Knelson Continuous Variable Discharge Concentrator: Analysis of Operating Variables

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ABSTRACT

The Knelson Continuous Variable Discharge (CVD) is a continuous centrifugal gravity concentrator for high-mass yield recovery applications. It has four operating variables that enable control of mass yield, product grade and recovery namely: fluidisation water, bowl speed, pinch valve open time and pinch valve closed time.

Plant testing of a pilot scale Knelson CVD6 was conducted to evaluate the effects of operating variables on mineral separation. The analysis of operating variable effects has provided a framework for the development of operating guidelines for the CVD.

INTRODUCTION

The evolution of gravity concentration from batch to continuous centrifugal machines has extended performance to higher recoveries and higher upgrade ratios at finer particle sizes. Semi-continuous units, such as the Batch Knelson and Falcon SB, have been widely accepted for recovery of free gold within grinding circuits. Fully continuous machines (Kelsey Jig, Falcon C, Knelson CVD) that can recover mass yields as high as 50 per cent have yet to find their niche. Extending the particle size limits of spirals, improved metallurgical performance over non-sulphide mineral flotation and pre-concentration are incentives to develop these devices further. Issues that need to be addressed are mechanical reliability, water use, and separation performance (Burt, 1999; Brewis, 1995; Clifford, 1999; Holland–Blatt, 1998).

The selection of appropriate operating variable levels for ores with varying particle sizes, mineral compositions and pulp densities represents a significant challenge.

In the Falcon C, feed enters through the top and travels down to the bottom of a rotating bowl where centrifugal acceleration forces particles to the wall. The particles travel up the bowl section where heavy particles displace light particles along the bowl wall. At the top of the bowl is a concentrate collection ring with valves positioned radially at the back of the ring. The valve aperture size is controllable and remains open. The tailing material forms the innermost layer on the bowl wall and overflows the bowl to a tailings launder (Falcon, 1999; Silva, Santos and Torres, 1998). The Falcon Model C is the simplest machine as it has only two operating variables; bowl speed and valve aperture size. No additional water is required to operate the machine.

In the Kelsey Jig, particles are fed into the top and enter the vertical jig bed. The water pulsation cycles in the hutch, behind the bed, facilitates particle separation. The centrifugal acceleration imparted on the heavy particles causes them to travel radially outward through ragging and into a hutch. Low density particles travel upwards across the bed and overflow to a launder. The three controllable variables in the Kelsey Jig are bowl speed, ragging size/density and pulsation stroke length (Geologics, 1999; Silva, Santos, Torres, 1998; Wyslouzil, 1990).

In the Knelson CVD, feed is introduced to the top of the machine through a feed tube into the centre of the bowl section. The feed hits a plate at the bottom of the bowl section and is dispersed radially to the bowl wall. The particles are accelerated to a g-force defined by the bowl speed and travel up the wall towards the ring. The partially upgraded slurry enters the separation ring where fluidisation water, supplied through holes in the ring wall, is added to fluidise the bed of packed particles. Concentrate is extracted through pinch valves at the back of the ring. The pinch valve timing (open/closed) can be adjusted. Light particles overflow the bowl into a tailings launder (Knelson, 2001).

The Knelson CVD has four main operating variables: bowl speed, fluidisation water flow rate, pinch valve open time and closed time. These variables also all interact, meaning, for example, that the best bowl speed at one set of pinch valve open/closed times may not be the best at another set of times. Therefore, the appropriate selection of variable levels is a complicated problem that requires a systematic approach.

This paper demonstrates the effects of operating variables on separation performance. The data was obtained from laboratory and plant testing of a pilot scale Knelson CVD6. By comparing the rates of change of grade and recovery with incremental changes in the operating variables, a set of basic guidelines for developing a control strategy is proposed.

EXPERIMENTAL PROGRAM

Two pilot scale test programs were conducted: one program was conducted at UBC using synthetic mixtures of magnetite and quartz, and a second program was conducted at an operating copper-zinc mine using the zinc cleaner tailings stream as feed. Both test programs were conducted using a pilot scale Knelson CVD6 concentrator.

At UBC, the pilot scale testing facility consists of an agitated feed tank, a slurry feed pump for the CVD6 concentrator and a Sala pump that pumps the combined products (concentrate and tailings) to a storage tank. At the end of a test the combined products can be drained from the storage tank back into the feed tank for retesting. Samples of each stream collected during the test are dried, weighed and split to obtain sub-samples for analysis and the remaining portions are added back to the feed tank. The feed slurry solid content is adjusted by decanting water from the feed tank prior to running a test.

Synthetic mixtures of quartz and magnetite were used in the tests at UBC. Mixtures of quartz (P_{80} = 425 μm) and two sizes of magnetite, coarse (P_{80} = 425 μm) and fine (P_{80} = 125 μm) were prepared with grades of one per cent and four per cent magnetite by weight. Test products were analysed for magnetite content using a Davis Tube.

Testing at the copper-zinc mine involved installing the CVD6 to treat the flotation zinc cleaner tailings stream. The stream had a P_{80} of about 103 μm and average grades Au 5.2 g/t, Cu 1.9 per cent, Zn 14.7 per cent, Pb 1.5 per cent, Fe 31.2 per cent and S 34.0 per cent. The material contained approximately 17 per cent silicate minerals.

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The sulphide minerals were primarily sphalerite, galena, chalcopyrite and pyrite. Microscopic examination of polished sections revealed that many unliberated particles were present, which makes separation difficult as the specific gravity differential is decreased and locked particles dilute concentrate grades.

Zinc cleaner tails slurry was pumped from a pump box to the CVD6 separator and the tailings and concentrate products were combined and returned to the rougher flotation circuit.

For each test the operating parameters levels were set and the CVD was run for at least 15 minutes to ensure steady-state conditions prior to sampling the feed, concentrate and tailings. Feed and concentrate sample weights and collection times were recorded to calculate the mass yield. The samples were filtered, oven dried and split for assay. All samples were assayed for Au, Cu, Zn, Pb, Fe and total S. Operating conditions for the test program are outlined in Table 1.

TABLE 1

Outline of test program.

Bowl speed (rpm)	Pinch open (s)	Pinch closed (s)	Fluidisation water (l/min)
500 - 1000	0.18	4	30
625	0.18	2 - 8	30
700	0.18	2 - 8	30
850	0.18	2 - 8	30
625	0.18 - 0.22	4	30
700	0.16 - 0.2	4	30
850	0.14 - 0.18	4	30

RESULTS AND DISCUSSION

Results from testing on both the quartz magnetite mixtures and zinc cleaner tailings stream were used to evaluate the effects of the operating variables on separation performance. For the zinc cleaner tailings, the objective was to recover gold bearing sulphides that were not recovered in the copper or zinc flotation circuits. The gold is believed to occur as finely disseminated grains in sulphide mineral particles, which prevents the recovery of a high-grade gold concentrate. Chalcopyrite and sphalerite in this product represent grains that were not recovered by flotation, some of which occur as middlings. The following summarises the results of testing each of the operating variables.

Fluidisation water

The effect of fluidisation water on grade and recovery was investigated with the synthetic feed of quartz and magnetite. As seen in Figure 1, when operating below 6 gpm, product grade and recovery are both negatively impacted. However between 6 and 10 gpm, the recovery levels off and the grade is only slightly reduced. To minimise water addition, while achieving good separation, the results demonstrate that the CVD6 should be run with a fluidisation water flowrate of about 6 gpm for this application. This operating level was also found to be appropriate when testing other ores.

The fluidisation water is believed to have two functions. It is necessary for upgrading of heavy minerals in the ring by dilating the bed of particles and allowing high density particles to displace low density particles. Secondly, the fluidisation water helps the packed bed of concentrate particles to flow through the pinch valves.

At high bowl speeds, water is displaced by the particles forcing the water to the centre of the bowl where it overflows. Therefore, the CVD can also de-water the concentrate. If the solid content becomes too high, the valves can become plugged preventing the recovery of concentrate. No plugging problems have been observed when using fluidisation water flowrates greater than 6 gpm in the CVD6. These observations imply that higher fluidisation water flow rates may be required when operating at high bowl speeds or when processing materials containing coarse/high density particles.

Bowl speed

Tests were conducted on the zinc cleaner tailings at bowl speeds ranging from 500 to 1000 rpm. The relationship between gold grade and recovery versus bowl speed is shown in Figure 2. The slope of the grade versus bowl speed curve shows two distinct
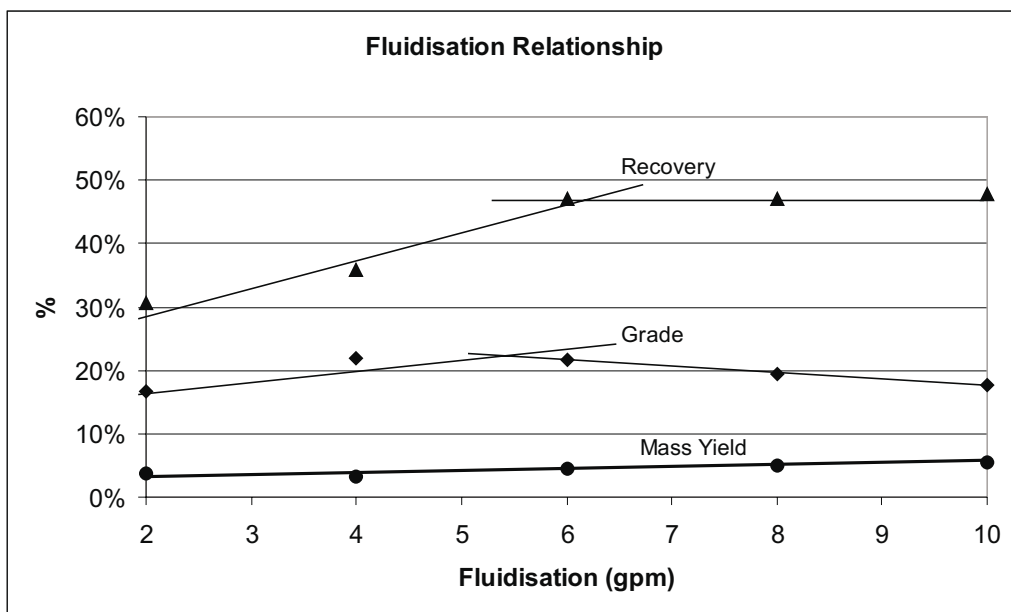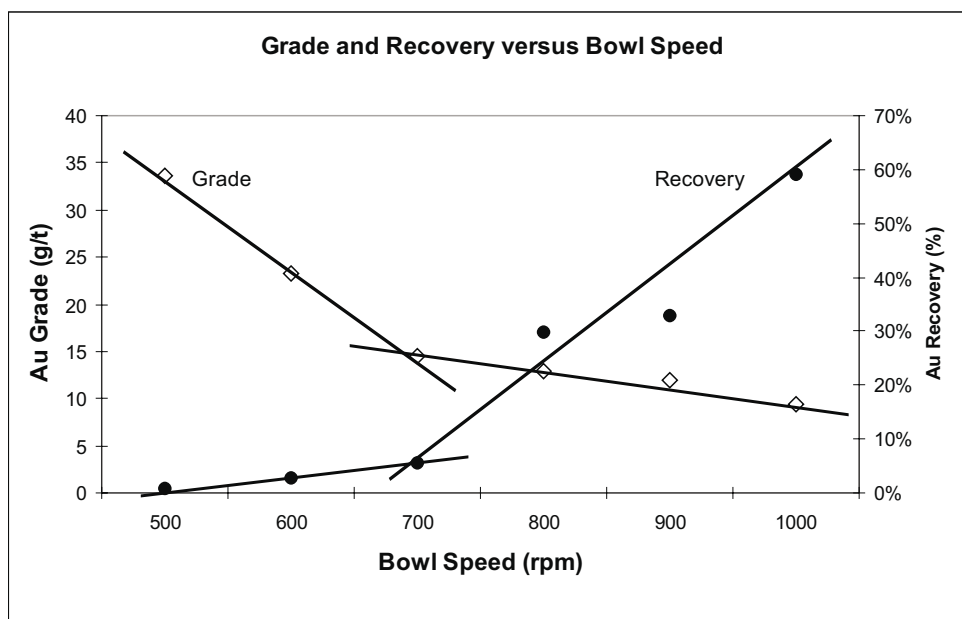

FIG 1 - Fluidisation water relationship.

FIG 2 - Grade and recovery versus bowl speed.

zones. Between 500 rpm and 700 rpm, the grade decreased significantly from 35 g/t to 15 g/t gold. However, beyond 700 rpm the slope flattens; increasing the speed from 700 rpm to 1000 rpm lowers the grade by only five per cent. There is a transition zone for grade between 650 rpm and 750 rpm.

The recovery mirrors grade, having two distinct slopes at low and high bowl speeds. Between 500 rpm and 700 rpm there is only a three per cent increase in the recovery, but between 700 rpm and 1000 rpm there is a 55 per cent increase. There is clearly a change in separation mechanism that occurs at the transition speed of about 700 rpm that affects the performance.

There are two separation zones in the CVD, the short bowl section and the fluidising ring. In the bowl section, stratification of high-density particles occurs such that as the stream flows up the bowl an upgraded layer enters the ring. The degree of stratification likely increases with bowl speed.

In the ring section, bowl speed is believed to affect the grade and recovery via two main mechanisms. Firstly, bowl speed affects the amount of dilution of high-grade product by low-density particles and secondly, it affects the degree of light particle displacement by heavy particles.

A grade profile in the ring would show a high-grade zone adjacent to a pinch valve with a decreasing grade toward the entrance to the ring. Visual observations made during testing with magnetite revealed that a high-grade cone of magnetite extends from the pinch valve and surrounding the cone is low-grade, mainly quartz, material. At low bowl speed, only a small amount of the ring material is drawn through the valve, so only high-grade material is recovered. With increasing bowl speed, the mass recovered though the pinch valve increases. As a result, more of the concentrate ring material is removed per cycle, which dilutes the concentrate grade.

At low rpm (<700 rpm), high-grade concentrates were obtained at low recoveries. The low speed allows light particle displacement by heavy particles. Despite the fluidisation water addition in the ring, at increasing bowl speed the packing of particles hinders the displacement reducing the amount of upgrading that takes place in the ring. The transitional bowl speed indicates the speed at which these hindering effects make upgrading ineffective. Beyond the transition, the majority of the upgrading likely occurs in the bowl section. Therefore bowl speeds for the CV6 should be kept below 700 rpm.

Pinch valve open time

Pinch valve open times were varied from 0.14 to 0.22 seconds, while other operating variables were set (Table 1). The effect of open time was evaluated at three different bowl speeds (625 rpm, 700 rpm and 850 rpm). These test's conditions were selected with consideration of the gold recovery objectives for the mine.

Figure 3 shows that the concentrate grade decreased with increasing pinch valve open time. The trend was the same at all three bowl speeds except that the curves were shifted downwards with increasing bowl speed.

Figure 4 shows that the recovery increases with increasing pinch valve open time. Increasing bowl speed shifts the recovery upwards. Recovery increases more rapidly at higher rpm's per incremental change in pinch valve open time. This trend is more visible beyond the transition point in the recovery versus pinch valve open time curves. The rate of change in recovery versus pinch valve open time decreases with decreasing bowl speed. This effect can be seen in Figure 4 where the linear trend line slopes become flatter when comparing the 850 rpm, 700 rpm, and 625 rpm lines.

The data trends were drawn as curves in Figures 3 and 4 with straight lines superimposed. The straight lines indicate two distinct sections for each rpm tested with a transition zone located around the intersection of the lines (transition point). The trend lines extend beyond the transition zone to show that the transition is smooth. This suggests that the mechanism responsible for the change in slope does not occur at a specific point. However, the transition point is useful to distinguish between zones dominated by different separation mechanisms.

For pinch valve open times up to the transition point, the steep decrease in grade can be explained by the dilution of the high-grade material near the pinch valve resulting from the recovery of lower grade material. Increasing the pinch valve open time further, beyond the transition point, further increases the proportion of the low-grade material in the ring that is recovered. However, the incrementally increased recovery of low-grade material increases dilution. Therefore the grade levels off and eventually approaches the feed grade.
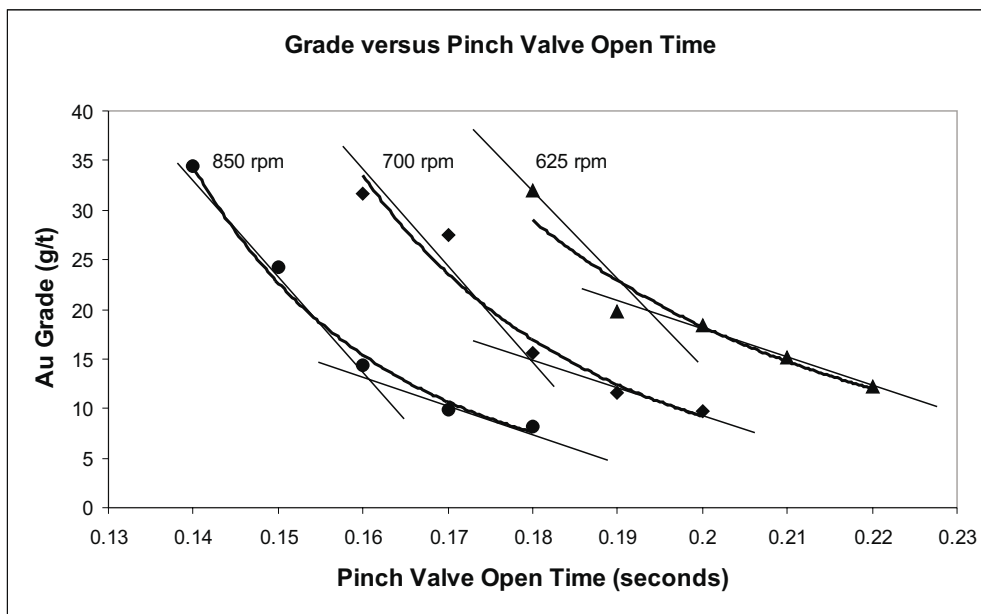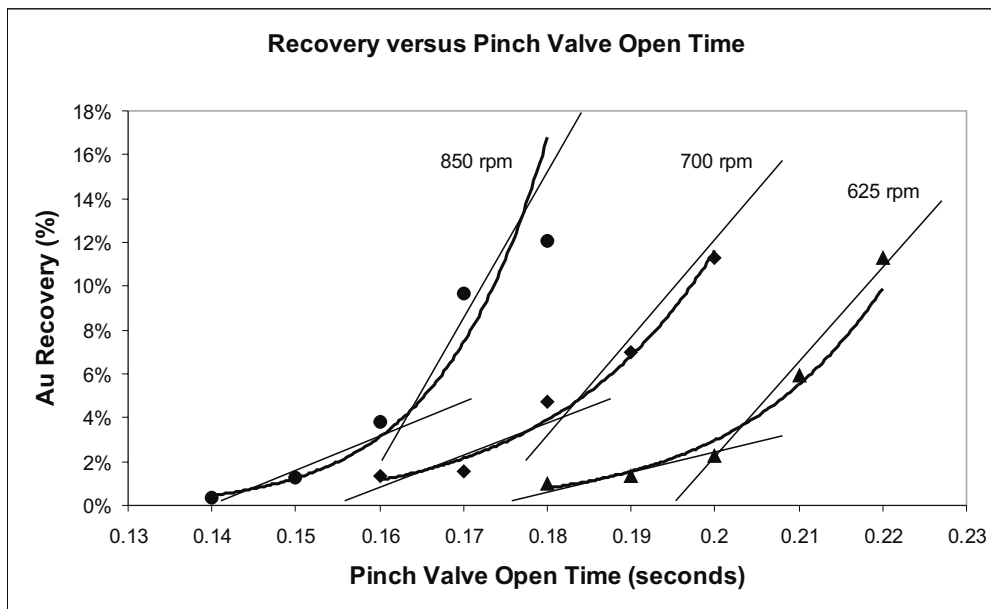
Fɪɢ 3 - Grade versus pinch valve open time.

Fɪɢ 4 - Recovery versus pinch valve open time.

Pinch valve closed time

Pinch valve closed times were varied from two to eight seconds while hold other operating variable levels constant (Table 1). As shown in Figure 5, the concentrate grade increased with increasing pinch valve closed time. A longer pinch valve closed time allows for more upgrading in the concentrating ring resulting from heavy particles displacing light ones. Figure 5 also shows that while upgrading took place at a bowl speed of 625 rpm, at higher bowl speeds (700 rpm and 850 rpm) the concentrate grades were not affected significantly. These results support those described above, which suggested that high bowl speeds inhibit upgrading in the ring. At high bowl speeds, packing in the ring likely prevents particle displacement.

At 625 rpm, the absence of a clear transition point indicates that the grade will continue to increase with closed time at a uniform rate. Eventually the grade would approach a constant value that depends on particle specific gravity and size.

As described above, visual observations reveal that cones of coarse high density material radiates from the pinch valves. The particle size gradation within the cone ranges from coarse near the pinch valve to fine further away from the valve.

As shown in Figure 6, the recovery decreases significantly for pinch valve closed times up to about three seconds and then decreases at a much slower rate. This transition point represents an operating limit for pinch valve closed time. Based on operating experience with the CVD, it is not practical to use pinch valve closed times of less than three seconds because the upgrade ratios are low.
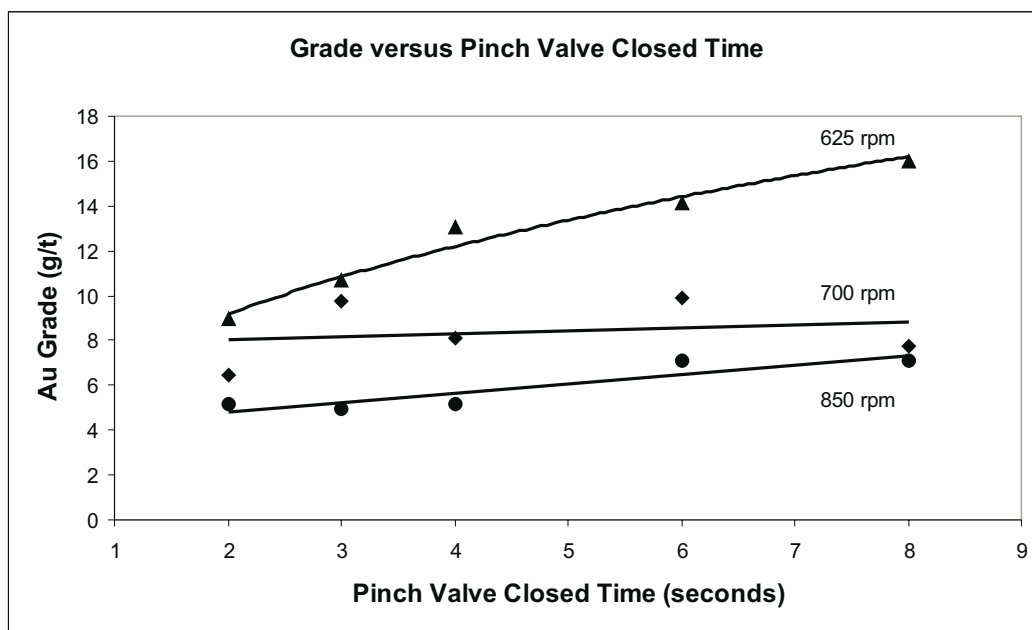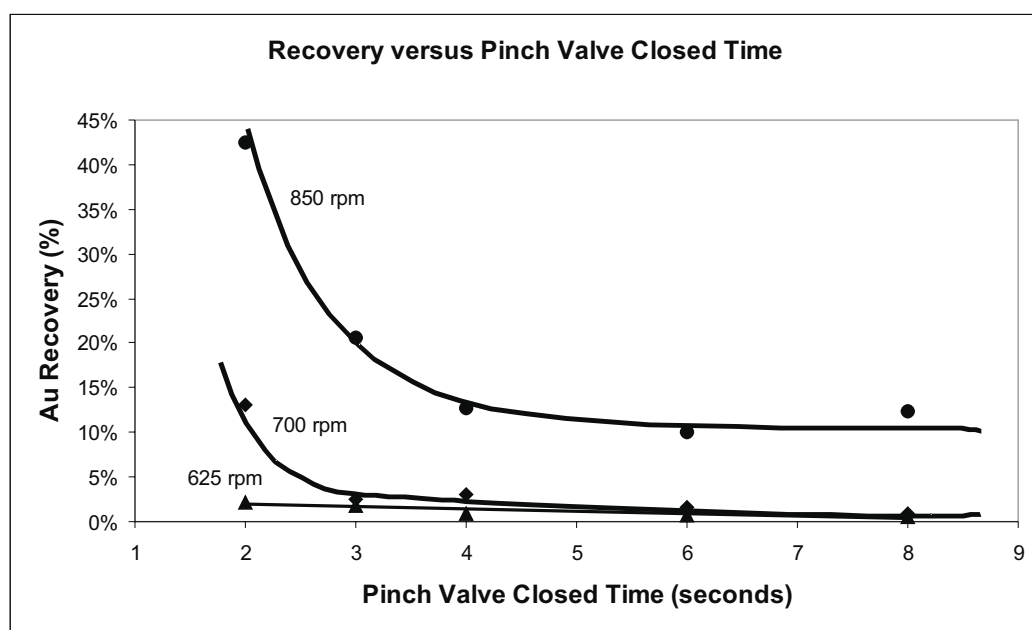
FIG 5 - Grade versus pinch valve closed time.

FIG 6 - Recovery versus pinch valve closed time.

At 625 rpm, there was almost no recovery over the whole range of pinch valve closed times. This result was explained by the small pinch valve open time used for these tests, which did not allow significant mass pull. The recovery curves shift upward with increased bowl speed.

OPERATING VARIABLE PERFORMANCE RATIO

As demonstrated by the results of this study, the CVD has the ability to achieve a wide range of metallurgical results. Figure 7 shows a plot of recovery versus grade for gold. Each point on the plot represents a different set of operating conditions. The upper bound on the plot identifies the maximum performance of a CVD6 for this ore. It is important to know how to manipulate the operating variables in order to operate a CVD as close to the upper bound as possible.

Knowing the effect of each variable on both grade and recovery aids in developing an operating strategy. For all variables tested, changes in the level to increase the concentrate grade resulted in a decrease in recovery and vice versa. To assist with the development of an operating strategy, a methodology for comparing the change in grade and recovery at a specified operating variable range was established.

Each of the operating variables has different ranges and increments (units) of change. Bowl speed is measured in rpm, pinch valve closed times in seconds, and pinch valve open time
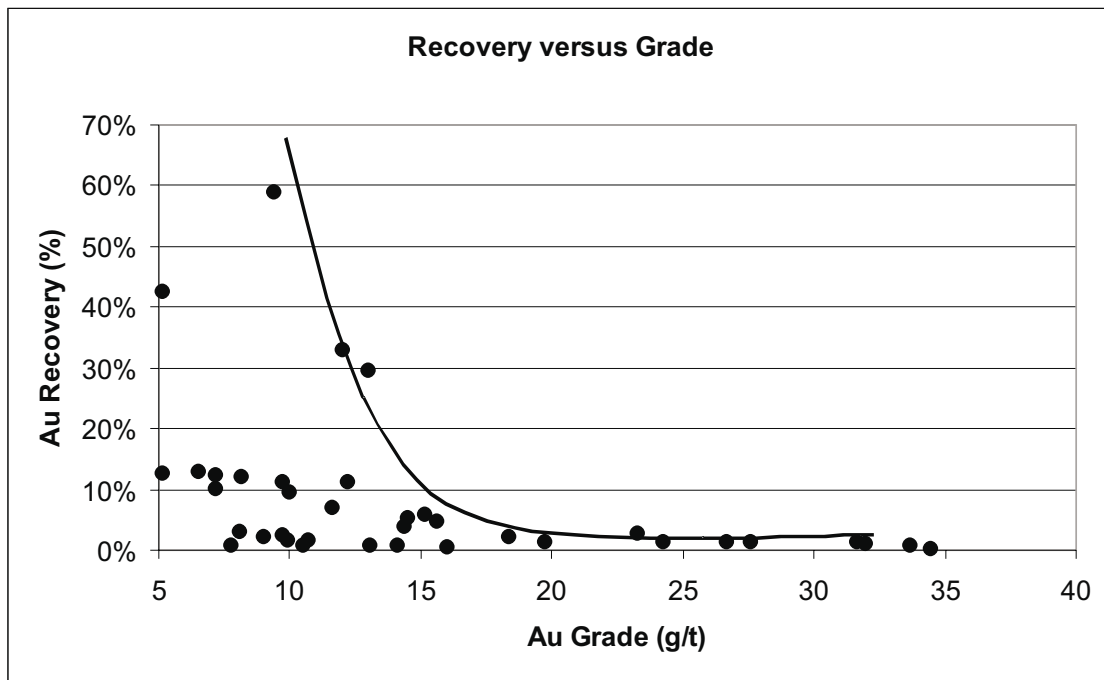
FIG 7 - Recovery versus grade.

in fractions of a second. The difference in units makes direct comparison of slopes impossible. Instead, broad operating ranges were selected for the three operating variables. Each operating range was broken down into equal increments called levels. A midpoint in each operating range was identified for each operating variable. The midpoints were all selected from previous operating experience as conservative operating levels.

Tests were selected where one variable at a time was changed while the other three variables were held at midpoint levels. For each operating variable, grade versus parameter level and recovery versus parameter level plots were generated. Linear trend sections on these plots were identified and trend lines drawn.

The slopes for grade versus parameter level and recovery versus parameter level were divided to produce a ratio of the change in grade versus the change in recovery. This ratio of slopes was used to compare the overall impact of a variable on the separation performance and is referred to as the operating variable performance ratio (ovp ratio).

Comparing the ovp ratio for each operating variable quantifies the combined grade and recovery effect of changing each operating variable. Since grade and recovery always have opposing slopes a net negative ratio results in all cases. For comparison, the absolute value of the ovp ratio was used. Table 2 shows the direction of the trends.

The ovp ratio is a semi-quantitative tool for selecting an operating variable to change when tuning the operation of a CVD. As discussed before, the CVD will have a maximum performance boundary condition for grade and recovery as demonstrated in Figure 7. The ovp ratio gives the operator a map of which operating variable to change in order to achieve boundary condition performance or to move to another point on the boundary line. If the objective is to increase predominantly grade (shift horizontally on Figure 7), then a high ovp ratio is desired. However if recovery is the objective a low ovp ratio is desired. The ovp ratio is a guideline for roughly quantifying an operating variable's overall effect on separation performance.

Table 2 summarises the ovp ratios that were generated at each variable level. Due to transition points in the trends, the ratios change for bowl speed and pinch valve closed time. In Table 3, a high ovp ratio at low bowl speed (403), with all other variables at midpoints indicates that an increase in bowl speed will influence grade the most. Pinch valve open time had a constant ovp ratio throughout the tested range meaning that it would have the same result on grade with any incremental change in open time. Other than at low levels, pinch valve closed time also has a uniform effect on grade. In general, these results indicate that pinch valve open time generates the greatest change in grade per incremental change in operating variable level.

For the majority of the operating range (levels 3 − 7), pinch valve open time should be used to make coarse adjustments in grade. Fine-tuning of the grade should be performed with bowl speed. If intermediate tuning is needed, the pinch valve closed time can be effective.

When considering ovp ratios from a recovery perspective the results mirror those for grade. Levels 3 through 6 in Table 3 represent a reasonable operating range. Low ovp ratios in this range for bowl speed indicate that bowl speed has the greatest effect on recovery per change in grade. If a significant change in recovery is required with a minimum effect on grade, bowl speed should be adjusted. A mid-range ovp ratio of 32 for pinch valve closed time classifies this variable as a mid-range tuning variable for recovery. The ovp ratio of 182 for pinch valve open time indicates that it is not an effective variable for tuning recovery.

TABLE 2
General trends for operating variables.

	Grade	Recovery
Increasing fluidisation water flowrate	Decreases	Increases (to a limit)
Increasing bowl speed	Decreases	Increases
Increasing pinch valve open time	Decreases	Increases
Increasing pinch valve closed time	Increases	Decreases

TABLE 3

Rate of change in grade versus rate of change in recovery.

Level	Actual bowl speed setting (rpm)	Actual pinch open setting (seconds)	Actual pinch closed setting (seconds)	Bowl speed OVP ratio	Pinch open time OVP ratio	Pinch closed time OVP ratio
1	500	0.17	2	403	182	1
2	600	0.18	3	403	182	32
3	700	0.19	4	10	182	32
4	800	0.20	5	10	182	32
5	900		6	10		32
6	1000		7	10		32
7			8			32

For fine-tuning of the machine, the operating variables can be adjusted in smaller increments. The resolution of control on the operating levels will influence how much fine control a variable can have. The bowl speed resolution is 1 rpm, pinch valve open time 0.01 seconds, and the pinch valve closed time 0.1 seconds. The pinch valve open time is the only operating variable that was tested in the smallest increment possible.

When testing a new feed in a CVD, a systematic approach for finding the appropriate operating variable levels should be employed.

1. First run the machine at the centre-point conditions: 700 rpm bowl speed, mid-range (0.18 seconds) pinch valve open, four seconds pinch valve closed. Pinch valve open time is described as mid-range because all CVD's have unique valve histeresis that changes the pinch valve open ranges.

2. Determine the grade and recovery for the centre-point test. The relationships for each operating variable's effect on grade and recovery can be used to tune the performance. It is recommended to only change one variable at a time.

CONCLUSIONS

The CVD has four operating variables that affect the metallurgical performance and therefore levels must be selected to achieve the desired metallurgical results. For all operating variables, changing the levels to increase grade causes a reduction in recovery and vice versa. A good understanding of the effects of each variable is important to developing an operating strategy for optimum performance.

The CVD's operating variables are fluidisation water flowrate, bowl speed, pinch valve open time, and pinch valve closed time. Table 2 summarises the general trends observed when increasing each of the operating variables.

Fluidisation water was found to be necessary for upgrading and concentrate flow through the pinch valves. Fluidisation water has little effect on grade and recovery as long as it is run above a threshold limit (6 gpm for the CVD6).

Analysis of the effect of bowl speed on separation performance showed that to allow upgrading, bowl speeds should be run below 700 rpm. The trend in the bowl speed versus grade curve indicates that grades increase in a linear manner with decreasing bowl speed. More testing is needed at low bowl speeds to determine upgrade limits.

After setting the fluidisation water flow rate and selecting an appropriate bowl speed, product grade and recovery can be optimised by adjusting the pinch valve timing. The pinch valve open and closed times have an interrelated effect for achieving separation performance. Increasing the closed times allows for more upgrading in the ring. The required open time is the time needed to drain the upgraded product from each cycle of operation.

A ratio of the change in grade versus the change in recovery was defined as the operating variable performance ratio (ovp ratio). The ovp ratio was used to quantify the operating variable's overall effect on separation performance. The ovp ratio is considered a useful parameter to help decide which variable should be changed to cause an improvement in grade or recovery.

The Knelson CVD has more operating variables than any other commercially available continuous centrifugal gravity concentrator. The ability to affect separation by controlling each of the variables makes the separator versatile with a wide range of applications. However, a good operating strategy to achieve the desired separation performance requires a good basic understanding of the effects of each variable and their interactions.

ACKNOWLEDGEMENTS

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