# Innovative technologies for uranium processing – impact-based real-time particle size measurement and non-invasive flow measurement

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Base and precious metals have been adopting newly available technologies for measuring key parameters in the grinding circuit, specifically flow rate and grind size. These same technologies can be applied to uranium processing, providing advantages over current instruments. Non-contact flow measurements using an array of sensors wrapped around the outside of a pipe have enabled safe, accurate flow readings in particularly abrasive and harsh slurry environments. The principle of operation of this technology and its application in such environments are described. Until a few years ago, control of grinding circuits has been stymied by the lack of a real-time measurement of particle size reporting to the hydrocyclone overflow. With the introduction of the impact-based particle size measurement method four years ago, grind control systems can depend on a real-time measurement of particle size on individual hydrocyclone overflows with virtually 100% data availability. The principle of operation of this sampler-free measurement technology, its implementation, and measurement performance are discussed. Correlations to plant data indicating the influence, or lack of influence, of operational characteristics such as hydrocyclone feed density and cluster pressure are shown.

## INTRODUCTION

To enable proper control of a grinding circuit, it is necessary to have accurate, reliable information about key operating parameters. Two such parameters are flow rate and particle size. Slurry flow measurements in a minerals processing plant, and particularly on a hydrocyclone feed line, are challenging, making it difficult to obtain reliable and accurate flow readings. The array-based flow meters have proven to provide accurate and, due to their non-invasive implementation, reliable flow readings. This technology is truly unique (Baker 2016). Automated particle size measurements have been traditionally performed with automated samplers that obtain samples from the consolidated overflow of a cyclone battery and feed the slurry samples to ultrasonic, laser, or caliper-based particle sizers. These particle sizing systems have update rates of the order of minutes and uptimes that typically range from 20% to 80%. The new technology using an impact-based technique provides for a sampler-free system with four-second updates from each cyclone in a battery.

## NON-INVASIVE FLOW MEASUREMENT

### Principle of Operation

Sonar array-based meters track and measure the mean velocities of coherent disturbances travelling in the axial direction of a pipe. These disturbances can take many different forms and can propagate at different velocities. Their propagation method and velocities include those that are conveyed with the flow (slowest velocity – fluid flow), those that propagate in the fluid or slurry (mid-range velocity – acoustics), and those that propagate in the pipe walls (fast velocity – vibrations). The sonar array-based meters discriminate between the three main types of disturbances through a combination of frequency and velocity differences (O'Keefe, Maron, and Gajardo, 2007).

Disturbances that are conveyed by the flow include density variations, temperature variations, and turbulent eddies. The overwhelming majority of industrial flows will have turbulent eddies that travel with the flow, thus providing an excellent means of measuring the flow rate as described below. Turbulent flow is composed of eddies, also known as vortices or turbulent eddies, that meander and swirl in a random fashion within the pipe but with an overall mean velocity equal to the flow; that is, they travel with the flow. An illustration of these turbulent eddies is shown in Figure 1. As these turbulent eddies pass by any fixed location on the pipe, they will exert a small dynamic stress on the inside of the pipe wall. The strain induced in the pipe wall from these dynamic stress fluctuations is converted to an electrical signal by a passive sensor array wrapped partially or fully around the pipe. Each such passive sensor element in an array of sensors will detect the unique signal from each collection of turbulent eddies. The separation between sensors in the array is shorter than the coherence length of the turbulent eddies, thereby resulting in similar voltage signatures from each sensor in the array with only a delay in time. When sonar array processing is applied to the output signals of the array, the velocity at which these turbulent eddies pass through the array of sensors is determined, thus providing the propagation speed of the fluid within the pipe (Nelson, 2001). This process is illustrated with one collection of turbulent eddies in Figure 1, but in practice is applied to numerous collections of turbulent eddies.

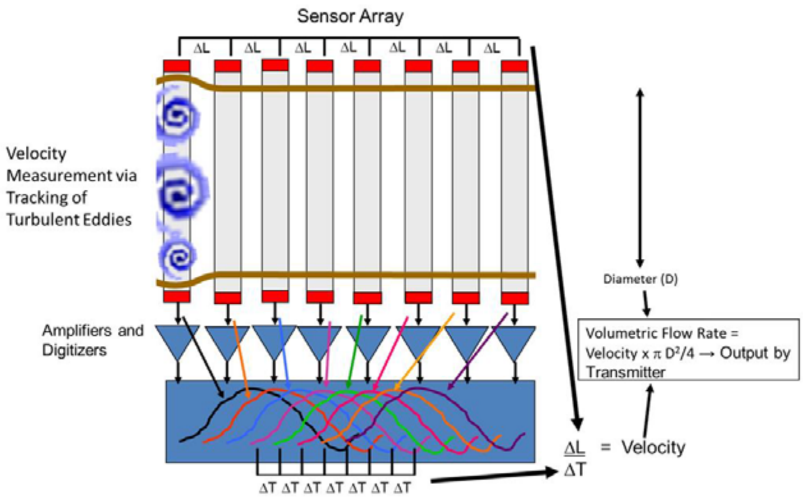


*Figure 1. Illustration of signal detected by passive sensors in array from one collection of turbulent eddies.*

**Implementation of Measurement Technique**

In a commercial embodiment of this measurement principle, seen in Figure 2, a flexible band of passive sensors is wrapped around and tightened onto the pipe. This is a dry fit that does not require gels or couplants since ultrasonic waves are not used. The sensor band is always 50 cm long in the axial direction of the pipe for pipes that are smaller than 1 m diameter and equal to the circumference of the pipe in the orthogonal dimension. The typical installation procedure and hardware embodiment is outlined in Figure 2. The pipe is first wiped down and any high points are sanded or filed away to ensure good mechanical contact. The flexible sensor band is then wrapped around the pipe and a series of captive screws on the sensor band is used to tighten the band onto the pipe. Each screw uses a stack of spring washers to allow for pipe expansion and contraction, as well as to ensure a set clamping force without requiring torque wrenches or screwdrivers. A protective cover with signal conditioning and diagnostics electronics is installed over the sensor band, and the sensor band is connected to the electronics in the cover. The cable from the sensor head to the transmitter is installed and wired to the transmitter. Finally, the front panel menu on the transmitter is used to configure the transmitter.


*Figure 2. One implementation of array-based flow meter.*

**Case Studies on Hydrocyclone Feed Lines**

Measurement of flow on hydrocyclone feed lines is performed primarily to determine the circulating load in a grinding circuit. To calculate the circulating load, both the volumetric flow and the percentage of solids must be measured. The percentage of solids is typically measured with a nuclear density gauge and must be corrected for any entrained air bubbles by using the gas void fraction (air content) measurement of the array-based flow meter, which is the only technology known to be able to perform this measurement on a cyclone feed line in an industrial environment.

Multiple comparisons of electromagnetic flow meters and array-based flow meters for measuring the volumetric flow on a cyclone feed line have been performed. When the flow meters are compared against pressure, it is expected that the flow will be proportional to the square root of the pressure but with influences from the number of open cyclones. This comparison is shown in Figure 3. The array-based flow meter had an $R^2$ of 0.86 and root mean square error of 17.7; whereas, the electromagnetic flow meter had an $R^2$ of 0.24 and a root mean square error of 54.7 when trended against a model using the square root of the pressure.

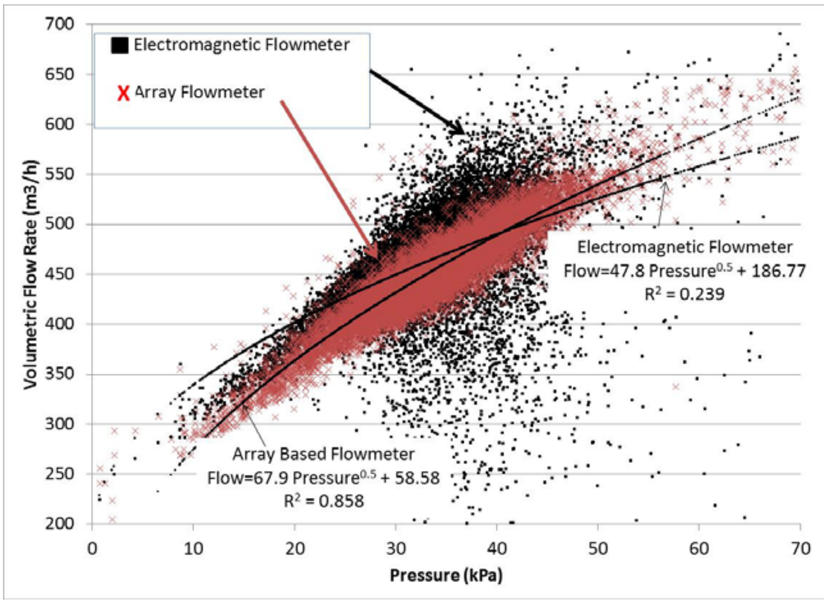


*Figure 3. Hydrocyclone feed line electromagnetic flow meter (black squares) and array-based flow meter (red X) compared to pressure.*

**Calibration Robustness with Changing Slurry Density**

Most flow meters were initially designed to measure liquid flows and have subsequently been adapted to measure multiphase fluids, typically slurries. Calibration of flow meters and the resulting accuracy specifications are typically performed under laboratory conditions using water as the fluid. Slurry calibration is not typically performed, but can be done with tank fill, tank drawdown, and dye and nuclear tracer tests. To measure the effect of slurry on the calibration of a flow meter these tests would have to be repeated with water only and then with slurry. Alternatively, this test can be performed using slurry pipelines, particularly long pipelines, which have slurry and water present at the same time but at different points in the pipeline. In these situations, slurry is transferred in the pipeline above the required minimum flow velocity until there is insufficient slurry available in the tank feeding the pipeline to maintain flow or the suction head of any pumps. At that point the feed from the tank is stopped and water is injected into the pipeline to maintain the required minimum flow velocity. One such case is illustrated in Figure 4, where in a 50 km copper concentrate pipeline, water was introduced at times as evidenced by the readings from the nuclear density gauge at the beginning of the pipeline and the nuclear density gauge near the end of the pipeline. In Figure 4, the water slug is seen to pass from one location to the next, as evidenced by the drop in density.

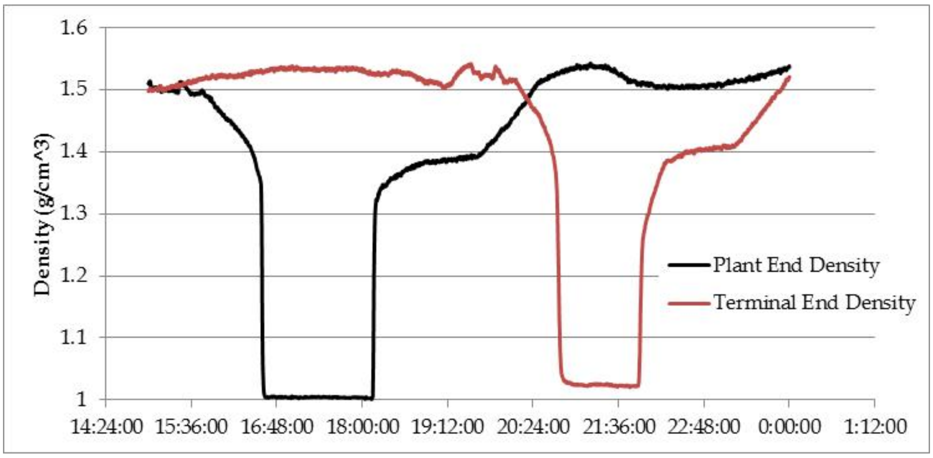


*Figure 4. Density readings from nuclear density gauges at the two ends of a 50 km pipeline, showing water slug passing from the plant end to the terminal end.*

The volumetric flow readings from the array-based flow meter are shown in Figure 5. During the transition from slurry to water, some disruptions in the flow can be seen, but despite both flow meters measuring fluid with different densities, the flow readings are essentially the same. In this figure, the size of the plant-end data points on the graph had to be increased in order to be seen behind the terminal-end data points.

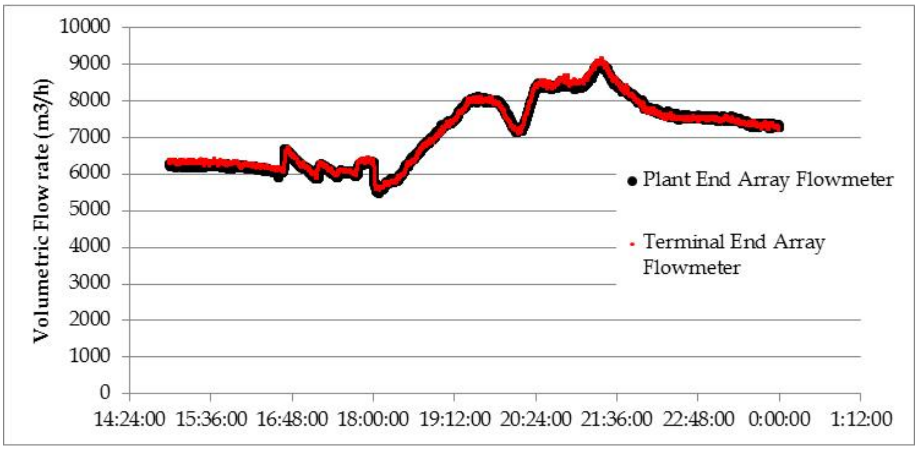


*Figure 5. Volumetric flow readings at plant end and terminal ends using a SONARtrac array-based flow meter.*

Not all flow meters exhibit this resistance to changing solids content. The slurry electromagnetic flow meters installed on this pipeline showed sensitivity to solids content, as seen in Figure 6.

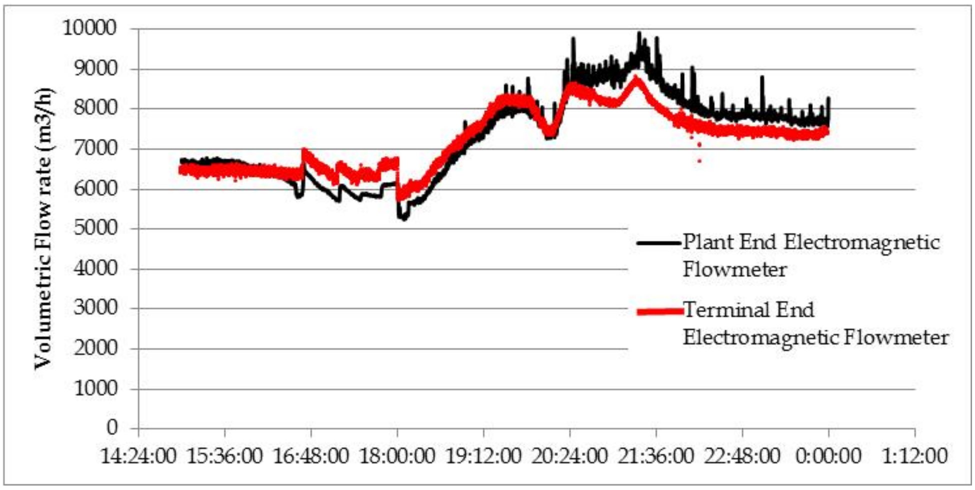


*Figure 6. Electromagnetic flow meter readings of volumetric flow with varying density.*

**IMPACT-BASED, REAL-TIME HYDROCYCLONE PARTICLE SIZE MEASUREMENT**

**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, seen in Figure 7, is centred upon a probe that is inserted into the slurry stream via a two-inch (50 mm) hole in the overflow pipe. Particles within the slurry stream impact the surface of the probe, generating travelling stress waves within the probe. A sensor converts these travelling 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 per cent or more of the slurry stream, thus obtaining information from orders of magnitude more particles than traditional sampler-based technologies. Also, because of the location of the sensor downstream of the hydrocyclone and the presence of an air core at that point, the sensor produces no change in the back-pressure seen by the hydrocyclone.


*Figure 7. CYCLONEtrac PST particle sizing sensor mounted on hydrocyclone overflow pipe.*

**Implementation of Measurement Technique**

The commercial implementation of the particle sizing system includes a measurement probe with its associated electronics on each cyclone overflow pipe, as seen in Figure 7, and a junction box that consolidates the processed signals from the individual sensors and sends them to a computer that is typically located in the control room. Final processing takes place in that computer, and the resulting particle size information is transferred to the plant system via an integrated OPC server. Currently, the software provides a single size that is to be used by the control system. This system is outlined in Figure 8.

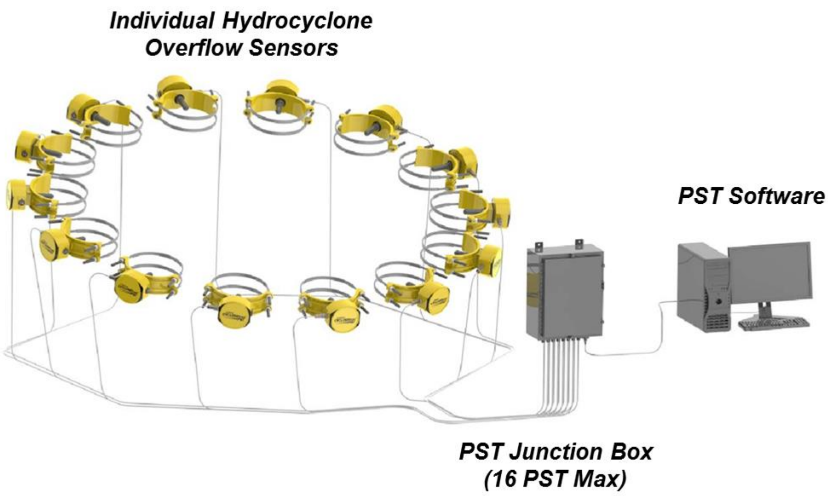


*Figure 8. Particle sizing system schematic.*

On-line cyclone overflow sizing methods, whether laser diffraction, ultrasonic, caliper, or impact-based, require calibration by correlating their signals to reference particles or to samples that are correspondingly analysed with laboratory screens. The impact-based CYCLONEtrac PST also requires calibration to compensate for influences from cyclone 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, startups, shutdowns, and grindouts. 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 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. Cyclone overflows typically 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 commissioning at a phosphate concentrator are shown in Figure 9.

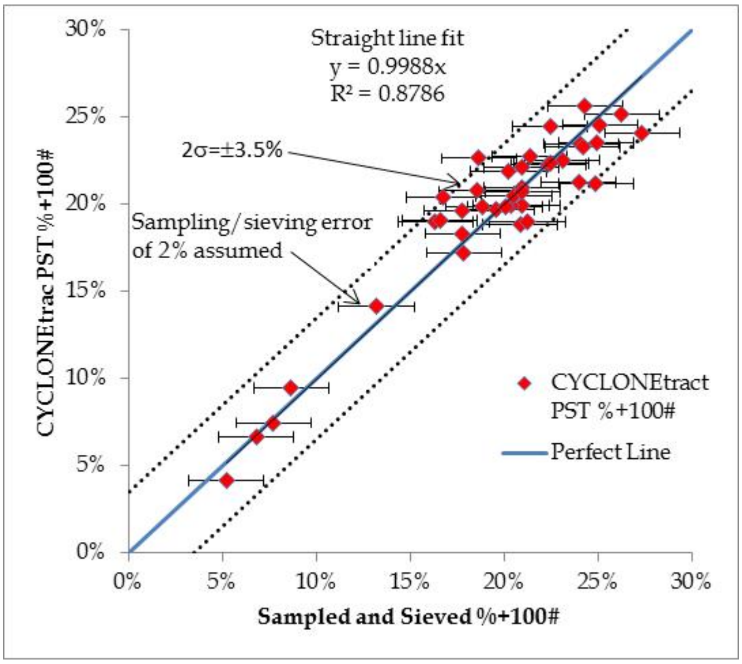


*Figure 9. Example of PST results from sa ingle cyclone compared to sampled and sieved measurements.*

**Selected Real-Time Measurements during Plant Operations**

This technology was used to measure the variability in the particle size reporting to the overflow of a cyclone. Variability occurs due to changes in feed density to the cyclone battery, pressure or flow changes to the cyclone battery, changes in the ore hardness reporting to the grinding circuit, changes in ore specific gravity, and changes in the feed rate to the grinding circuit. The degree to which these changes affect the particle size depends on the fundamental influences on a cyclone and on the circuit. To the first order these can be ascertained by correlating the particle size with the plant parameters that are typically measured, such as cyclone battery pressure, cyclone feed density, and grinding circuit solids feed rate.

First, the correlation with pressure from two different mine sites are shown in Figure 10 and Figure 11. In the data from mine site no. 1, it can be seen that pressure was controlled mostly between an upper limit and lower limit but was clustered around several major points. This data was captured over a 48-hour period with data every four seconds and no filtering. Additional filtering was found to reduce the correlations. At mine site no. 2, the pressure was tightly controlled, but the particle size varied from 0% to 50% retained by a 150 µm sieve. This data was captured over an 86-hour period at a similar data rate to that at site no. 1.

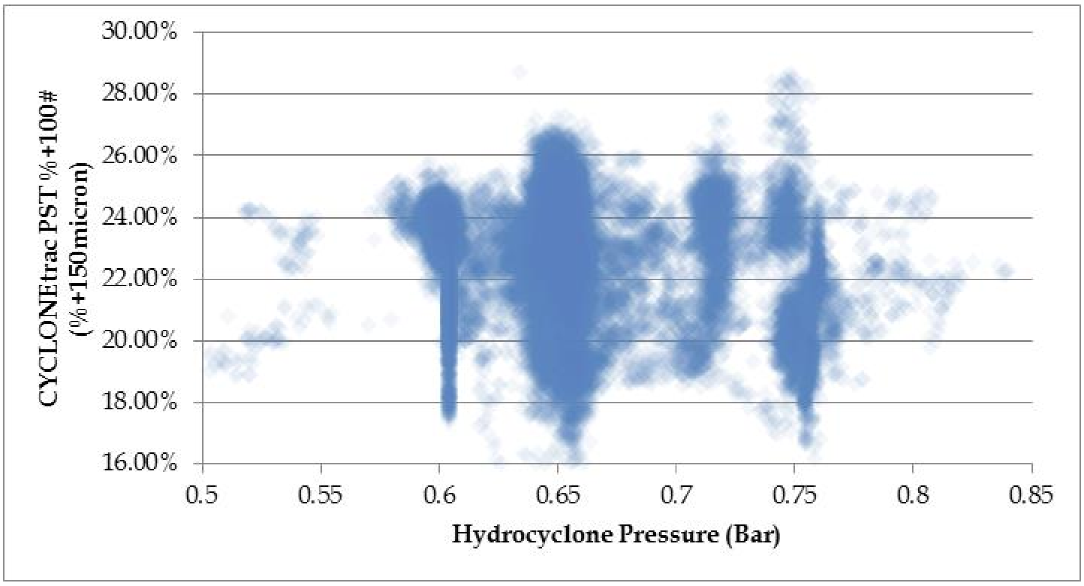


*Figure 10. Particle size retained by 100 mesh screen as measured with CYCLONEtrac PST versus hydrocyclone battery pressure at mine site no. 1.*

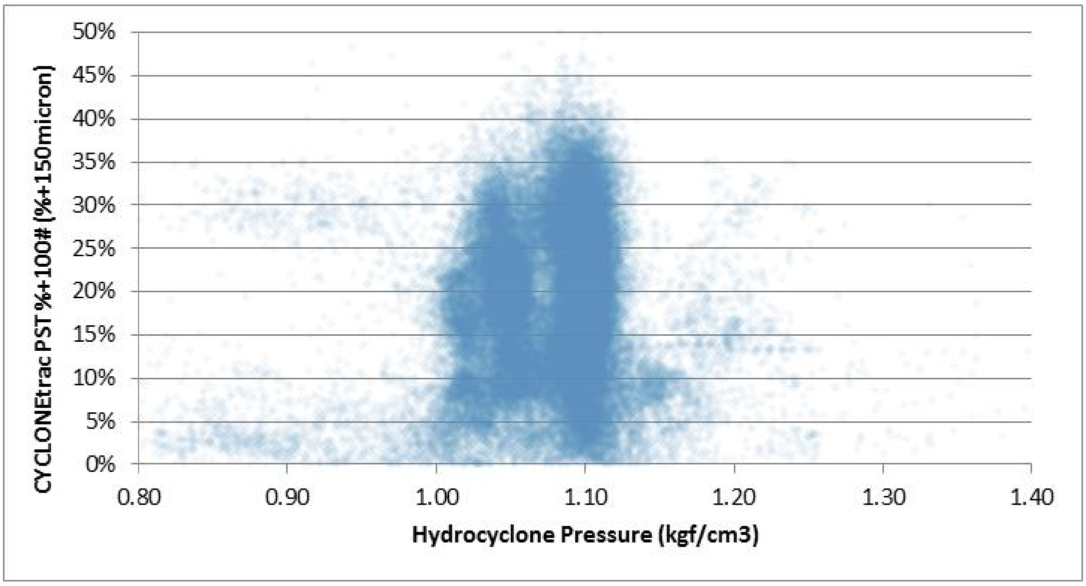


*Figure 11. Particle size retained by 100 mesh screen as measured with CYCLONEtrac PST versus hydrocyclone battery pressure at mine site no. 2.*

Second, the correlation with percentage solids in the cyclone feed from the same two different mine sites is shown in Figure 12 and Figure 13. In the data from mine site no. 1, it can be seen that the percentage solids varied between 32% and 46%, and the particle size varied by approximately twelve percentage points. At mine site no. 2, the percentage solids varied from 55% to 64%, but the particle size varied from 0% to 45% retained by a 150 µm sieve.

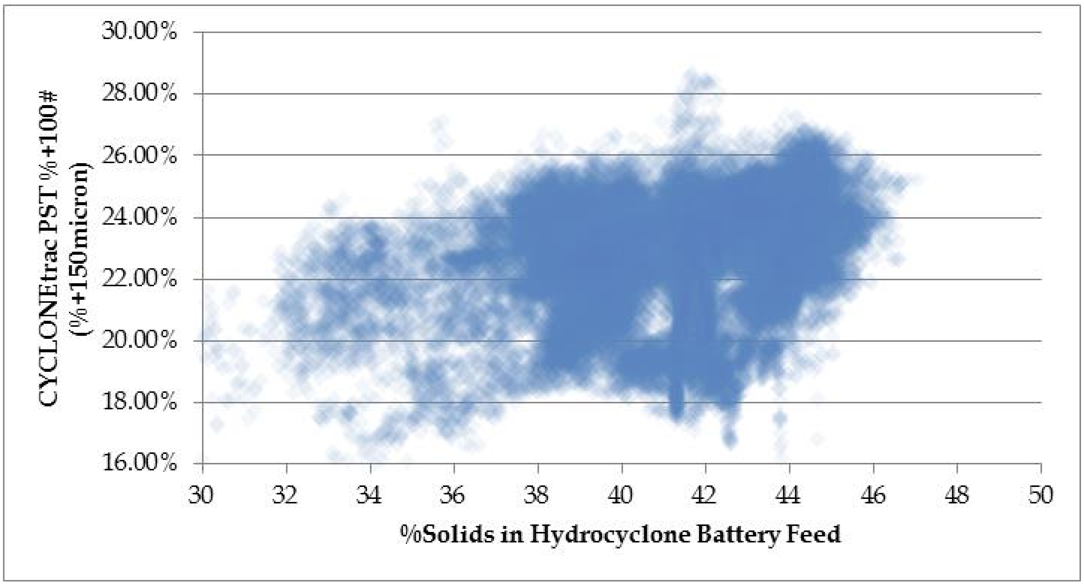


*Figure 12. Particle size retained by 100 mesh screen as measured with CYCLONEtrac PST versus % solids in the feed to the hydrocyclone battery at mine site no. 1.*

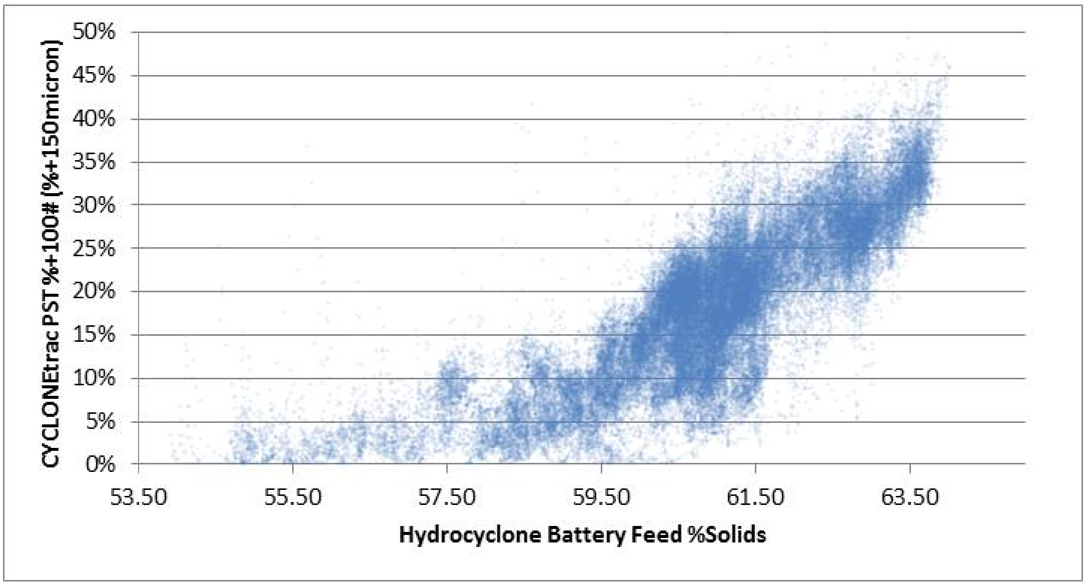


*Figure 13. Particle size retained by 100 mesh as measured with CYCLONEtrac PST versus % solids in the feed to the hydrocyclone battery at mine site no. 2.*

The particle size reporting to the cyclone battery overflow at mine site #2 appears to correlate well with the density or percentage solids in the feed to the hydrocyclone battery. At mine site no. 1, the correlation is not as strong; therefore, other plant parameters were examined. The strongest correlation was found to be associated with the mass flow of the solids fed to the hydrocyclone battery, as shown in Figure 14.

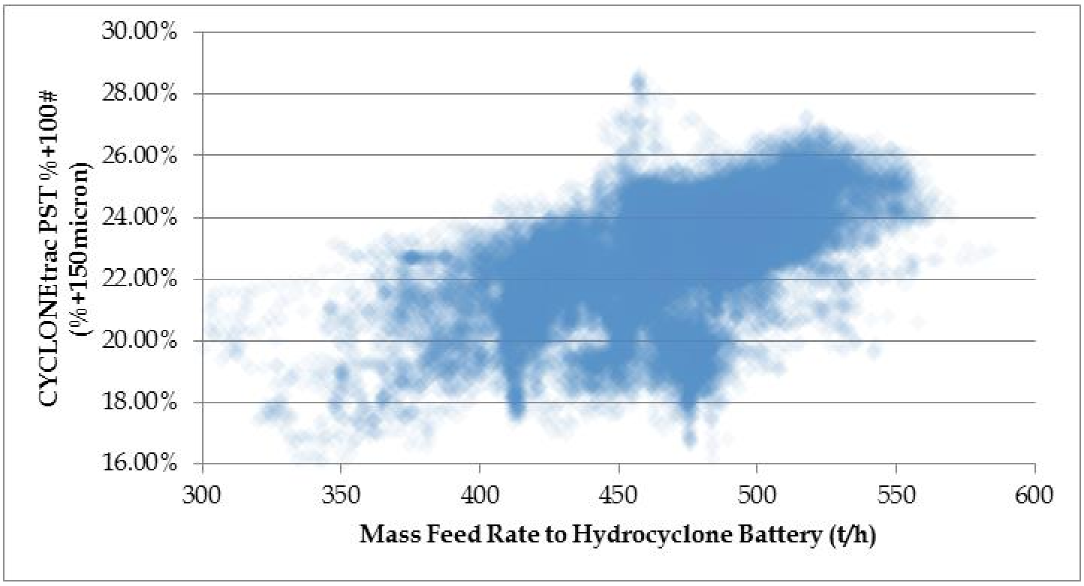


*Figure 14. Particle size in the hydrocyclone overflow as a function of the mass flow rate of solids fed to the hydrocyclone battery at mine site no. 1.*

**Changes in Control Strategy Enabled by Real-Time Particle Size Measurement**
The influences of various operating parameters on the particle size in the hydrocyclone overflows necessitate different control strategies. From this data and data from other sites, it does not appear that holding any particular operating parameter constant will result in a constant or controlled particle size. Instead, the particle size must be measured and used to adjust one of the operating parameters until the desired particle size is obtained.

Such a control system was implemented at a 150 t/d copper concentrator (Cirulis *et al*., 2015). The basis of control relied on manipulating the hydrocyclone feed density within other circuit constraints, as seen in Figure 15.

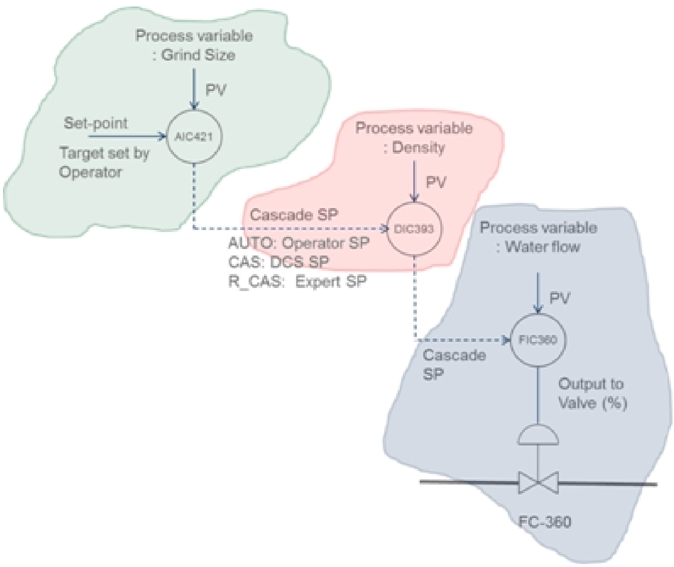


*Figure 15. Cascaded control loops used to optimize grind value.*

Figure 16 shows grind size stability under automatic control. The natural variability of grind size is shown by the CYCLONEtrac PST signal on the left . The grind size is driven to a set-point by observing the PST signal and manually adjusting the feed density. Without automatic control the grind size fluctuates while the density remains constant. Finally, the right-hand portion of the graph shows the grind size stability under automatic control. The control system automatically adjusts the density set-point to maintain the grind size at set-point.

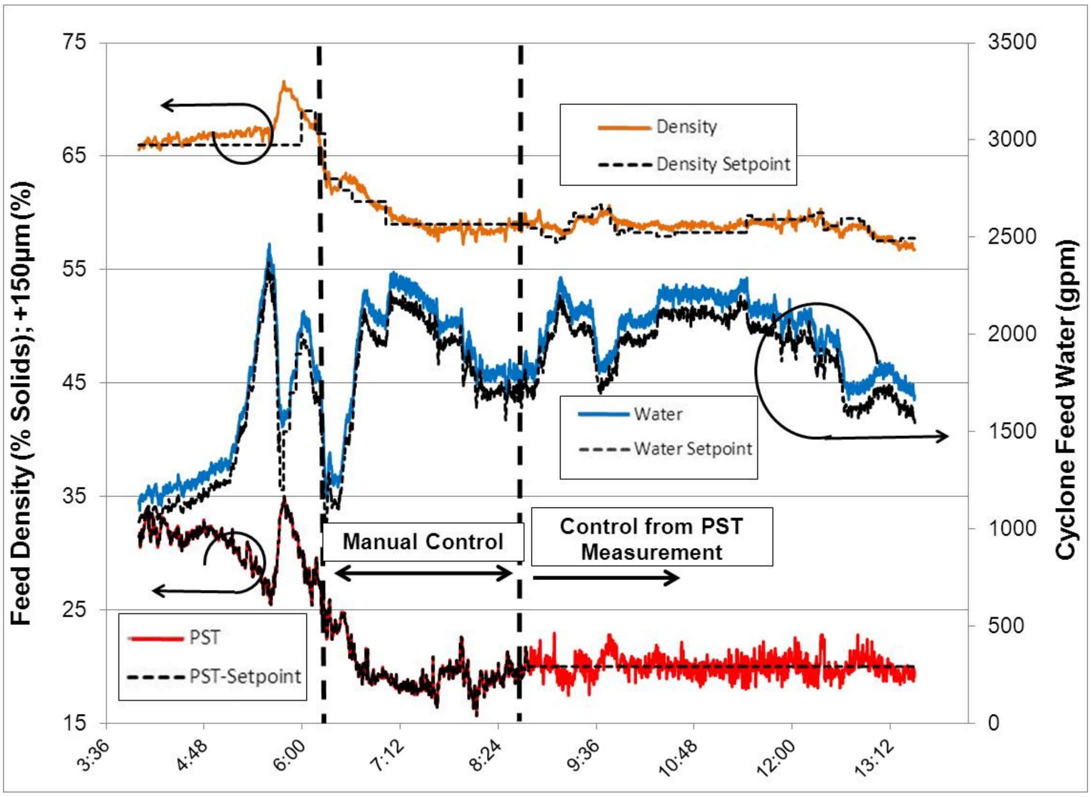


*Figure 16. Manipulating density for CYCLONEtrac PST control.*

**CONCLUSIONS**

The array-based flow meter has demonstrated the ability to acquire accurate flow readings on hydrocyclone feed lines and is not affected by slurry density for well-mixed flows. The impact-based particle sizing system has demonstrated good accuracy and, due to its four-second update rate, its suitability to be used in a control system to control particle size. The four-second update rate has also provided insight into the correlations between particle size and cyclone pressure, cyclone feed density, and cyclone feed mass flow rate. These correlations indicate that the particle size cannot be controlled by holding one of the variables constant. Instead, a demonstrated method for controlling particle size is to directly measure the particle size and adjust one of the parameters that influence this size until the desired particle size is obtained.

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