other units with one or many semi-batch centrifuges, with little or no test work, and reported increases in gravity recoveries. In other cases, a semi-batch centrifuge gravity circuit was shoehorned into existing grinding. In virtually all cases, significant gold recoveries are achieved. Figure 5 (Laplante and Xiao, 2001) shows that GRG recovery is proportional to the **logarithm** of the recovery effort (i.e. the proportion of the GRG circulating load recovered into bullion). It follows that even when half the planned recovery effort is achieved, around 12% GRG recovery is lost. For typical free milling ores, whose GRG content is about two-thirds of the total gold content, this corresponds to a relatively small drop of 8% in gravity recovery. This explains why few gold gravity circuits are deemed to perform poorly. The logarithm relationship does, however, limit the upside potential of improved gravity recovery: increasing the recovery effort follows a law of very rapidly diminishing returns.

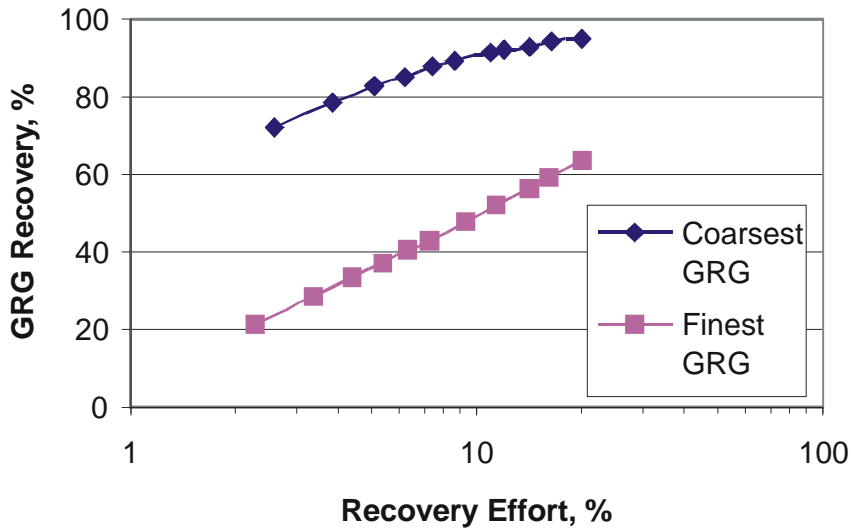


Figure 5 GRG Recovery as a Function of the Gravity Recovery Effort (Laplante and Xiao, 2001)

The challenge of gravity circuit design for gold, then, is to estimate the economic potential of gravity recovery and adjust the recovery effort (i.e. the capital and operating costs of the gravity circuit) accordingly. The best approach to gravity circuit design is to obtain an estimate of gravity recoverable gold content with the GRG test or other methods. The economic potential of gravity recovery is then estimated. A limited number of circuit options are then costed and their projected gravity recovery and economic impact estimated. Classical economic analysis criteria (i.e. NPV, IRR) are then used to select the best option. The procedure is illustrated in Laplante (2002).

Continuous Centrifuges. A limited number of successful applications of continuous centrifuge units have been reported (Laplante, 2000). The actual number of successful applications and units on order is much higher, but this information is generally not published or difficult to confirm independently.

The most successful application of the Falcon continuous concentrator is at Tanco, Manitoba (Deveau, 2000), for the scavenging of tantalum-bearing minerals. The gravity tailing is treated in a two-stage circuit, the concentrate of a Falcon C20 unit (now C2000) being treated by a Falcon C10 (now C1000) unit. This paper suggests that for relatively new units operating at high Gs, a close relationship between the supplier and client to address wear problems and creativity on the part of the user are essential for successful applications. A second application at Kettle River gold mine sees a Falcon C4000 upgrade a cyanidation feed (cyclone overflow) into a 7% yield (with a gold recovery of 16-18%). The concentrate is directed to the first tank of the cyanidation train, which has a very high retention time and high cyanide additions. The tailing is combined with the discharge of the first cyanidation tank. The metallurgical benefit of the application is difficult to measure on account of the variability of the ore, but it is estimated at 0 to 5%, with an average of 1.5%. The unit has also been extensively tested for coal cleaning (Luttrel et al, 1995)

The Renison application of the Kelsey jig is well documented (Beniuk et al, 1994), and is only one of the many applications for tin (cassiterite) recovery (e.g. Wyslouzil, 1990). The unit is also used for the recovery of tantalum minerals at Greenbushes (Western Australia), and the separation of zircon from kyanite in beach sand operations. Recent test work on iron ore has yielded promising results, and a circuit is being commissioned in the early 2002 in Western Australia for the scavenging of gold and gold carriers from a cyanidation tailing. The iron ore and gold applications represent a bold move to the recovery of relatively low value materials (for gold because of the

low gold content of the feed treated, about 0.3 to 0.5 g/t). If these prove successful, the number of Kelsey jig users could increase significantly.

The Knelson CVD and Mozley's MeGaSep are relatively new comers in centrifuge separation. To date, the only commercial application of the CVD is a talc cleaning duty in Eastern Canada. The MeGaSep precursor, the MGS C902, has been used extensively in tin before, but its low capacity, typically 2 to 5 t/h, was clearly a deterrent. Other, non-publicized, applications include the sporadic cleaning of flue dust at the Horne Smelter in Noranda, Québec. The MeGaSep is claimed to achieve capacities of 30 to 60 t/h, which would make it viable for a much larger number of applications than its predecessor.

The web sites of most suppliers has been significantly improved in the past tow years. For potential users, this is a welcome development. Independent parties have produced much of the data that can be downloaded from these sites. The address of relevant web sites is given in appendix.

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Kelsey Jigs (Roche Mining)	http://www.geologics.com.au/
Knelson Concentrators	http://www.knelson.com.ca.org/
MGS and MeGaSep	http://www.mozley.co.uk/mg.htm
Spirals/Shaking Tables/Density Separators	http://www.outokumpu.com/mintec/physicalseparation.htm
Cones/Spirals/Shaking Tables	http://www.mdmintec.com.au