Measurement and control of grinding circuit performance by real-time particle size measurement on individual cyclones

C. V. O'Keefe
CiDRA Minerals Process

Proper control of grinding circuits is essential for realizing the recovery and throughput goals of a beneficiation plant. Currently, control is determined by the availability, accuracy, and responsiveness of key measurements. Ideally, the real-time measurement of the particle size reporting to the overflow would be used to control the particle size produced by the grind circuit. Until a few years ago, this measurement was not available in real time with sufficient reliability for control systems, therefore surrogates, cyclone feed density or pressure or both, were used. The introduction of the impact-based particle size measurement method four years ago changed the situation and the ability of the industry to control their grind circuits. The results of testing the performance of this measurement technique at ten beneficiation plants and correlation with plant conditions reveal the inadequacy of controls based on pressure or density, and the need for direct control based on particle size. The principle of operation of this sampler-free measurement technology, its implementation, and measurement performance will be discussed. The control methods that are enabled by this unique system for both individual cyclone and battery level control will be illustrated.

INTRODUCTION

In mineral beneficiation involving grinding, mineral recovery and grade are strongly dependent on the particle size delivered to downstream beneficiation processes. An optimal or target grind size is established based on the desired plant economics. Until recently, proper control of this target grind size has been hampered by the lack of the direct, real-time, sampler-free measurement of the particle size. This measurement problem has been solved with the implementation of real-time novel instrumentation that involves robust sensors that are mounted on the overflow pipes of individual cyclones (Wills, 2009), thus providing information on the performance of each individual cyclone as well as the entire cyclone battery or cluster.

PRINCIPLE OF OPERATION

Acoustic impact-based particle size tracking is a unique method for measuring and tracking particle sizes in cyclone overflow lines. The implementation of this technology is centred upon a probe that is inserted into the slurry stream via a two-inch (50 mm) hole in the overflow pipe as seen in Figure 1. Particles within the slurry stream impact the surface of the probe, generating travelling stress waves within the probe. A sensor converts these traveling stress waves into an electrical signal, and proprietary signal processing techniques translate these signals into a particle size measurement that is output every four seconds. The sensor effectively samples a few percent or more of the slurry stream, an amount that is orders of magnitude greater than what is sampled by other traditional technologies that utilize online samplers and that do not sample individual cyclones. Also, because of the location of the sensor downstream of the cyclone and the presence of an air core at that point, the sensor produces no change in the back-pressure seen by the cyclone.

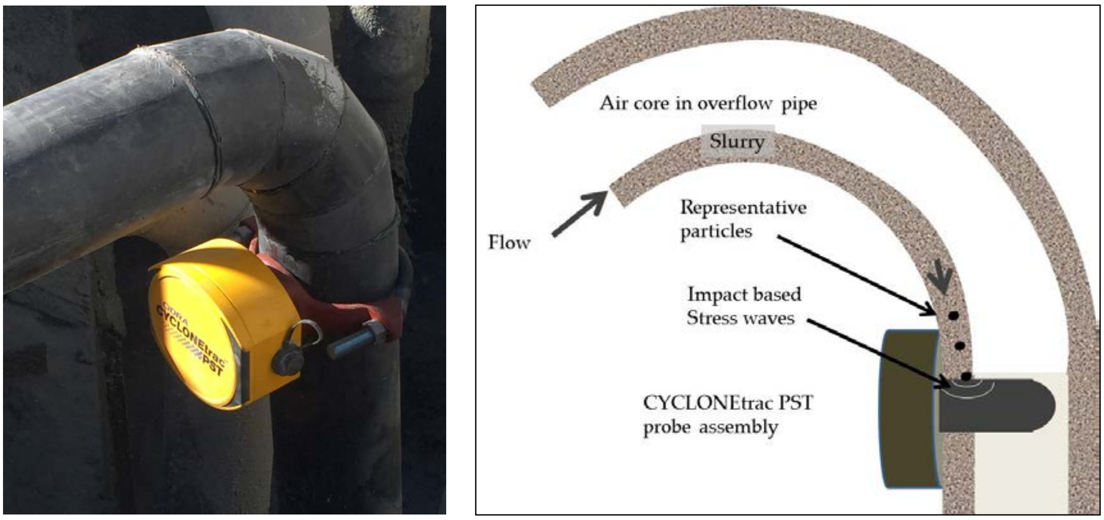

Figure 1. CYCLONEtrac PST - installed on overflow pipe (left); illustration of principle of operation (right).

IMPLEMENTATION AND PERFORMANCE

The CYCLONEtrac PST system consists of a sensor probe assembly on each cyclone as seen in Figure 2, one to two junction boxes per battery, and a control room computer. A second junction box will be required if there are more than 16 cyclones on a battery. The sensor probe assembly is made up of a hardened proprietary probe that penetrates into the overflow pipe and is in contact with the overflow stream, and an integrated electronics package that is protected by a sealed metal enclosure. The sensor probe assembly is powered by 24 V and communicates to a junction box using MODbus protocol. From the junction box the information is transferred to the control room computer via an Ethernet or Fibre over Ethernet line. The supplied control room computer transfers the particle size information to the plant DCS system via an OPC interface.

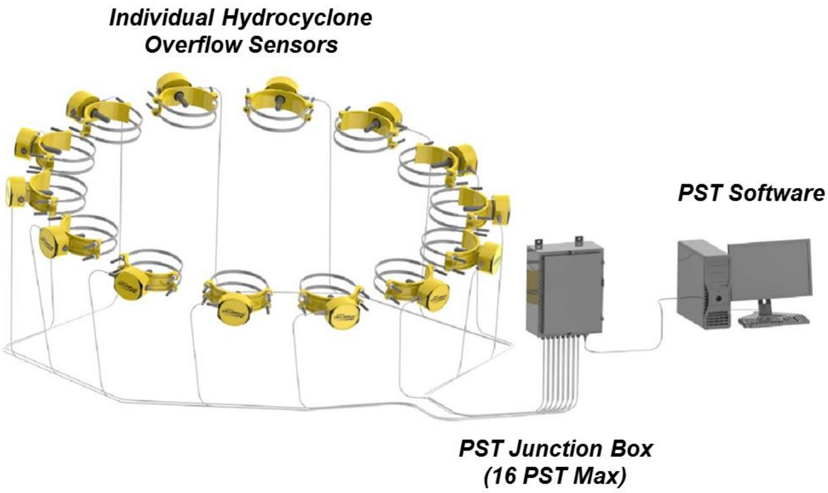

Figure 2. Illustration of particle sizing system.

Online cyclone overflow sizing methods, whether laser diffraction, ultrasonic, calliper, or impact based, require calibration by correlating their signals to reference particles or to samples that are correspondingly analysed with laboratory screens (Outotec, 2009). The impact-based CYCLONEtrac PST also requires calibration to compensate for influences from cyclone type, ore type, and sensor installation location. To ensure a good composite calibration that can be applied across all the cyclones in a cluster, calibration samples must be taken from the overflow of each cyclone in a cluster. Once such calibration takes place, it does not have to be performed again even if the probe is replaced. In addition, samples must be taken beyond the expected operating range of the cyclones to ensure accurate measurements when the cyclone is operating outside its normal operating range, including but not limited to roping events, start-ups, shutdowns, and grind-outs. This avoids the measurement uncertainty that occurs when calibration models are used to extrapolate measurements beyond their calibrated range. For rapid processing of samples, a single sieve size is used with a custom wet sieving procedure and equipment to generate a calibrated number, such as percentage of material passing the sieve size or retained by the sieve size.

The resulting calibrated signals exhibit a standard deviation that is less than 4.5 percentage points from the ideal. An undetermined but significant portion of this standard deviation can be attributed to the sampling. This observation is due to the typical situation in which the cyclone overflows have limited access for sampling, so a full cross-stream sample is difficult to obtain. Instead, plunge cuts or partial cross-stream cuts are performed. Assuming a sampling and sieving error of two percentage points, the results from the commissioning at a major copper concentrator are shown in Figure 3. In this example, the samples were sieved with a 150 µm screen. The assumed sampling error of two percentage points is shown as error bars.

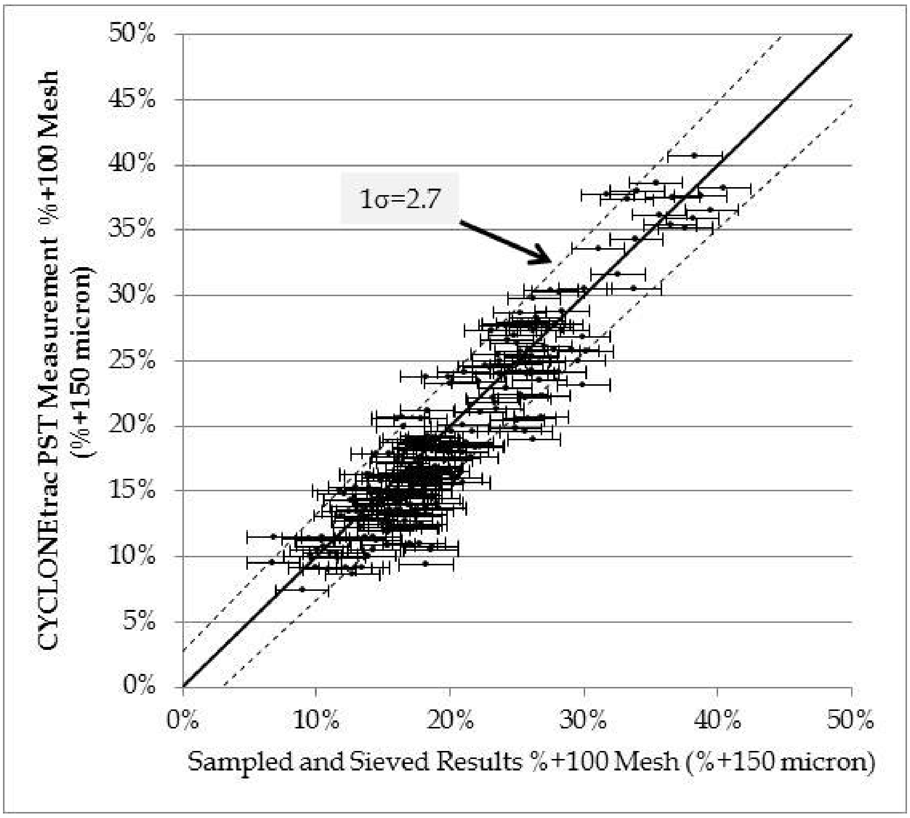

Figure 3. Comparison of CYCLONEtrac PST measurement with sampled and sieved data from a major copper concentrator. Dashed lines indicate calculated one standard deviation of 2.7.

An illustration of application at a grind size approximately half that of the previous example is shown in Figure 4. In this example, samples were sieved with a 74 µm screen. As in the previous example, an assumed sampling error of two percentage points is shown as error bars. The data for this example was taken on a single cyclone but with approximately the same results in terms of the standard deviation. The samples at approximately 70% retained by the 74 µm sieve were taken during roping events, demonstrating the expected increase in particle size during those events. This technology was tested at a variety of sieve sizes from 74 µm to 150 µm with a diverse range of metals, minerals, and ores, including gold in quartz, metasedimentary, metavolcaniclastic rocks, and metabasalts ore; porphyry copper ore; phosphate with silica, mica and magnetite; and iron ore with silica (O'Keefe *et al.*, 2016).

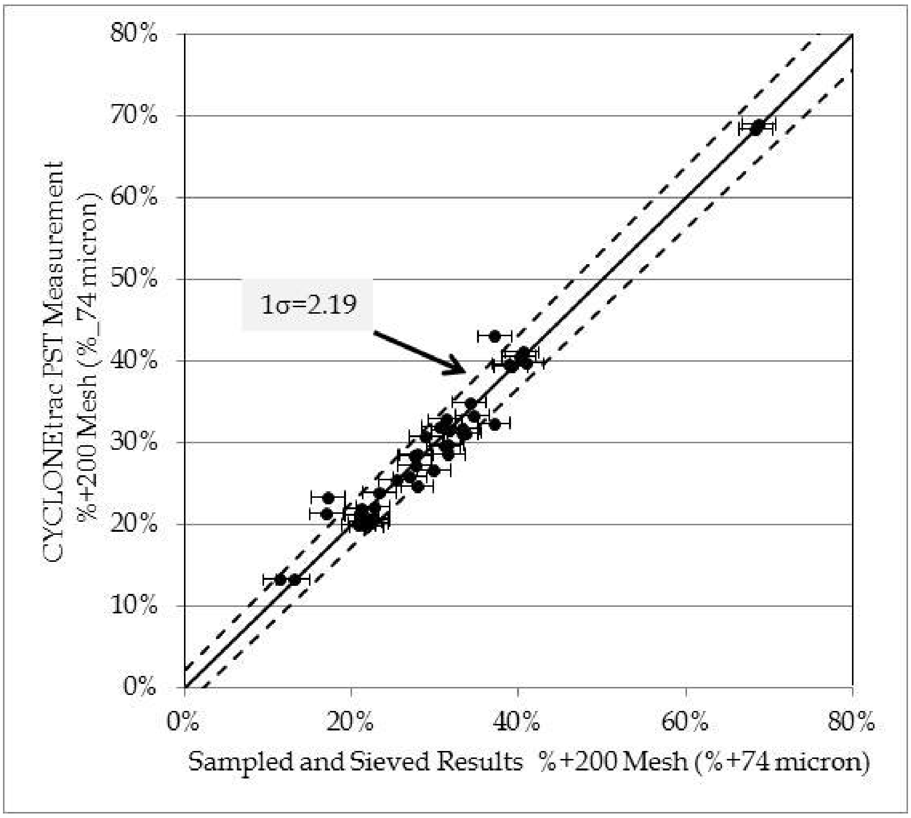

Figure 4. Comparison of CYCLONEtrac PST measurement with sampled and sieved data from copper, gold, and silver concentrator. Dashed lines indicate calculated one standard deviation of 2.17.

INDIVIDUAL CYCLONE MONITORING

Cyclones within the same battery or cluster often exhibit different cut-points. Both static and dynamic differences between cyclones have been noted by the author. Static or quasi-static differences can be attributed to dimensional variations. An example of the differences between cyclones on the same battery over a one-month period is shown in the histogram in Figure 5. From histograms and other analysis, including differences between means while cyclones are turned on, static or quasi-static variations can be seen.

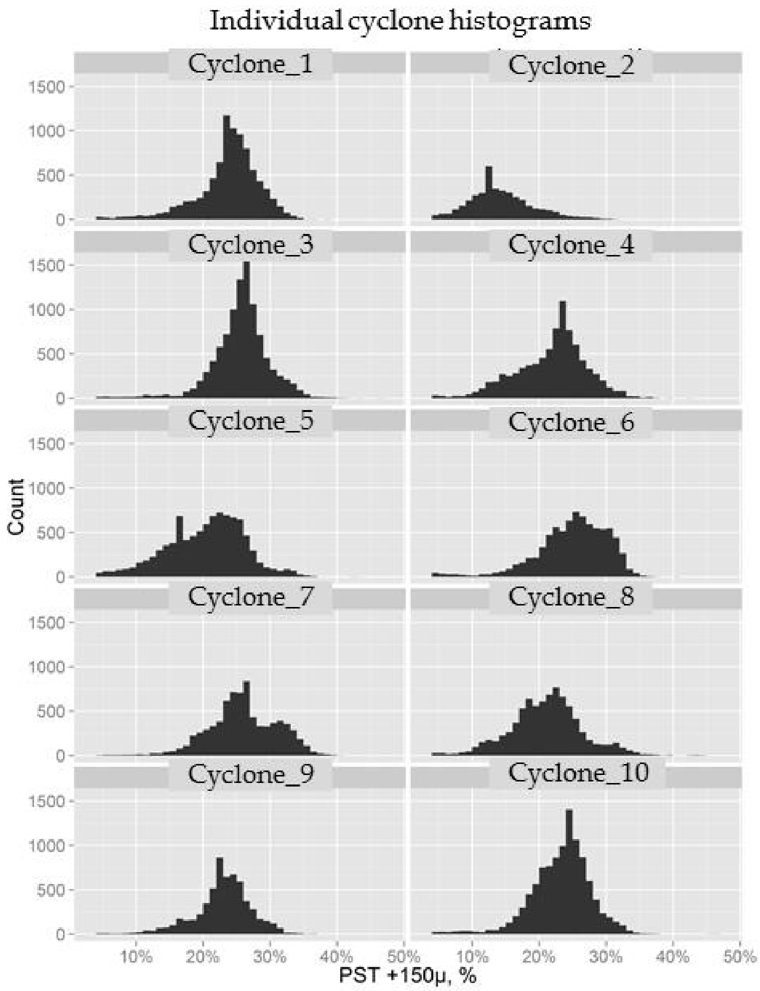

Figure 5. Histograms of particle sizes from the 10 cyclones on a battery over a one-month period.

Correlations between the cyclones in a battery can be viewed via scatterplots and a correlation matrix as seen in Figure 6 and Table I. The data-points from the transitions that occurred when the cyclones turned on were excluded from the scatterplots and the correlations. In this particular case some of the cyclones had good correlations with each other, particularly cyclones 1, 7, and 8 with correlations at 0.90 or greater. There were other groupings of cyclones and a few cases, such as cyclone 5, which had a poorer correlation with other cyclones, staying at 0.83 or below.

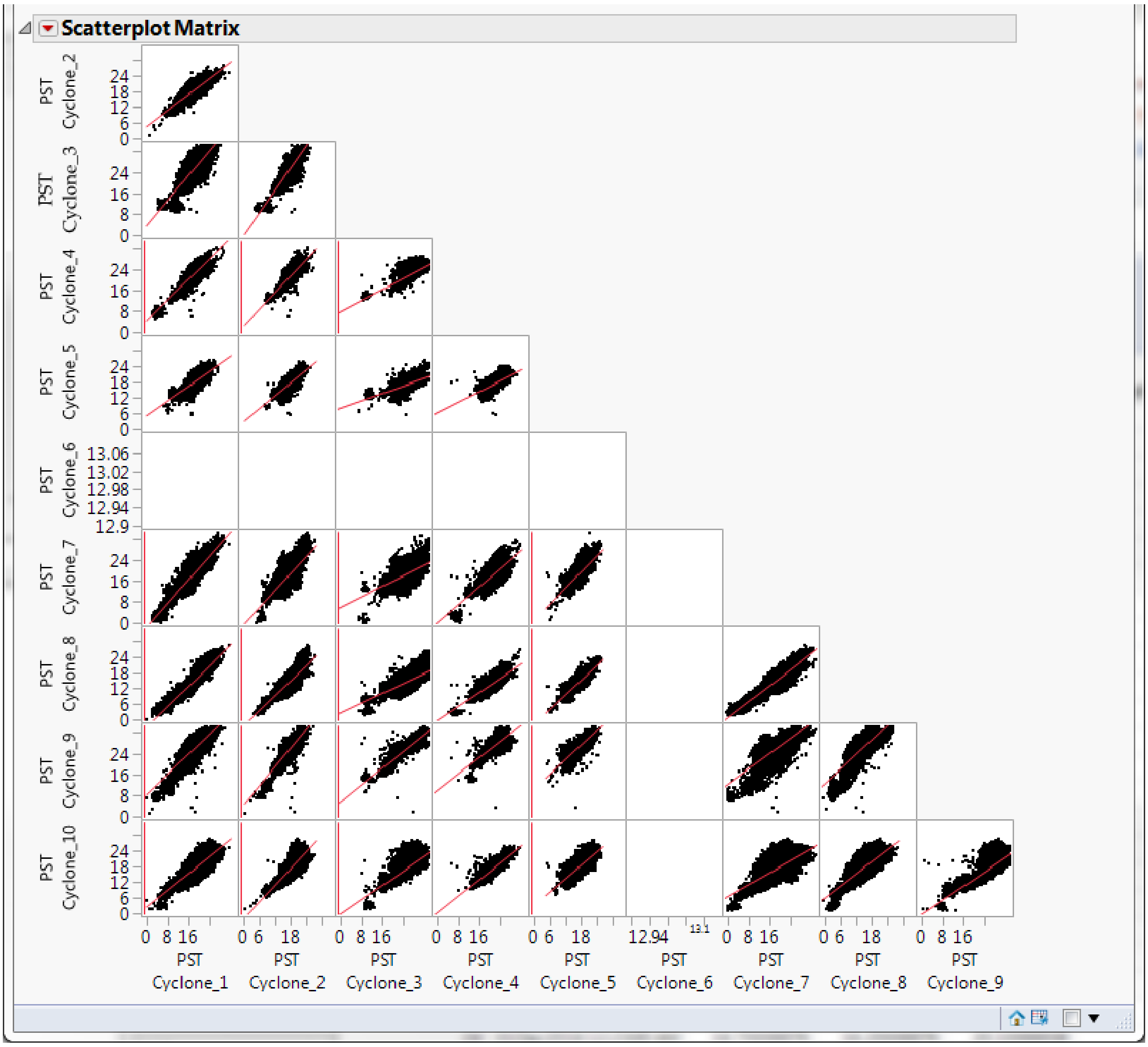

Figure 6. Scatterplots of particle size measurements from CYCLONETRAC PST on individual cyclones.

Table I. Correlation matrix with Pearson correlation coefficients indicating particle size correlations between cyclones on the same battery.

CYCLONEtrac PST Reading on Cyclone #										
Cyclone Number	1	2	3	4	5	6	7	8	9	10
1	1.00	0.82	0.71	0.84	0.79	0.00	0.90	0.93	0.74	0.69
2	0.82	1.00	0.88	0.85	0.81	0.00	0.78	0.81	0.87	0.82
3	0.71	0.88	1.00	0.75	0.69	0.00	0.60	0.75	0.93	0.79
4	0.84	0.85	0.75	1.00	0.63	0.00	0.75	0.80	0.77	0.89
5	0.79	0.81	0.69	0.63	1.00	0.00	0.78	0.83	0.72	0.66
6	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
7	0.90	0.78	0.60	0.75	0.78	0.00	1.00	0.92	0.71	0.63
8	0.93	0.81	0.75	0.80	0.83	0.00	0.92	1.00	0.73	0.71
9	0.74	0.87	0.93	0.77	0.72	0.00	0.71	0.73	1.00	0.76
10	0.69	0.82	0.79	0.89	0.66	0.00	0.63	0.71	0.76	1.00

Dynamic changes in the differences between cyclones have also been noted. An example taken over a one-day period is shown in Figure 7. Several areas are highlighted, including one where cyclone 8, which was exhibiting similar signal levels to cyclone 10, differs by three percentage points from cyclone 10 for a period of 84 minutes. At the same time cyclones 1 and 7 also drop in reported percentage of solids retained by the target sieve size. Speculation on the cause of these changes currently centres on a shift in the flow or density distribution to the cyclones.

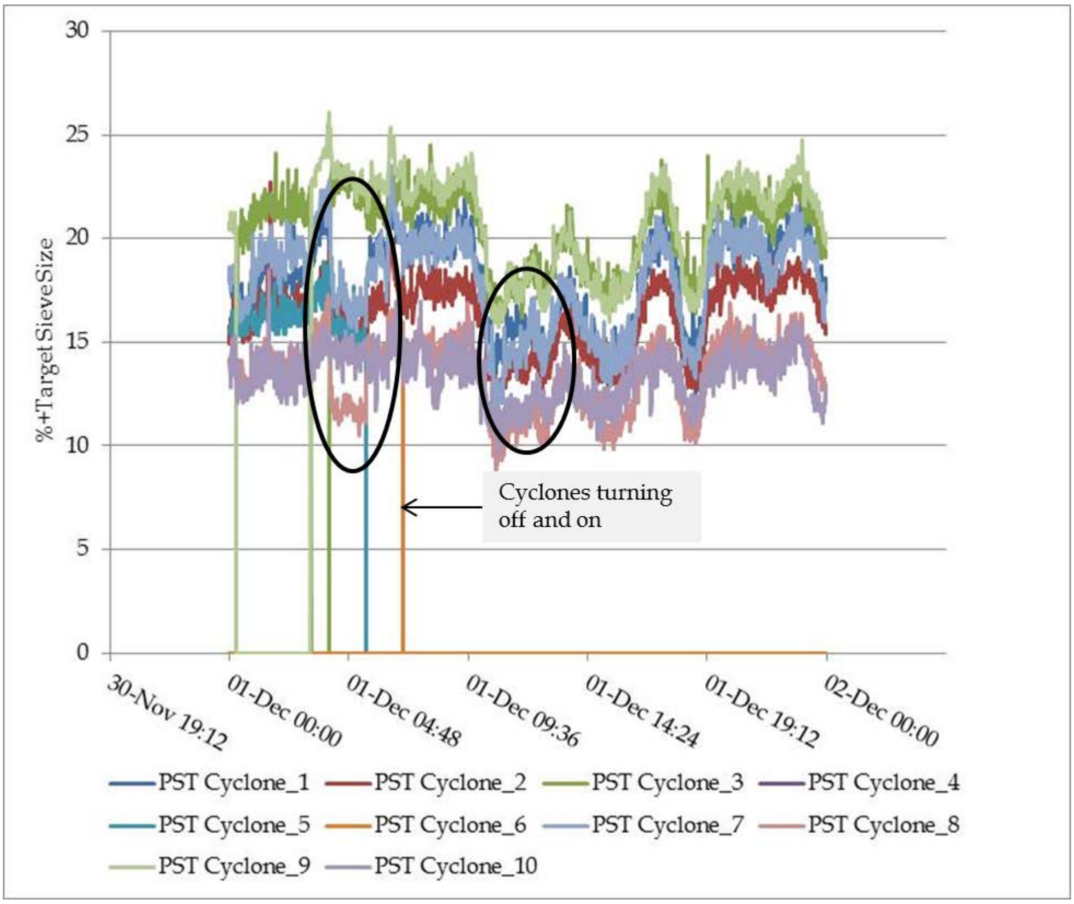

Figure 7. Time trace of particle size measurements on different cyclones on same battery indicating static and dynamic differences.

CORRELATION BETWEEN REAL-TIME PARTICLE SIZE AND GRINDING CIRCUIT OPERATING CHARACTERISTICS

A variety of models have been developed to calculate the overflow particle size. The cut size calculation produced by these models depends on a variety of influences, including dimensions of the cyclone vortex and apex, which can wear and change diameter, volumetric flow rate into the cyclone, volume fraction of solids being fed to the cyclone, feed size distribution, slurry viscosity, specific gravity of the solid particles, and specific gravity of the liquid phase. The validity of the models themselves is limited by the assumptions used in the first principle models and by the data-sets used in the empirical models. This leaves significant uncertainty in the results; thus, a direct measurement is required. Operational parameters, such as mass flow rate into the grinding circuit, density of the slurry feeding the cyclone battery, number of open cyclones, and volumetric flow rate into the cyclone battery, can be measured and adjusted. To control particle size, it is both necessary to measure the size and to have a means of controlling it. To determine whether an operational parameter can significantly influence the size, correlations between each operational parameter and the particle size are determined.

A particle sizing system was installed on a battery in a precious metals facility with a target grind size of 20% retained by the target sieve size. The particle size averaged from the operating cyclones was compared to battery pressure and battery feed density. The cross-plot between the pressure and the particle size is shown in Figure 8. The correlation is poor but trends with a positive slope, implying that the particle size increases with increasing pressure, which is contrary to the equations used to model the behaviour of cyclones. The cross-plot between the particle size and the cyclone battery feed density exhibits a stronger trend, as seen in Figure 9, and does follow the expected sensitivity, exhibiting an increase in particle size with increasing density. Since the influence of the pressure was contrary to the models, a cross-plot of the pressure with feed density was created as seen in Figure 10. The pressure increases with increasing feed density, which implies that the feed density has a stronger influence on particle size than pressure.

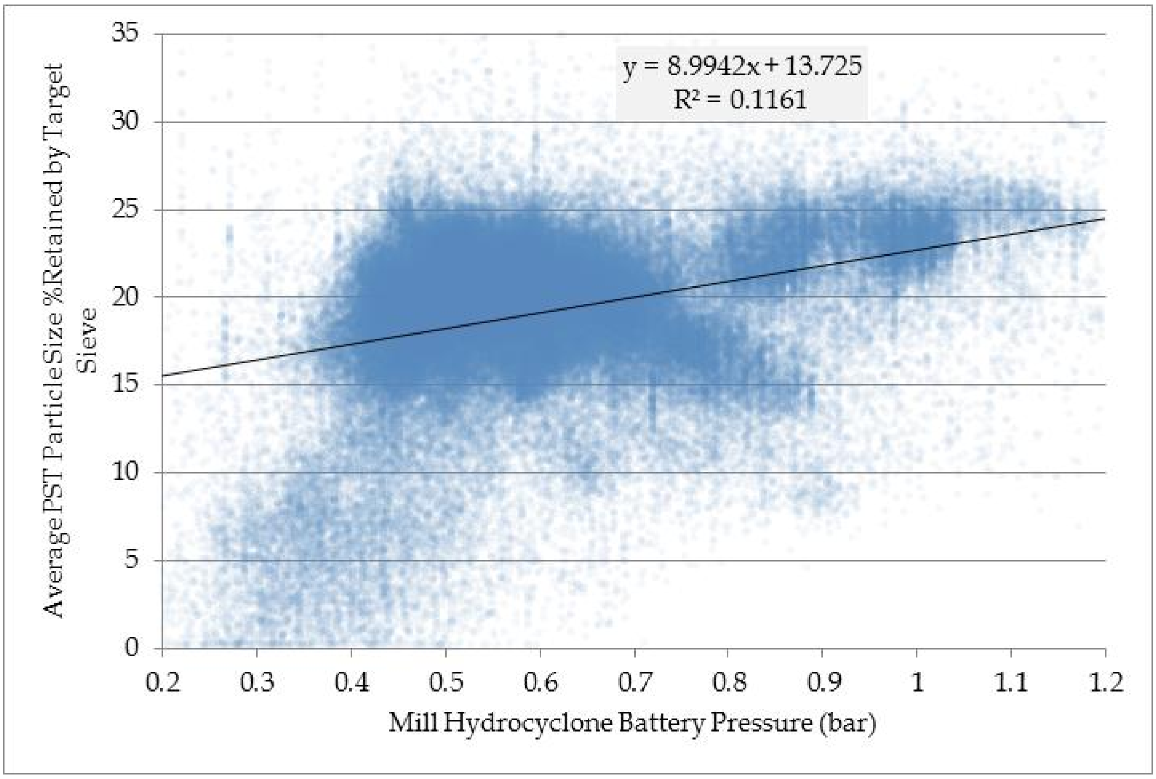

Figure 8. Cross-plot of particle size as averaged from operating cyclones versus cyclone battery pressure.

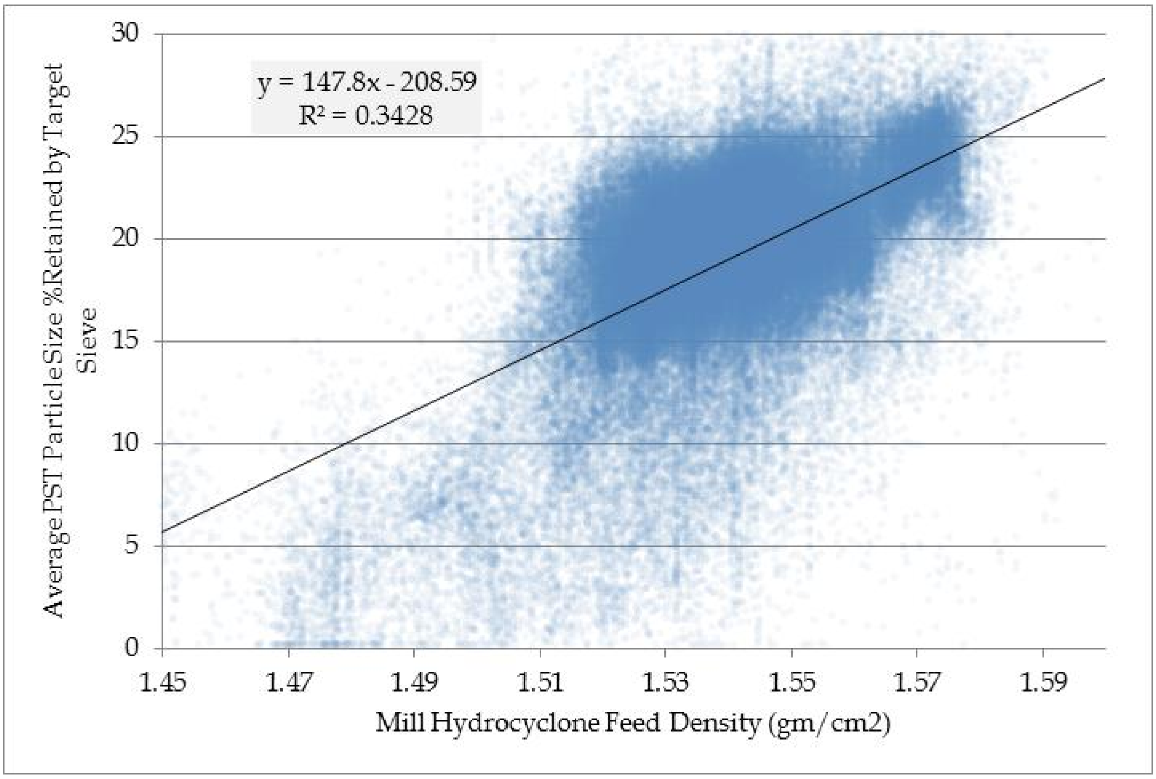

Figure 9. Cross-plot of average cyclone overflow particle size versus cyclone battery feed density.

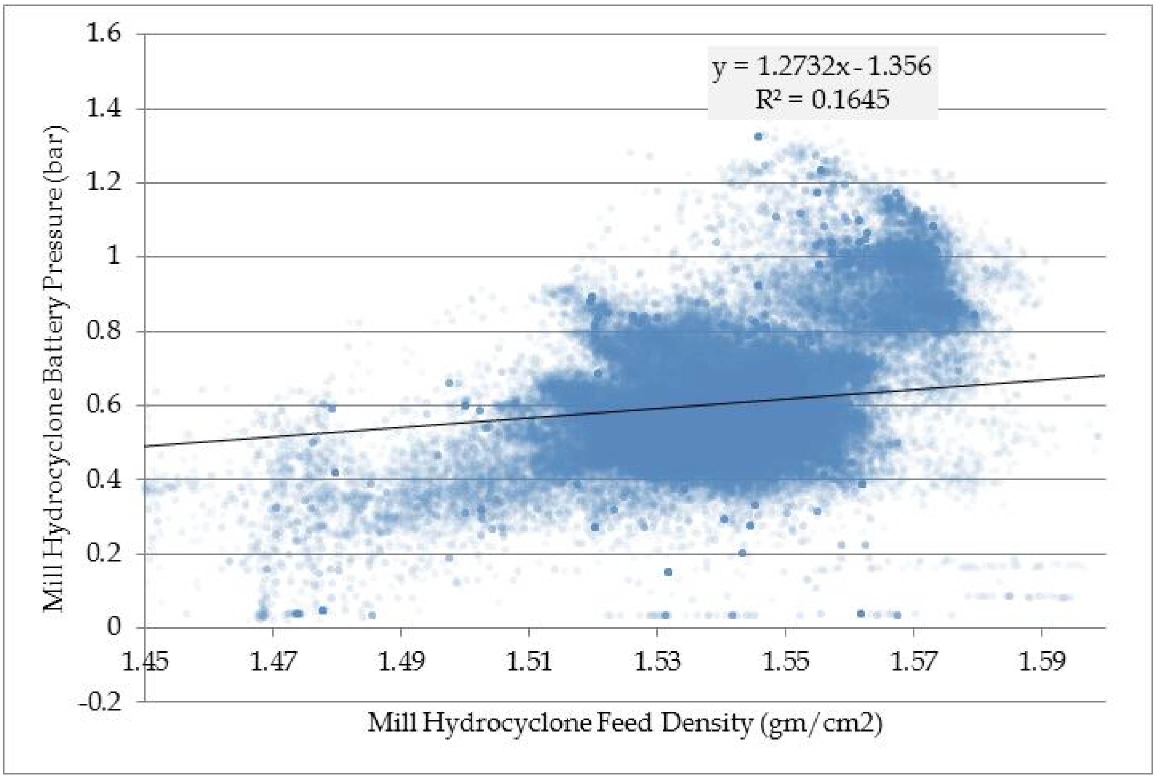

Figure 10. Cyclone pressure plotted versus cyclone feed density.

The results from this plant are typical when compared to other tests performed using the CYCLONEtrac PST to measure particle size and correlate the changes in the size to operational conditions. Cyclone feed density is the predominate driver of particle size in the cyclone overflow.

CYCLONE CONTROL METHODS ENABLED BY CYCLONETRAC PST MEASUREMENT

Several control methods are enabled by the CYCLONETRAC PST measurement, but they can be broadly classified into two groups: (1) cyclone level control and (2) battery level control. Cyclone level control can be further subdivided into a control mode for coarse particle prevention and a control mode for sharpness increase. For coarse particle prevention, the individual cyclones are monitored in order to close a cyclone that is passing particles whose size distribution exceeds a threshold. By closing such cyclones, the battery sharpness will increase, but more importantly, the loss of recovery due to the passing of oversize particles and potential continuation into a roping condition can be prevented.

For battery level control, the CYCLONETRAC PST measurement is used by the control system to adjust operating conditions that will affect the overflow particle size. Typically, density or percent solids in the cyclone battery feed have the largest impact, thus a control system in which the difference between the measured particle size and the desired particle size is used to adjust the percent solids can be used to control the particle size. Such a system is outlined in Figure 11.

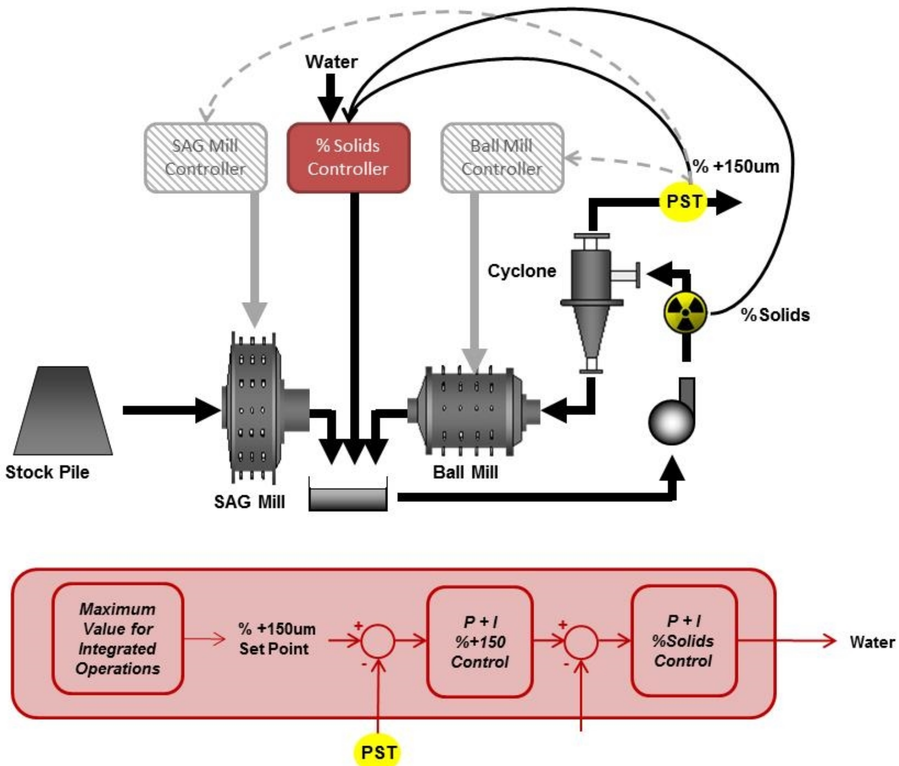

Figure 11. Example of battery level particle size control using CYCLONETRAC PST measurement.

RESULTS OF USING CYCLONETRAC PST IN CONTROL SYSTEM

By controlling particle size both by adjusting the size in order to maximize economic value and by reducing variability in the size, it is possible to increase the efficiency of the ball mill circuit. An example of the impact of using the particle size measurement to control the size is shown in Figure 12. During the 5½ month period covered by this data-set, the control mode operated under density control and under particle size control at different times. The slope and offset of the best line fits for the data under density control *versus* particle size control indicate that operation under particle size control on the average results in more favourable results. The square of the Pearson product moment correlation coefficient or R2 is higher under particle size control than under density control, also indicating a more favourable operating mode (Cirulis *et al*., 2015).

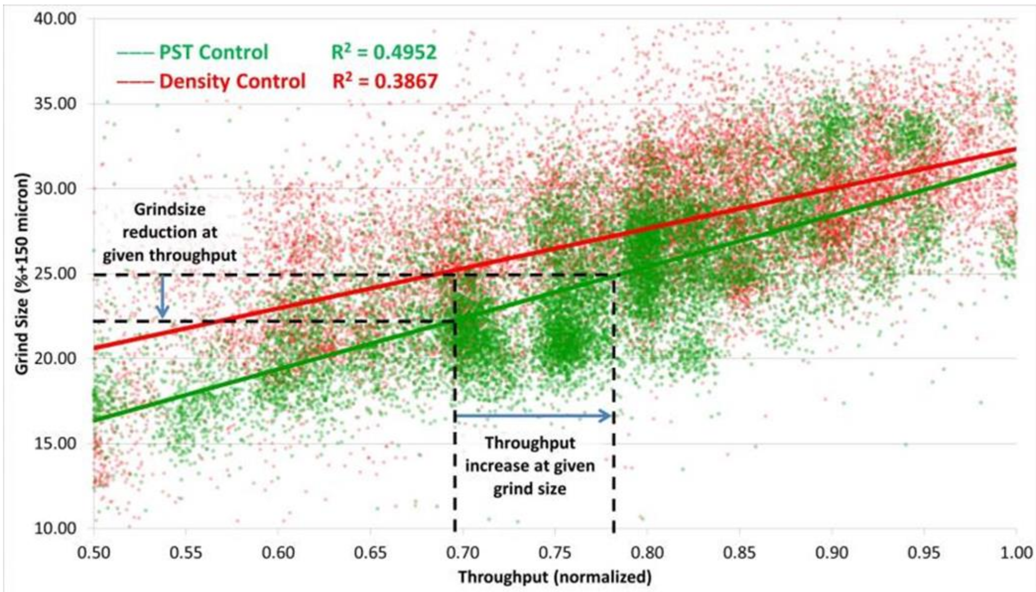

Figure 12. Impact of using control enabled by CYCLONEtrac PST measurement compared with traditional density control.

CONCLUSIONS

The impact-based particle sizing technology implemented in CYCLONEtrac PST has demonstrated accurate particle size measurement. Due to its real-time measurement with a four-second update, it has enabled battery level control that resulted in throughput increases for the same particle size or reduced particle sizes with the same throughput. The four-second update rate, with minimal lag between the time the slurry impacts the probe and the time the measurement is reported, has enabled correlations between plant battery operating conditions, such as pressure and feed density to particle size. These correlations indicate that feed density is a much stronger driver of particle size compared to pressure. The changes in particle size at a fixed feed density indicate that the particle size cannot be controlled by holding the feed density constant. Instead, particle size must be measured, and this measurement must be used to adjust feed density in order to adjust the particle size.

ACKNOWLEDGEMENTS

The author is grateful to the plant personnel and corporate partners who have provided the opportunity to test this unique technology and who provided the plant data required to obtain an understanding on how particle size in the cyclone overflow is influenced. The author also wishes to thank Susan McCullough and Alessandra Castillo from CiDRA for proofreading this paper.

REFERENCES

Cirulis, D., Dunford, S., Snyder, J., Bartsch, E., Rothman, P., Maron, R., Newton, D., O'Keefe, C., and Mercuri, J. (2015). Process optimization using real time tracking of coarse material in individual cyclone overflow streams. *Proceedings of MetPlant 2015*. Australasian Institute of Mining and Metallurgy, Melbourne. pp. 93-109.

O'Keefe, C., Maron, R., Cirulis, D., and Medina, J. (2016). Multiple concentrator survey of real-time individual cyclone particle size tracking (PST). *Proceedings of Procemin 2016, the 12th International Mineral Processing Conference*, Santiago, Chile, 26-28 October. Velásquez, C. (ed.). Gecamin Ltda, Santiago.

Outotec Oy. (2009). PSI® 300. On-line slurry particle size analyser. http://www.outotec.com/globalassets/products/analyzers-and-automation/ote_psi300i_particle_size_analyzer_eng.pdf

Wills, B.A. and Finch, J.A. (2016). *Wills Mineral Processing Technology: An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery,* 8th edn. Butterworth-Heinemann, Amsterdam.