A COMPARATIVE STUDY OF TWO CENTRIFUGAL CONCENTRATORS

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ABSTRACT

In this paper, the performance of the Knelson Concentrator and of the batch and continuous Falcon Concentrators are compared. The units are based on different operating principles, and as such they perform quite differently. The Knelson yields very high free gold recoveries over a wide size range of both the recovered and rejected species. It is ineffective in recovering very fine (<15 μm) or flaky gold, as encountered in flotation feeds, concentrates or tails. It is the preferred unit for gold recovery from grinding circuits. The batch Falcon is effective in the fine range, typically less than 37 μm for gold. Its recovery zone is quickly saturated when there is significant heavies in the feed. It works best as a pre-concentration unit. The continuous Falcon is a versatile unit which is capable of recovering fine heavies (density down to 5 g/cm^3), especially from coarser gangue.

INTRODUCTION

The purpose of this presentation is to describe the mode of operation of two Canadian centrifugal concentrators, the Knelson and Falcon. It is hoped that it will prove informative to prospective users in the selection, testing and optimization for applications of either machine. The work is based on testwork both in Canadian mills and at McGill. I am indebted to many colleagues at these locations. Appropriate references will be made to articles further describing the work, either already in the open literature or in preparation.

Although this work is meant to be more practical than scholarly, it is appropriate to begin by considering how the two units achieve selective recovery. This will become useful in establishing a suitable testing methodology, which will then be described, and interpreting typical results . In the last section I will attempt to define appropriate applications for the two units. This is a thankless task, as I am likely to miss some applications or to make projections based on partial results, as much of the work is still in progress. In deference to the reader and both manufacturers, areas where reasonable doubt still remains will be identified.

MECHANISMS

Knelson Concentrator

The Knelson creates a fluidized bed against which particles are thrown and collide. Upon collision, particles are slowed down. They then accelerate, at first at a rate proportional to their density, and independent of their size or shape. This, for gold particles, is appreciably faster than sulphide or silicate particles. Despite the high centrifugal force (a theoretical 60 g), this phase is very short, generally less than one millisecond (Laplante, Shu and Marois, 1992), as the finer and flakier gold particles reach their terminal settling velocity more rapidly than the coarser gangue particles. Distances travelled are in the order of a few micrometers. Particles then collide again, and are slowed down. The differential initial acceleration process is repeated. As the differential settling distances are very short, the process must be reproduced many times to result in a sharp separation. It also implies that the process heavily depends on strong density differences, and this might limit the type of separations possible. However, it does mean that separations based on large density differences should be successful over large size distributions, although fine and flaky particles should, eventually, experience loss of recovery because of the earlier onset of terminal velocity.

When testing the Knelson, poor performance (5-25% recovery) was typically achieved when treating relatively fine feeds (typically 80% -75 μm) which had already reported to a cyclone overflow. These may be cyclone overflows per say, or products of a later stage, typically streams of flotation circuits (concentrates and tails). Gold can be rejected even though it is free and at a size which would normally make it easily recoverable by Knelson. Early testwork strongly suggests that much of the losses are liberated gold. It was at first thought that the fineness of the gangue was the cause of poor recovery. Testing with fine feeds (80% -75 μm) but gold from cyclone underflows (Laplante, Shu and Marois, 1992) yielded a gold recovery comparable to that of the original material (a cyclone underflow). The extreme flakiness of free gold particles reporting to cyclone overflows, and not the fineness of the feed, must therefore be the main cause of poor recovery. This is supported by photographic evidence (Figure 1).

The Knelson can be equipped with an automatic discharge system, in the CD units (Knelson Concentrators, 1992). This flushing action requires approximately two minutes, during which feed to the unit must be interrupted. Manipulation of the concentrate is minimized and the length of the loading cycle can be decreased, which may increase overall recovery[1]. A

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[1] This has not been the experience of the author, over limited test periods (>>), but has been reported by a least one operator, based on testing over a longer time period (McMullen, 1992).

Figure 1 Scanning Electron Microphotograph of a Kustelite Flake Not Recovered by Knelson (Kustelite is a 2:1 Ag:Au alloy)

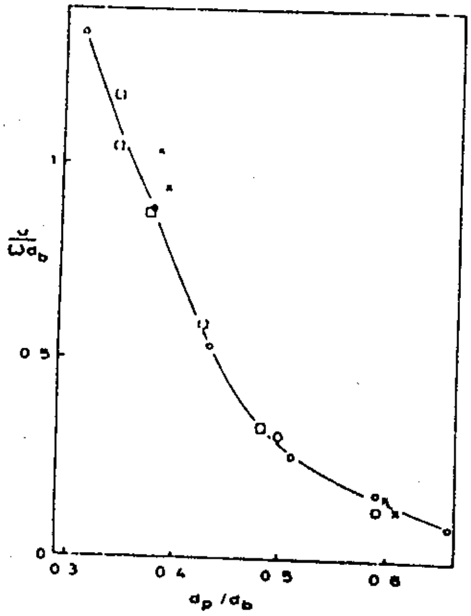

Figure 2 Dimensionless Percolation Velocity, $u/\omega d_b$, as a Function of Particle Diameter Ratio, d_p/d_b (p: percolating; b: bed)

continuous Knelson is being developed (Knelson, 1992), but no prototype was available for testing as of November 1992.

Falcon Concentrators

The recovery mechanisms of the Falcon concentrator are quite different from those of the Knelson. The Falcon is operated at higher rotation speeds than the Knelson, without fluidizing water. Operation of the batch unit is quite distinct from that of the continuous one. Upon starting and first feeding the Falcon, a bed of material quickly accumulates non-selectively (generally after a few seconds); once this bed is formed, selective recovery begins, and a second bed of denser particles progressively forms onto the first. When this second bed saturates, recovery stops, or drops dramatically. This is partly because capture sites are no longer available, and partly because segments of the bed are periodically eroded by the flowing slurry. This occurs in part progressively, and in part catastrophically, yielding erratic performance (Buonvino, 1992). A third stratum is generally visible above the concentrate (McAlister, 1992), made mostly of gangue particles that can readily be eroded away. Logically, this third stratum must be loosely held in place, to permit the growth of the underlying concentrate layer. In the continuous Falcon, a recovery slot circles the bowl; material is removed via the slot into 24 inner hoppers where slurry density is carefully maintained by periodic removal of concentrate using twin valves that are sequentially actuated.

TABLE 1 Percolation Characteristics of Cuboid Particles (Bridgewater, Cook and Drahun, 1985).

Material	Density (g/cm^3)	. Dimensions (in mm)	$u/\omega d_b$	$D_z/\omega d_b^2$	Pe_y
Acrylic Resin	1.19	8 x 8 x 4	0.87	0.042	2.4
Brass	8.37	8 x 4 x 4	1.43	0.084	1.3
Brass	8.37	8 x 8 x 2	2.18	0.140	1.6

The Falcon Concentrator is not unlike a wrapped around Reichert Cone (this is particularly striking for the continuous unit). Like the Reichert Cone, interstitial trickling is a critical recovery mechanism. It is made possible by the Bagnold force, which dilates the bed (Bagnold, 1954). Trickling then naturally takes place, as finer particles experience a higher probability of encountering an opening of suitable size for percolation. In other words, the dilated bed acts as a dynamic sieve, and finer particles more easily percolate through this bed. Figure 2 shows the dimensionless percolating velocity (absolute velocity = u) of particles of diameter d_p in a media of diameter d_b experiencing a shear ω, as a function of the ratio of particle size d_p/d_b (Bridgewater, Cook and Drahun, 1985). The percolation rate increases with decreasing percolating particle size. Table 1 shows some percolating velocities, dispersion coefficients and Peclet numbers for cuboid particles, from the same study. It is apparent that particle shape has a significant effect on both percolation velocity and dispersion coefficient. What is more surprising is that the effect of density is limited (increasing specific density from ≈1 to ≈8 results in only a twofold increase in percolation velocity.

The above results are not easily applied to separators such as the Falcon or the Reichert Cone. But they help understanding and interpreting observed behaviours. For example, Figures 3 and 4 give typical separation results for a Reichert tray (Nudo, 1985) and a Reichert cone (Miele and Kay, 1992). Increased recoveries are observed with decreasing particle size, up to about 40 μm for the first case and 75 μm for the second. Recoveries then begin to decrease again, as settling velocities become too low for particles to move into the voids available below. Bridgewater, Cook and Drahun (1985) suggest a limiting size for concentration of 25 μm, which is in good agreement with the acknowledged limitations of the Reichert Cone (Burt, 1984). It should be noted that even very dense particles above 300 μm can be difficult to recover, which can be serious drawback.

The Reichert cone, because it relies on the trickling of fine particles through a bed of coarser particles, is inherently incapable of producing very high concentrate grades (as the coarse light bed progressively disappears, so does the concentration mechanism!). For many applications, this is not a critical problem, and the usual solution is to direct the concentrate to a different unit more capable of achieving high concentration ratios (e.g. spirals or tables).

The Falcon concentrator, because of the large rotation velocities, lowers both the size of optimum and minimum recovery below 25 μm. This is both an advantage and a disadvantage. Consider Figures 5 and 6, which the performance of a Falcon B6 (batch, 6" rotor) and a C20 (continuous, 20" rotor). Performances are similar, although that of the batch unit can only be maintained over a few kilos of feed, and that of the continuous unit can be maintained for hours, probably days, at 15 t/h. The ability to recover a mineral of density equal to 5.2 from a gangue of density 2.7, especially below 50 μm, is clearly demonstrated. However, recovery above 100 μm is poor, not unlike the recovery of the Reichert tray/cone above 300 μm (particularly evident in Fig. 4). For the batch Falcon (Fig. 5) recovery increases with particle size above 300 μm (the same observation holds for the Reichert tray in Fig. 3).

TESTING METHODOLOGY

Knelson

Laboratory testing with a 7.5 cm Knelson is a simple and effective way to predict the performance of a full scale unit, typically a 76 cm unit. This is illustrated in Figure 7, which shows the tailing grade of 7.5 and 76 cm units (Putz, 1992). Each of the four feed samples corresponds to one hour of operation of a four hour cycle of the 76 cm Knelson used at Lucien Béliveau Mine to process a flash flotation concentrate (Gignac et al., 1990). The two tails are very closely correlated. Recovery progressively drops throughout this particular cycle, because of changes in feed characteristics. The tail grade is slightly lower for the lab unit, which yielded an average recovery of 49%, compared to 45% for the plant unit.

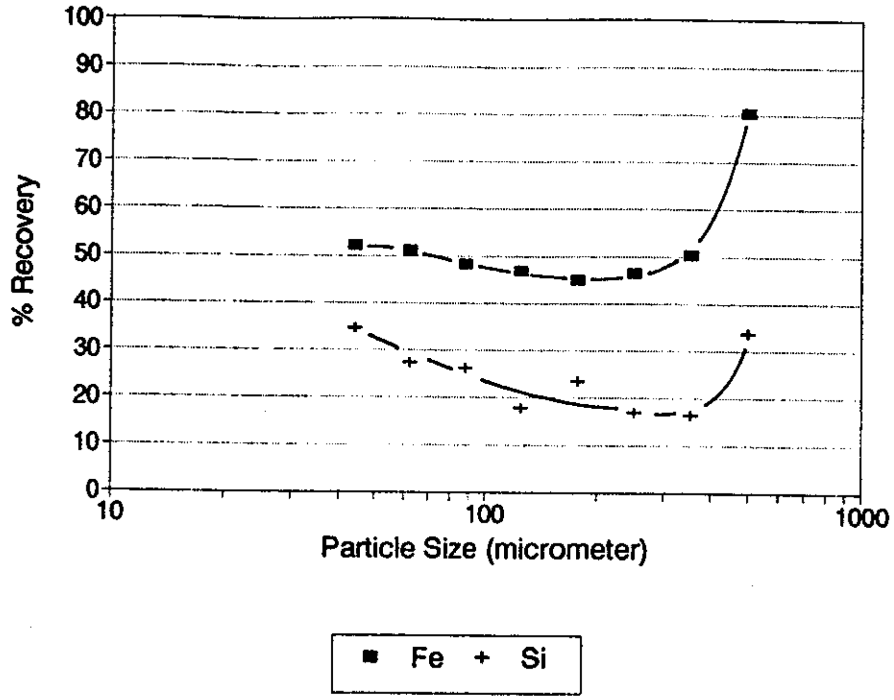

Figure 3 Recovery of Hematite (Fe) and Silica (Si) as a Function of Particle Size for a Reichert Tray (Feed: fine tails from Mines Québec Cartier)

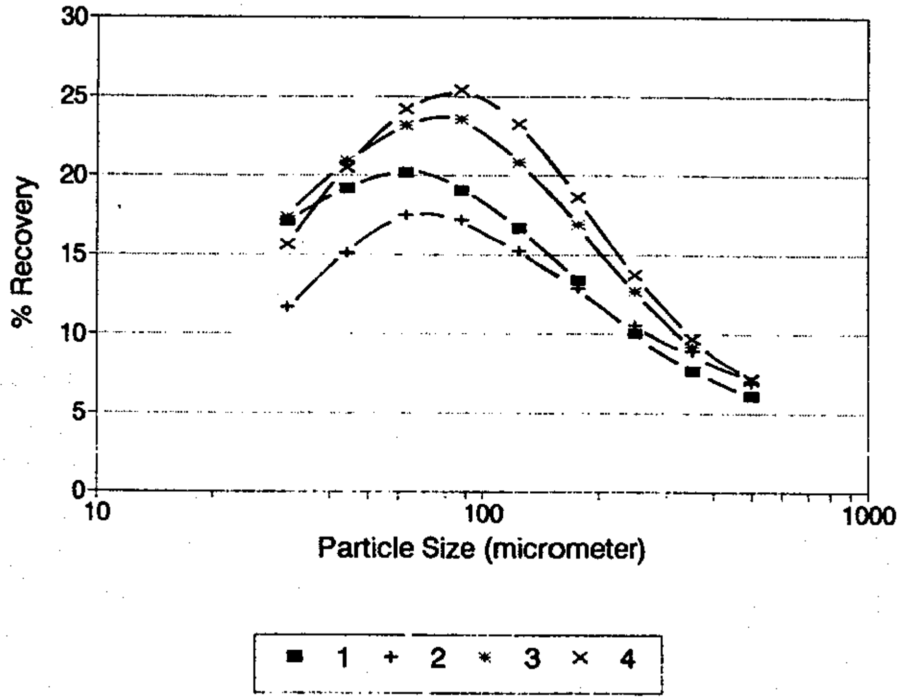

Figure 4 Yield Ratio (Yield/Overall Yield) for each DS stage as a Function of Particle Size (4DS Reichert Cone at East Kemptville Ltd.)

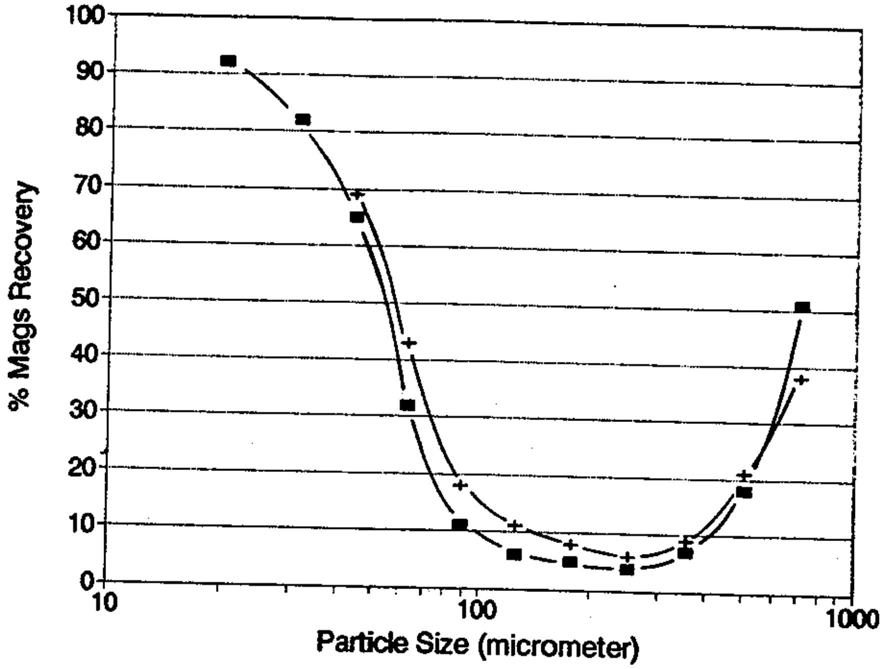

Figure 5 Fe Recovery vs. Particle Size for a Falcon B6 (feed: artificial magnetite/silica mixture, 5:95 ratio) from Buonvino (1992)

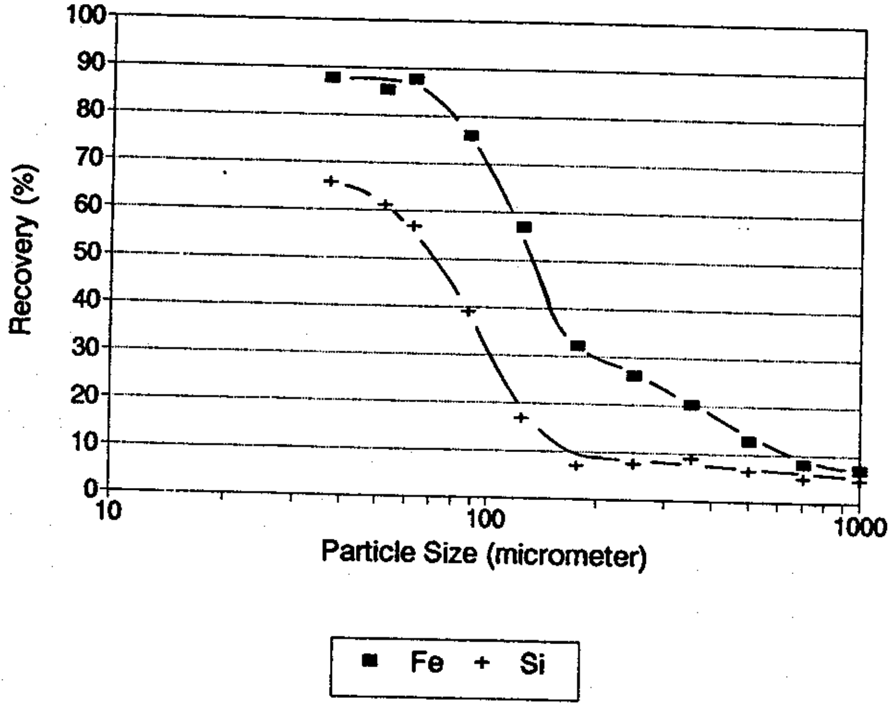

Figure 6 Fe Recovery vs. Particle Size for a Falcon C20 (feed: cobber tails at Iron Ore of Canada Ltd.)

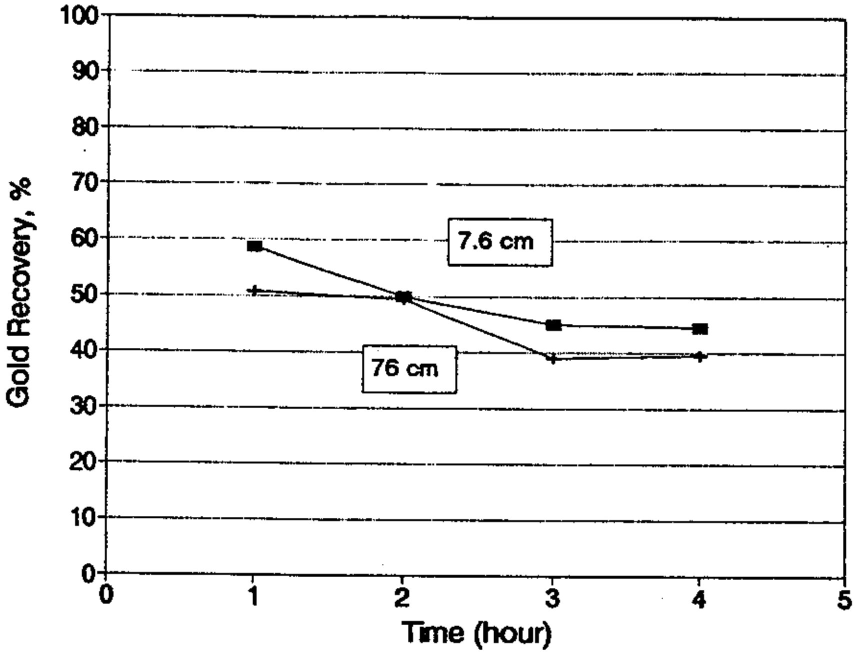

Figure 7 Au Recovery for 76 cm and 7.5 cm Knelsons (feed: flash cell concentrate, one hour samples of a four hour cycle; from Putz, 1992)

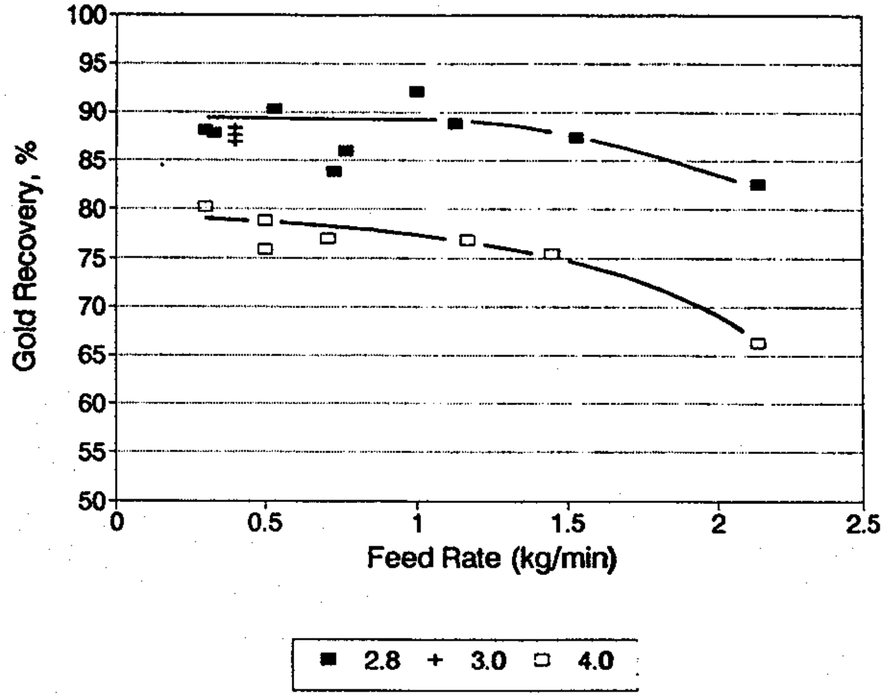

Figure 8 Au Recovery as a Function of Feed Rate for a 7.6 cm Knelson (from Laplante, Shu and Marois, 1992)

The data of Figure 7 was obtained at very low capacities for both the plant and laboratory units. One possible problem is how the two units may react differently to an increase in feed rate. Figure 8 shows how the lab unit responds to such increases, at two different feed solids density, 2.8 and 4.0 g/cm^3 (Laplante, Shu and Marois, 1992). The loss of recovery is particularly apparent at high feed density and feed rate. No plant data are yet available for the full range of feed rate of the plant unit (0-40 t/h), which is a source of uncertainty.

The major source of uncertainty in predicting the recovery of a Knelson-based gravity circuit stems from its location in the circulating load. The preferential accumulation of free gold over the size range where Knelson recovery is very effective means that gold recoveries from streams such as cyclone underflows or ball mill discharges will be high, typically 50 to 90% (Banisi, Laplante and Marois, 1991). However, once a Knelson is installed and gold is progressively recovered, gold's circulating load will dramatically decrease and the feed to the Knelson will become markedly different (less responsive to gravity recovery). A second problem stems from the limited capacity of the Knelson, which means that typically only a small fraction of the circulating load will be processed. Part of the unprocessed feed may be recycled back for another opportunity for treatment, but it may also undergo grinding (in which case it is likely that some of the progeny will be recoverable by gravity, and some not) or report to the cyclone overflow. These two problems abundantly illustrate that predicting gold recovery is not a trivial task.

Falcon

Testwork with the Falcon should be conceptually simpler, as the unit is best designed to treat non-recycle streams such as cyclone overflows or flotation concentrates (because it recovers best fine particles from relatively fine feeds). If a sample of such streams is available, testwork can readily proceed. The Falcon is also designed to process full streams rather than bleeds, which is potentially another simplification. Caution should be exercised when preparing a material with the size distribution of a cyclone overflow with laboratory mills: gold is not classified finer as in a hydrocyclone, and as a result its size distribution is much coarser, as shown in Table 2 (Wibisono, 1985), and quite conducive to recovery with a Knelson, but it would prove refractory to recovery with a Falcon.

TABLE 2 Comparative Size Distributions of Laboratory and Plant Flotation Feeds (lab: rod mill grind; plant: ball mills and cyclones) (Wibisono, 1985)

	Laboratory, % Passing		Plant, % Passing	
Species	75 μm	25 μm	75 μm	25 μm
Ore	60	30	55	30
Gold	10	37	58	21

However, testwork with the Falcon has its own scale-up problems. First, the lab unit is batch, and its behaviour changes markedly with time (Laplante et al, 1993). For the B6, efficiency drops sharply after about 20 kg of feed has been processed, in the presence of a dense phase of significant grade. To alleviate this problem, Falcon Concentrators, when testing material, has often taken the approach of reprocessing a feed up to five times to insure good recoveries. This procedure is probably warranted when attempting to simulate the performance of the continuous unit, which does not experience bed overload. However, as there are little data available on the performance of the continuous unit, this procedure still remains to be validated.

Predicting the performance of a full scale Falcon (i.e. B30) from that of a lab unit (B6) is also a procedure that has yet to be validated. However, the scale-up ratio is less than that of a Knelson (a diameter ratio of 5 rather than 12 for the Knelson), which should make scale-up easier. As with the Knelson, little or no scale-up data are in the open literature yet.

A major drawback of using the batch unit is the accumulation of up to 80% of the concentrate in a non selective way at the beginning of each test. This is particularly troublesome when trying to predict the performance of a cleaning stage, or when trying to achieve very pure concentrates. For gold, it implies processing huge amounts of material in a rougher stage to generate enough feed for a cleaner stage. Even then, upgrading may prove difficult; this will be demonstrated later.

CASE STUDIES

Reprocessing Table Tails

TABLE 3 Gold Recovery from the Knelson (7.5 cm) and Falcon (B6) Concentrators (Feed: Table Tails from Lucien Béliveau Mine)

Comparative Metallurgy		
Unit	7.6 cm Knelson	Falcon B6
Concentrate Grade, g/t	7183	4153
Recovery, %	81.6	33.4
Yield, %	2.1	2.6
Main Tail Grade, g/t	32	688
Second Tail Grade, g/t	-	636
Third Tail Grade, g/t	-	852

A successful application of the Falcon to treat table tails has been reported (Muir, 1989). Table tails are also very suitable Knelson feeds. Hence, this should be a good application to compare the Knelson and Falcon. Table tails from Lucien Béliveau Mines (Gignac et al., 1982) were processed with both the Falcon B6 and the 7.6 cm Knelson (Huang and Laplante, 1992). Results are summarized in Table 3 and Figure 9. The Knelson recovers 82% of the gold at a grade of 7200 g/t, both better than the Falcon, despite the fact that a three stage test was used for the latter (rougher/cleaner/recleaner). Figure 9 shows that the Knelson outperforms the Falcon in all size classes except the finest, which is exactly what would be expected from the concentration mechanisms described above: the Falcon is essentially a fines recovery unit, whereas the Knelson is more versatile. The table tail at Lucien Béliveau is relatively fine, because the gravity circuit feed is a flash cell concentrate. Similar work is being performed on another, much coarser table tail. Because the performance of the Falcon deteriorates as the feed coarsens (Laplante et al, 1993), the performance gap is expected to widen for this second application.

The above results strongly suggest that a shaking table is not the best unit to treat a Knelson concentrate, because it fails to recover fine gold effectively. The use of collector bearing water might exacerbate the problem (Johnston, 1992). Alternatives are being investigated at McGill. One obvious choice is the Knelson itself. Preliminary work indicates that concentrate grades of at least 10-14% gold can be achieved at very high recoveries, above 95% (Liu, 1989; Putz, 1992).

In Table 3, the effect of two cleaning stages (for the Falcon test) is shown. Material is rejected at a lower grade than the rougher tail, yielding very high stage recoveries. However, not enough material is rejected to increase the grade of the recleaner concentrate to that of the Knelson. Such cleaning problems are typical of Falcon testwork, because the B6 yields typically 500 to 1000 g of concentrates (compared to the 100 g of the 7.6 cm Knelson). They could probably be alleviated by processing much larger quantities of rougher feed, but this is impossible or impractical for many applications.

Scavenging Gold from a Flotation Tail

This is a rather unusual application, where very fine gold-bearing pyrite and gold particles are to be recovered from the fine fraction of a flotation tail (the coarse fraction is already cyanided; Laplante, Liu and Cauchon, 1989). Batch test work at McGill (Buonvino, 1992) yielded sulphur (as pyrite) and gold recoveries shown in Table 4. Although no microscopic work has been performed to reveal the nature of the recovered species, the stream itself is very fine, 98%+ -75 µm, and by virtue of the double cycloning used to separate to flotation tail, free pyrite (or middlings of gold of equivalent density) is below 37 µm. This is a situation where the Falcon should excel (recovery of very fine particles from a fine and low density feed), and it does. The Falcon concentrate is not particularly upgraded, but its high pulp density (if the continuous unit is used) and relatively low flow makes it an ideal feed for the existing cyanidation circuit. It should be noted that the Knelson was tested for this application, but could not produce acceptable recoveries. When testing the final flotation concentrate, a similar result was obtained: Falcon recovery was typically above 30%, whereas for the Knelson recovery was well below 10%. Both concentrates, however, would be difficult to upgrade, as the usual approach, tabling, is ineffective for such fine products.

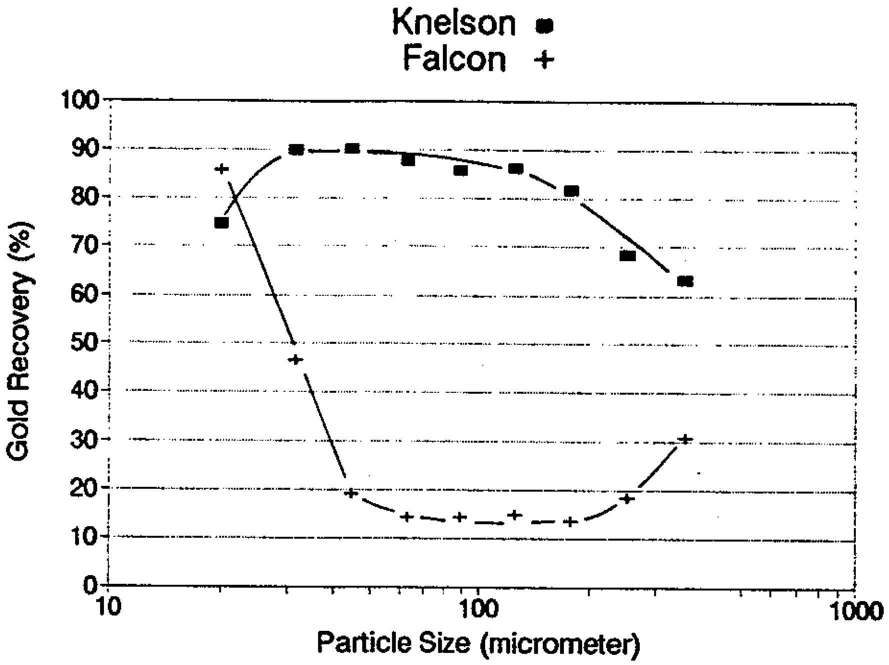

Figure 9 Gold Recovery as a Function of Particle Size for Knelson and Falcon Concentrators (feed: table tails from the Lucien Béliveau Mine)

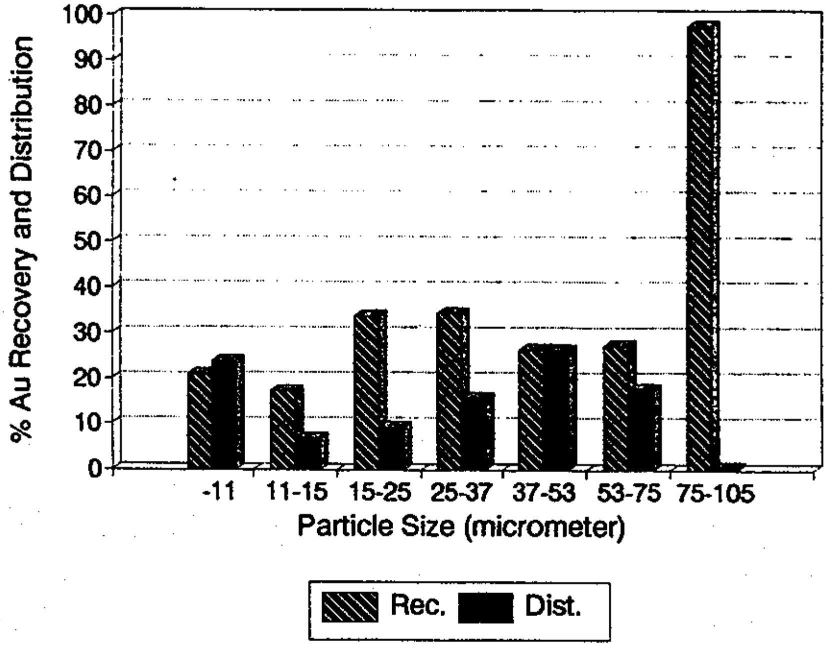

Figure 10 Gold Recovery and Distribution as a Function of Particle Size (Feed: Dumagami Flotation Concentrate; from Buonvino (1992))

TABLE 4 Gold and Sulphur (pyrite) Recovery, %, with a Falcon B6 (feed: fine flotation tail of Meston Resources; each point is the average of 3 tests at 10, 20 and 30% solids)

Feed Rate (L/min)	Sulphur (pyrite)		Gold	
	8° bowl	10° bowl	8° bowl	10° bowl
10	13	17	44	41
20	23	19	44	73

A similar application is the recovery of fine iron from the gravity (spirals) and magnetic separation tails of the iron ore producers of Northern Québec and Labrador. The Falcon C20, when tested on these ores, yielded good recoveries of fine iron, but at grades that fall short of the required 3 to 4 % SiO_2. Given the mode of operation of the Falcon (specifically the lack of water to expand the bed), fine silica is not effectively rejected, and failure to achieve the very stringent concentrate grade specifications in a single pass is not surprising. Applications where the continuous Falcon could be used as a pre-concentration device for very fine heavy phases are being investigated at McGill.

Recovering Gold from Various Streams of a Gold-Copper Ore: To assess the potential of gravity recovery at the Agnico-Eagle La Ronde Division, various streams were tested both with the 7.5 cm Knelson and a B6 Falcon (Buonvino, 1992). Testing with the Falcon established that the system would overload after about 20 kg of feed (Laplante et al., 1993). As a result, only 20 kg of feed were used.

TABLE 5 Comparing Gold Recovery, R, and Upgrading Ratio, U, for the 7.6 cm Knelson and B6 Falcon (all feeds from Agnico-Eagle La Ronde Division)

Stream	Falcon		Knelson	
	R, %	U	R, %	U
Primary Cyc. O/F	12	4.6	7 (?[1])	2.2
Second. Cyc. O/F	15	8.0	20	5.2
Regrind Mill Disch.	17	7.3	71	34
Flotation Conc.	22	5.5	-	-
Ball Mill Disch.	2	1.0	40	38

(1: dubious datum, probably an underestimate, as the calculated head is too high)

Table 5 summarizes results. The Knelson is seen as vastly superior for all streams within the grinding circuit. The Falcon performs poorly, with extremely low upgrading ratios and

TABLE 6 Advantages and Disadvantages of the Falcon and Knelson

Unit	Batch Knelson	Batch Falcon	Continuous Falcon
Cost	Moderate	High	Very High
Scale-up from lab data	Easy	Difficult	Needs Pilot Testing
Overload from heavies	No problem With Precious Metals	Overload in the presence of heavies	Does not overload
Plant Experience	Extensive	Some	Two prototypes Tested
Water Consumption	Can be a problem for some applications	None, Except for Concentrate Discharge	None, Can yield a Very Dense Concentrate
Automatic Discharge	Available	Available	Essential
Ability to recover gold	Excellent down to about 15 µm on non-flakes	Very good up to 37 µm	Probably like the batch unit
Ability to recover dense minerals (ρ=5-7)	Not known	Good but overloads easily	Very good below 75 µm
Ability to upgrade	Excellent with gold	Generally Poor	Very good, especially for pre-concentrations

recoveries. Size-by-size data (Buonvino, 1992) diagnoses the problem: whilst the Falcon is essentially a fine gold recovery unit, most gold in recycled streams is coarser (whereas the Knelson's recovery range coincides with that of gold in most recycled streams). Figure 10 shows that for the flotation concentrate the problem persists, albeit not as severely: although recovery is highest for the 15-37 and 75-105 μm classes, gold is most abundant in the -11 and 37-75 μm.

SELECTING THE APPROPRIATE UNIT

Before looking at specific applications, it is worth reviewing the pros and cons of each machines. For the Falcon, the batch and continuous machines are evaluated separately. As no continuous Knelson working prototype was available at the time of write-up, it was not evaluated. Table 6 presents a preliminary evaluation. What is clear is that on most gold applications, the Knelson is vastly superior (this would also be true of platinum applications, although there is no information available in the open literature). However, the continuous Falcon, still under development, shows significant potential for applications other than gold. The batch Falcon fares poorly, except for the recovery of very fine gold in a fine feed in the absence of large quantities of heavies (such as sulphides).

TABLE 7 Applications of the Knelson and Falcon

Unit	Applications
Knelson	Gold and platinum recovery within grinding circuits and for placers Excellent tool to measure free gold content (lab unit)
Batch Falcon	Gold Recovery (roughing) for limited applications Lab unit to predict the performance of the plant unit
Continuous Falcon	Gravity separations in the fine range (including gold) Densifying

Should gold be recovered from a recycled stream or from the final product of a grinding circuit? The former favours the Knelson, whereas the latter does the Falcon. The answer is case specific, but in most applications recovering gold as early as possible is the correct choice, to minimize smearing or accumulation within the grinding circuit. A third, important, consideration is that the rougher gravity concentrate, 0.5-5% Au, should be easily upgradable to smeltable grade, around 50% Au. This is extremely difficult to achieve with fine gold recovered from cyclone overflows, especially on a shaking table. When gold is recovered from a recycled stream, it is readily achieved.

Table 7 lists potential applications. For cases of gold recovery, the Knelson is the suggested route when recovery can be effected within the grinding circuit. The batch Falcon is best used as a lab unit or when a Knelson, because of water balance problems, cannot be used. Of the three, the continuous Falcon is by far the most versatile unit, although test work is still fragmentary. It is seen as a good scavenger of fine heavies from most streams, with the added benefit of yielding, if needed, a very dense concentrate. Its most serious drawback at the present time is the lack of a successful application that would serve as a "flagship" for the technology. Hopefully, this will come soon.

CONCLUSIONS

It is difficult to render a verdict on technology that has just recently emerged, and that is still evolving. Nevertheless, the author believes that the mineral processing community is best served when information is made public as soon as available.

Comparing two units, one of which is already well proven, and the other still trying to establish a presence, is also a difficult task. Difficult because much more is known about the first, and because traditional scholarly caution prevents asserting much about the second. The author has temporarily shed his academic 'cloak' to present and discuss the Falcon. Before putting it back on, the potential of the continuous Falcon for gravity recovery should be emphasized. It is hoped that Canadian mineral processors will be supportive of the effort.

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