EFFECTIVE USE OF ENERGY IN THE FLOTATION PROCESS

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Abstract

In flotation operations, energy consumption is often described as the primary contributor to the life cycle operational cost for flotation. However, flotation and centrifugal separation only contribute 4% of the total energy contribution from all mining and mineral processing operations. It can be shown that the effective use of an increase in energy can lead to higher concentrate recoveries. Minimizing flotation energy consumption purely to minimize operational cost could thus lead to poorer profitability. The effect of increased energy on higher concentrate product, needs to thus form a part of the overall power consumption versus overall profitability calculation.

Flotation models indicate that fine particle recovery increases as a function of dissipation energy and collision frequency. Both parameters are a result of increased energy consumption. While it appears that fine particle flotation kinetics is enhanced with an increasing energy consumption, it is suspected that coarse particle recovery is affected by the detachment sub-process. The effect of power on metallurgical performance is explored on a sized and unsized basis, to evaluate the contribution from the fine particles.

Three industrial applications are discussed in this paper, and it is demonstrated that .an increase in power increases the fine particle recovery. This paper will review fundamental parameters that influence fine particle recovery and is verified with plant data. The paper will also illustrate the benefits attained when an economic evaluation considers both energy and concentrate product.

1. Introduction

The lifetime energy consumption of a large mechanical flotation machine was estimated by Rinne and Peltola (2008) to be approximately two-thirds of the total life-cycle cost of the flotation process; while the initial investment cost was estimated to be approximately 6% of the total life-cycle cost. It was concluded that energy efficiency and energy cost have the largest influence on the overall operating cost of the flotation process. A report by the US Department of Energy (2010) shows that the flotation and centrifugal separation (only total percentage for both was presented) sub-process only accounts for 4% of the total energy consumption in mining and mineral processing. The energy cost contribution of the flotation process is thus extremely small, which transfers into insignificant energy saving potential. Furthermore, the current trend to increase the single cell volume and develop more efficient flotation machines, results in lower installed specific power.

It's been known for over 70 years (Gaudin 1931) that the flotation process in base metal operations works the best in an optimal recovery range of 20-120µm supplemented by a steep recovery drop-off for smaller and larger particles. Therefore, fine and coarse particle kinetics and thus recovery of these size particles often lag the recovery of the intermediary size classes in a retention time and froth carrying capacity-constrained environment. Coarse particle flotation may suffer from slower kinetics due to incomplete liberation or relatively greater detachment probabilities. Fine particle recovery is less likely to be hindered by partial liberation or the likelihood of detachment. It is generally accepted that bubble-particle collision frequency is integral to the recovery of the fine particle size class. After Schubert (1989, 2008) one can prove that the collision frequency (Z_{12}) between particle and bubble is proportional to the ratio of rate of energy dissipation (ε_R) and inversely proportional to the fluid viscosity ($\boldsymbol{v}$):

$$\mathbf{Z}_{12} \approx \boldsymbol{\varepsilon_R}^{\mathbf{1/2}} / \boldsymbol{v}^{\mathbf{1/3}} \qquad \text{Eqn.1}$$

Recognizing the alliance between ε_R and the mean energy dissipation rate ($\bar{\boldsymbol{\varepsilon}}$) Shubert (1989, 2008) defines the mean energy dissipation rate ($\bar{\boldsymbol{\varepsilon}}$) as the ratio of specific power input (P) to the slurry mass (M):

$$\bar{\boldsymbol{\varepsilon}} = P/M \qquad \text{Eqn.2}$$

In a detailed derivation and description of the bubble-particle collision mechanisms presented by Govender (2011), it is shown that the flotation rate constant, which is relative to the collision frequency (Jameson 2010), is thus contingent upon the power absorbed by the slurry mass in the flotation cell.

2. Results

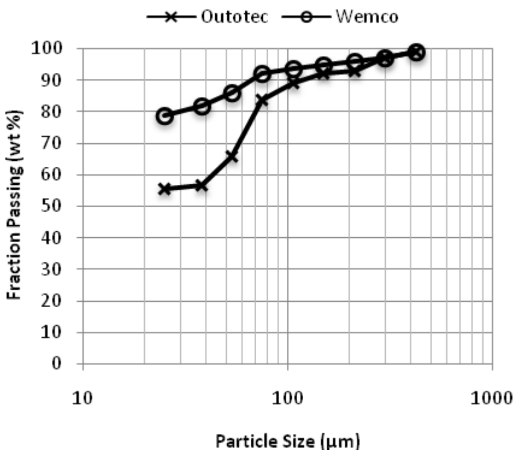
2.1 Western Limb Tailings Retreatment Plant

The Anglo Platinum Western Limb Tailings Re-treatment Plant (WLTRP) circuit has been previously described (Anyimadu et al. 2007), and at the time of testing, the primary rougher row comprised of nine 130m^3 Outotec flotation machines (Molelekeng and Balram 2006). A hydrodynamic and metallurgical comparison of the Outotec and Wemco® mechanisms was facilitated by retrofitting a standard 130m^3 Wemco® mechanism into the final cell in the row. The independently acquired hydrodynamic measurements are compared below (Molelekeng and Balram 2006):

Table 1: Summary of Hydrodynamic Evaluation

Parameter	Outotec	Wemco
Froth Depth (mm)	350	380
D_{32} (mm)	0.75	0.70
J_G (cm/sec)	0.97	1.09
S_B (1/sec)	77	93

The WLTRP feed composition is described as a mixture of finely oxidized PGM's (dating back to pre-flotation separation in the 1920's) and a more recent UG2 tailings stream (Anyimadu et al. 2007). No rougher feed particle size distribution is reported by Molelekeng and Balram (2006) while Anyimadu et al. (2007) reports that the plant feed density and particle size distribution are episodic. Typical IsaMill™ feed (or slower floating concentrate component) has an equivalent d_{90} of 25µm (Anyimadu et al. 2007) (or d_{80} of approximately 20µm, and similar to the size distribution of the overflow product recovered by the Outotec machine (Fig 1(a)).



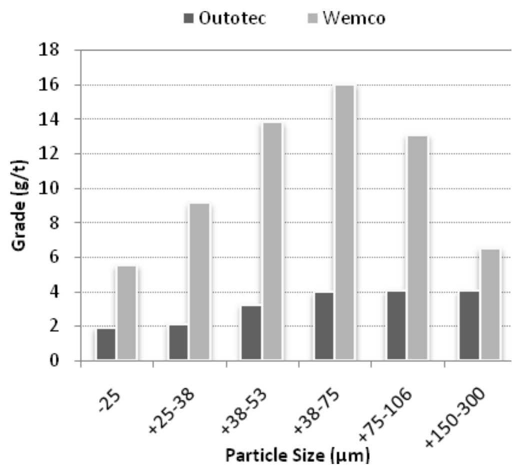


Figure 1. WLTRP Recovery by Size (a) and Grade by Size (b) Comparison

Fig 1(a) shows that Wemco® recovers a significantly higher number of fine particles. Insoluble or gangue recovery data is not reported by Molelekeng and Balram (2006), nor is an estimate of the solid and/or liquid carryover for each class size fraction. However, Molelekeng and Balram (2006) do report that the Wemco® cell was operated at a deeper froth depth relative to the Outotec machine, and contend that the entrainment component (not measured) may have contributed to the improved Wemco® recovery. The typical entrainment contribution of the Wemco® cell recovery is similar to that of the forced air cell, which makes this conclusion very unlikely. Entrainment is commonly defined as the unselective recovery into the froth phase due to water carryover/recovery and strongly depends on particle size. As can be seen in Fig 1(b), the concentrate grade of comparative size classes improved substantially in the Wemco® machine, thereby inferring an improved selectivity or gangue rejection, and a positive directional shift in the grade-recovery curve.

The absorbed power, and thus specific power input of the Wemco® cell was more than that of the Outotec cell. This means that the mean energy dissipation rate of the Wemco® was higher. Shubert (2008) has shown that the finer particle class flotation kinetics is accelerated with an increase in the mean energy dissipation rate. The Wemco® results shown in Fig 1(a) thus correlate well with what Shubert has shown.

2.2 **Mineral Park**

The Mineral Park Mine is located near Kingman, Arizona approximately 70 miles south-east of Las Vegas, Nevada. At the time of testing (April 2010), the rougher-scavenger flotation row consisted of five 257m^3 Wemco® flotation machines. The bulk concentrate stream was combined and pumped to the bulk cleaner circuit via an intermediary regrind step.

The effect of absorbed power on recovery was tested by varying the rotor speed on the final (scavenger) cell in the five-cell row, and measuring the additional copper and molybdenite stage recovery (if any). Originally installed with standard 400HP (300kW) motors and a standard rotor rotational speed of 113 rpm, the cell was enhanced with the flexibility of VFD–controlled 700HP (522 kW) nameplate capacity motors. Power absorption was varied with rotor speed, with 132rpm rotor speed representative of the 100% upper baseline case. It was anticipated that the stage recoveries from the cells at the head of the row were most likely limited by froth carrying capacity than kinetics. Therefore, by removing the expected interaction with froth recovery, the effect of rotor speed was expected to be most influential at the tail end of the row.

Fig 2 illustrates the effect of power (varied by impeller speed) on copper (Cu) stage recovery. The data represents the effect of increased absorbed power on the final scavenger cell only, and is plotted on a relative recovery scale, as a function of the maximum stage recovery achieved.

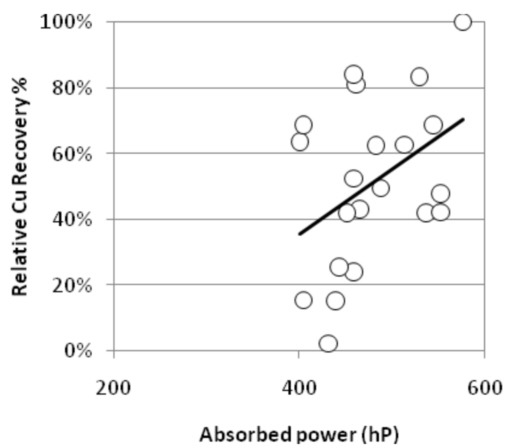


Figure 2 Relative Cu Stage Recovery as a function of absorbed power

The relative molybdenite (MoS_2) stage recovery is represented by Fig 3. A similar response is achieved in evaluating the effect of power inferred from variations in rotor speed.

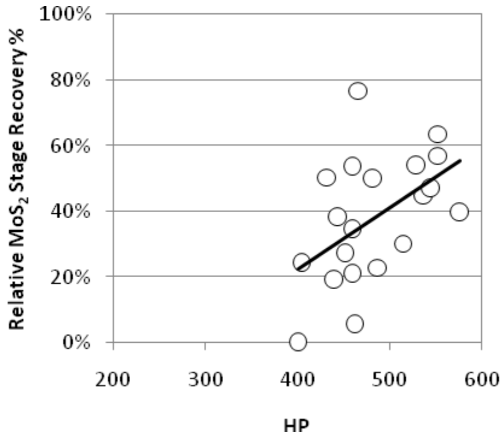


Figure 3 Relative MoS_2Stage Recovery as a function of absorbed power

Based on the results achieved after installation of the first 700HP motor – VFD combination on the cell #5, cell #4 in the rougher-scavenger row was retrofitted with a larger motor and the sheave was changed in April 2010. The chronological trends in Fig 4 clearly illustrate the general upward trend in MoS_2 recoveries and production with the increase in turbulent dissipation energy. Additionally, Cu yield appears stable or higher.

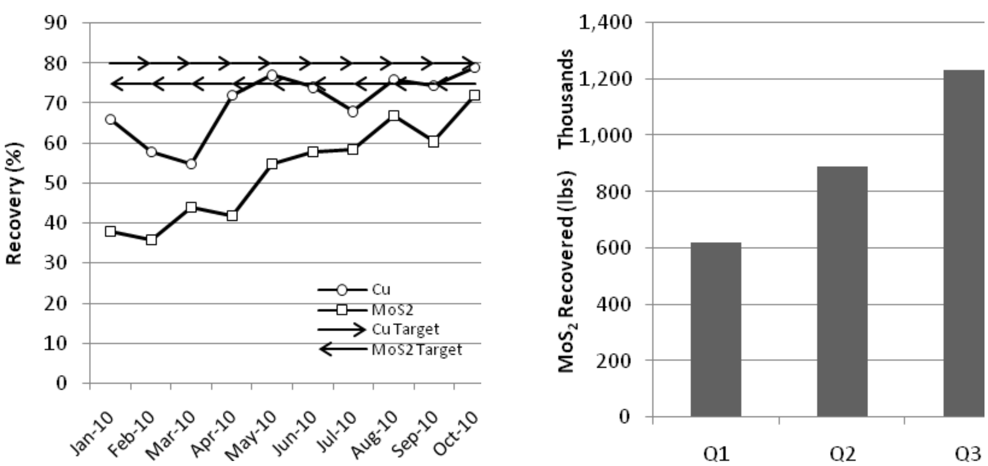


Figure 4 Mineral Park monthly Cu and MoS_2 recoveries (left), and molybdenite production by quarter (right) (http://www.mercatorminerals.com/docs/SCMC_Dec_2010.pdf accessed: December, 2010)

2.3 **Kennecott Utah Copperton Concentrator**

The Kennecott Copperton Concentrator consists of a SABC grinding circuit followed by a bulk beneficiation step. The six rows of Wemco rougher-scavenger cells produce a bulk copper-molybdenite concentrate. The fast floating rougher concentrate is diverted to rougher-cleaner columns, while the scavenger concentrate is re-ground. The re-grind circuit product is enriched in a series of cleaner-scavenger steps utilizing a combination of column and mechanically agitated machines (Zanin et al. 2009). Molybdenite separation from the bulk concentrate occurs in the molybdenite flotation plant (Zanin et al. 2009). The recent installation of the SuperCell™ flotation machines in cleaner-scavenger mode, allowed FLSmidth to optimize the largest operational flotation cells in terms of hydrodynamics and metallurgy. Forming part of the metallurgical optimization was a study of the effect of power absorption on Cu and MoS_2 recoveries. The data below relates to the 300m^3 Wemco® SuperCell™.

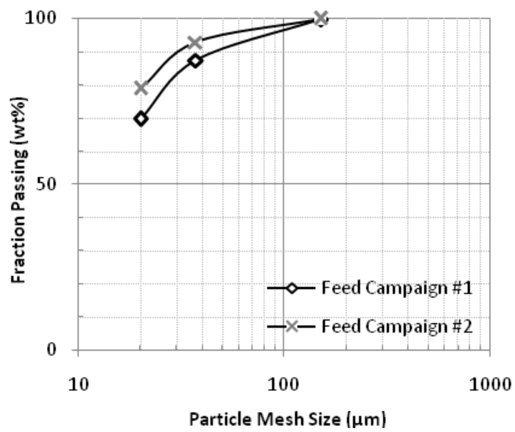


Figure 5 SuperCell™ semi-log feed particle size distribution

The relatively dilute feed to the SuperCell™ consisted of the regrind circuit classification overflow product, generally consisting of 5–10wt% solids. Fig 5 shows the feed particle size distribution for the first two campaigns of the SuperCell™ evaluation. The d_{80} for both campaigns ranged from 20 – 30µm, with a predicted d_{50} of less than 10µm.

The feed to the Supercell™ assayed approximately 10.5% Cu and 1% MoS_2. In this paper the metallurgical performance of the Supercell™ is evaluated for a constant feed flow rate (734m^3/h) and Cu grade (10%). Five test campaigns were run, accommodating mineralogical and reagent variations coupled with general process noise. Statistical design incorporated a full Central Composite Design (CCD) utilizing rotor speed and froth depth as input variables.

The effect of absorbed power on Cu and Mo recovery is presented in Fig 6. One needs to remember that this data is taken from factorial design and there are many other variables influencing the recovery at different levels. Despite these hindrances there is a clear trend showing the significant influence of power, as can be seen in Fig 6.

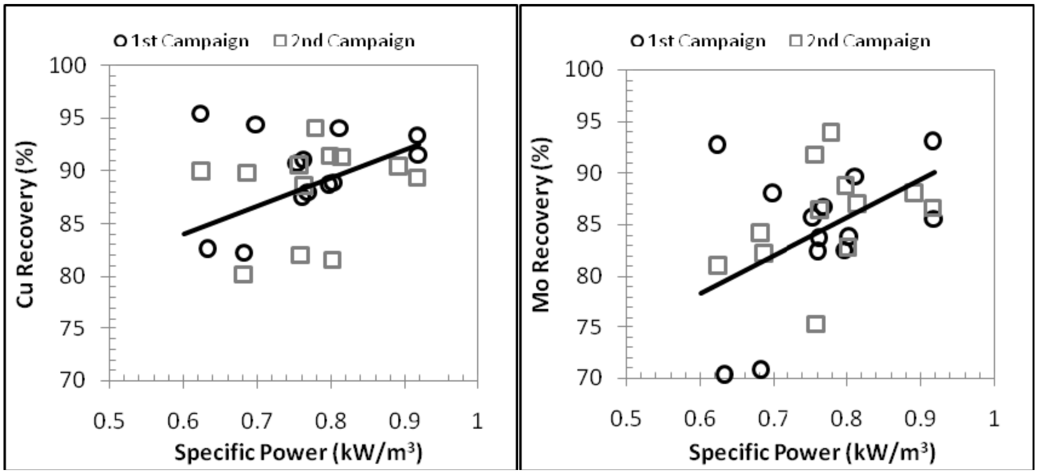


Figure 6 Cu and MoS_2 recovery as a function of specific power

Grano (2006); Schubert (2008); and Deglon (1998) report that the effect of power or agitation on recovery on an unsized basis is less likely to be observed due to fine particle recovery improvements being offset by the decrease in attachment efficiency of the coarser particle size fraction. With minor contribution from the coarse particle size fraction in the classified regrind mill product, the unsized SuperCell™ feed material could still be construed as fine. But, if the Cu and MoS_2 recoveries of the -20 micron size class are plotted as a function of the absorbed power (Fig 7), the fine-particle recovery-power relationship becomes visually more prominent. Fig 7 suggests that the fine particle recovery deficit commonly observed in base metals operations may be offset by increasing the impeller speed of mechanically agitated machines. An additional contributory effect is expected to have been provided by the dilute feed, as predicted by the ε_R/ν ratio.

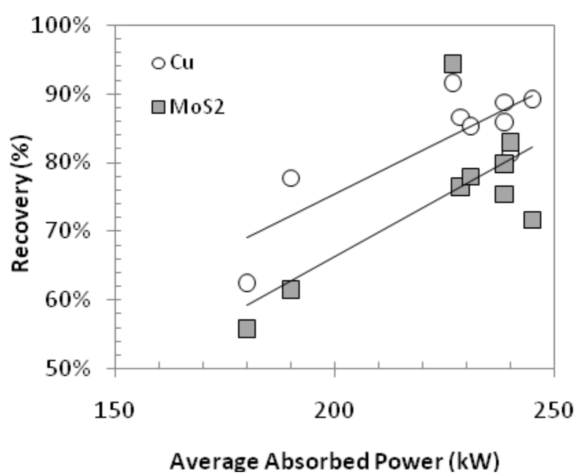


Figure 7 Cu and MoS_2 recovery of sub 20micron fraction

The development of statistically significant hydrodynamic and metallurgical models for the Wemco® SuperCell™ allowed for the more detailed study of the effect of absorbed power on metallurgical performance of the cell. Table 2 shows optimum operational conditions required to maximize Cu and MoS_2 recovery at a fixed concentrate grade. For the purpose of this exercise, metallurgical characteristics of the feed were maintained at average conditions (as previously described) and volumetric feed flow input was set to 681 m^3/h. With an increase in specific power from 0.74 to 0.84 kW/m^3, tabulated data exhibits an increase in the expected Cu and MoS_2 recovery responses of 2.7% and 3.1%, respectively. This increase in performance cannot be explained by higher air flow numbers as the value of this variable remains fairly constant. Additionally, an increase in pulp circulation, a possible contributory factor to higher recoveries, may not sufficiently explain such a strong effect on metallurgical performance. Thus, presented data further supports the importance of energy in flotation of fine particles.

Table 2: Summary of Hydrodynamic Evaluation

	Specific Power (kW/m^3)	Pumping Rate (m^3/min)	Induced Airflow (m^3/min)	Copper Grade Response (%)	Copper Recovery Response (%)	Molybdenite Recovery Response (%)
Scenario 1	0.74	185	35.1	28.0	86.0	82.9
Scenario 2	0.79	187	35.4	28.0	87.5	84.5
Scenario 3	0.84	195	34.0	28.0	88.7	86.0

Table 3 below shows recent hydrodynamic data from April 2011. This hydrodynamic data shows that the Sauter mean bubble diameter is very similar at the different speed tests. One can also see from Table 3 that the froth depth is greater at the higher speed. This deeper froth depth for the higher speed rotors was typical for all case studies in this paper. This deeper froth depth also reduces any possible entrainment effects that may exist.

Table 3: Summary of Hydrodynamic Data from April 2011

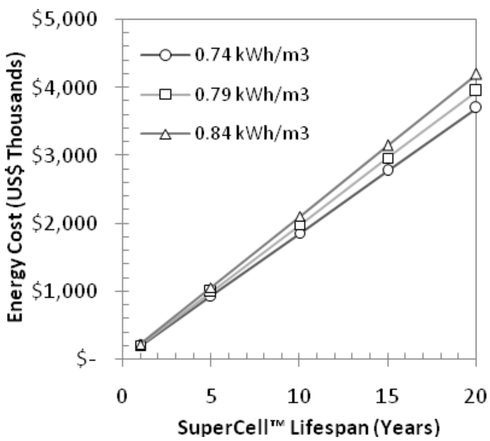
Description	RPM	Froth depth	Number of bubbles	Mean bubble diameter	Sauter Mean bubble diameter	Bubble diameter variance
Wemco300 Test 11	97	2	73994	0.95	1.72	0.31
Wemco300 Test 12	118	6	66233	0.94	1.84	0.36

2.3.1 **Economic Evaluation**

A basic economic analysis of consumed power and associated metallurgical benefits is presented in Figs 8–9. Comparison of absorbed power and metallurgical performance is based on above data for the Wemco® SuperCell™. The following inputs were used for the purpose of the evaluation:

- Electricity cost = 0.10 US$/ kWh,
- Copper spot price = 1.50 US$/lb
- Molybdenite spot price = 10 US$/lb
- Dry solids throughput = 44.3 Mtph

Energy cost over the 20-year lifespan of a single SuperCell™ ranges from US$3.7-4.2 million for the specific power range of 0.74–0.84 kW/m^3. However, additional power causes an extra gain in recovery for Cu (2.7%) and MoS_2 (3.1%) which may earn over an *additional* US$160 million in total revenue (Fig 9); revenue which would not have been produced by saving US$500,000 in energy cost.



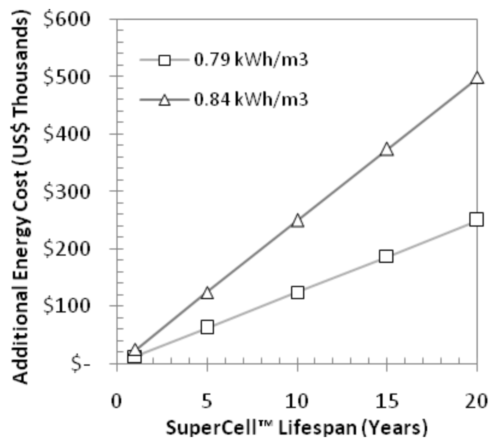


Figure 8 Sensitivity analysis of the energy cost (left) and additional energy cost for increasing energy inputs (right) over the average life of the 300m^3 Wemco® SuperCell™

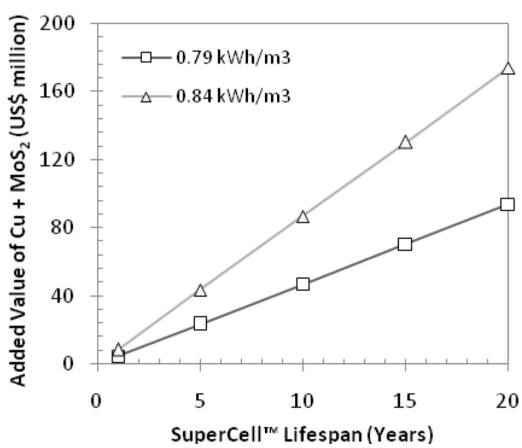


Figure 9 Value of additional Cu/MoS_2 recovered over the average life of 300m^3 Wemco® SuperCell™ for increased energy inputs

3. Conclusions

In flotation operations, energy consumption is often described as the primary contributor to the flotation process operational cost. However, when the mining sub-processes of extraction, materials handling and concentration are factored in, the relative contribution of beneficiation is relatively insignificant in the holistic evaluation. Moreover, the effect of geometric similarity in scale-up methodologies has resulted in an inverse correlation between flotation cell volume and specific power input.

The industrial data presented suggests that fine particle flotation benefits from higher turbulent dissipation energy and lower solids concentration. This is anticipated from the proportionality relationships between the flotation rate, collision frequency and the turbulent dissipation to viscosity ratio (ε_R/v). While it appears that fine particle flotation kinetics is enhanced with an increasing ε_R/v ratio, it is suspected that coarse particle recovery is affected by the detachment sub-process. Therefore, the proper manner to evaluate the effect of power on metallurgical performance dictates that the assessment should occur on a sized basis. If the contribution from the fine particles is high enough, it may also exhibit positive recovery responses on an unsized basis.

The experiences at WLTRP detail a dual benefit of improved grade and recovery through the utilization of a higher powered flotation machine. The need to liberate finer and more efficiently in PGM beneficiation processes offers the opportunity to utilize flotation machines with optimized specific power inputs and/or high power numbers.

The flotation rate of molybdenite in porphyry copper applications, which often lags that of copper (Zanin et al. 2009), has been shown to improve significantly with increased specific power input. Molybdenite flotation kinetics, and its response to power input, may be attributed to the platelet shape of molybdenite particles produced via specific fragmentation mechanisms (Zanin et al. 2009). The resulting shape factor may result in a flotation rate response that is more amenable to increased collision frequency. At Mineral Park, the scavenging efficiency of the primary beneficiation stage greatly improved with an increase in specific power input. MoS_2 and Cu stage recoveries were experimentally determined to correlate positively with an increase in impeller speed. Temporal plant data trends supplemented the significant improvement in MoS_2 recovery. With the Wemco® 300m^3 SuperCell™ operating in cleaner-scavenger mode at KUCC, positive responses of MoS_2 and Cu recovery to power input were noted on an unsized basis. On a sized basis, the relationship was visually further enhanced.

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- Rio Tinto Kennecott Copperton Concentrator Management
- All site personnel

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