Application of Unique Sonar Array Based Process Monitoring Measurement Equipment for Minerals Processing Applications

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INTRODUCTION

Minerals processing plants are faced with many challenges when striving to achieve throughput and efficiency requirements while maintaining operational costs within budget. Of particular concern are process control strategies that rely on accurate and repeatable volumetric flow and density measurement of multiphase slurries. These slurries consist of liquid, solids, and air where by the percent solids and percent entrained air is continuously changing. Traditional flow meter technologies such as ultrasonic, electromagnetic, turbine, orifice plate, vortex, venture, and Coriolis suffer from a range of performance shortcomings and can be very costly to maintain. Density meters are commonly used to help determine the solids content in a slurry stream, but are confounded by the entrained air in the slurry. This makes it difficult to calculate the mass flow of solids in a stream. A new class of flow meter technology utilizes a passive sensor array and sonar processing algorithms to measure not only volumetric flow, but also the phase fraction of entrained air. It does so accurately and reliably without making contact with the slurry. There are many applications within a minerals processing plant where by process control strategies may be improved and maintenance cost may be reduced by applying this technology.

PRINCIPLE OF OPERATION

Introduction

Sonar array-based flowmeters operate by using an array of sensors and passive sonar processing algorithms to detect, track, and measure the mean velocities of coherent disturbances traveling in the axial direction of a pipe. These disturbances are grouped into three major categories: disturbances conveyed by the flow, acoustic waves in the fluid, and vibrations transmitted via the pipe walls. Each disturbance class travels at a given velocity. For example, the flow will convey turbulent eddies, density variations, or other fluid characteristics at the rate of the fluid flow. Liquid based flows rarely exceed 9 m/s. Acoustic waves in the fluid will typically have a minimum velocity of 80 m/s and a maximum velocity of 1500 m/s. The third group, pipe vibrations, travels at velocities that are several times greater than the acoustic waves. Thus each disturbance class may be clearly identified and accurately measured.

Flow velocity measurement

Flow velocity may be determined by focusing on the disturbances that are conveyed by the flow. These disturbances can be density variations, temperature variations, turbulent eddies, or others. Within most industrial processes, the most common flow disturbance is turbulence. Turbulent flow is composed of eddies, also known as vortices or turbulent eddies, which meander and swirl in a random fashion within the pipe. The overall mean velocity of the disturbances is equal to the flow velocity. An illustration of these turbulent eddies is shown below in Figure 1. These eddies are continuously created. Once created, they break down into smaller and smaller vortices, until they become small enough to be dissipated as heat through viscous effects of the fluid. For several pipe diameters downstream, these vortices remain coherent retaining their structure and size before breaking down into smaller vortices. The vortices in a pipe have a broad range of sizes, which are bracketed by the diameter of the pipe on the largest vortices and by viscous forces on the smallest vortices. These vortices are distributed throughout the cross section of the pipe and therefore across the flow profile. Thus the average velocity of the fluid can be determined by tracking the average axial velocities of the entire collection of vortices.

Figure 1: Cutaway of pipe under sonar array sensor band illustrating turbulent eddies

Through the combination of an array of passive sensors and the sonar array processing algorithms, the average axial velocities of a collection of vortices or density variations is obtained. The sequence of events that occur to make this measurement possible is as follows:

- The passage of the turbulent eddies or density variations creates a small pressure change on the inside of the pipe wall
- This small pressure change results in a dynamic strain of the pipe wall itself Figure 2 (right hand side exaggerated)
- The mechanical dynamic strain signal is converted to an electrical signal through a passive sensor wrapped partially or fully around the pipe – no coupling gels or liquids are required
- This electrical signal is detected by each element of the array of sensors. These sensors are spaced at precisely a set distance from each other along the axial direction of the pipe.
- The resulting electrical signal from each sensor element is interpreted as a characteristic signature of the frequency and phase components of the disturbance under the sensor.
- An array processing algorithm combines the phase and frequency information of the characteristic signature from the group of sensor array elements to calculate the velocity of the characteristic signature as it propagates under the array of sensors. In most applications, a minimum flow rate of 0.9 m/s (3 f/s) is required to measure the flow velocity

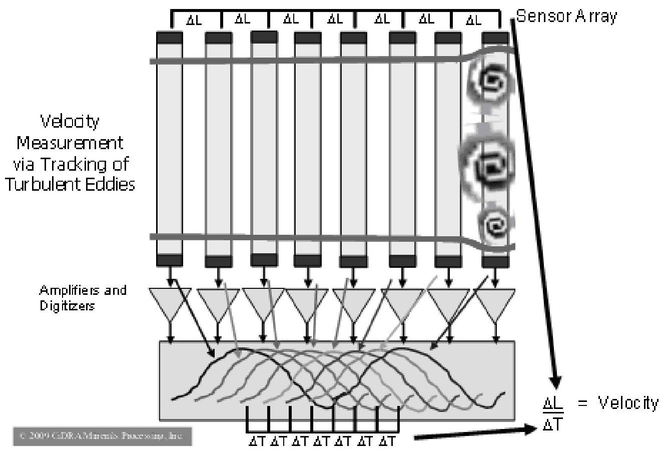

Figure 2: Illustration of strain induced in pipe walls by passing turbulent eddies, resulting in similar signals detected by sensor elements with time or phase differences, leading to velocity measurement

There are many challenges in performing this measurement in an industrial environment. The most difficult of which is resolving the relatively low level vortical disturbances from the relatively high noise levels. This noise includes acoustics and vibrations generated from large pumps and valves. The strength of the array processing algorithm is its ability to isolate and measure the velocities of the low level vortical components within the flow.

These velocity measurements have been demonstrated on many types of pipes with a wide variety of liners. The pipes include steel, PVC, HDPE, and fiberglass. The pipes can be lined or unlined. When lined, this has been demonstrated on rubber, urethane, cement, and Teflon lined pipes, as well as pipes with scale buildup.

Speed of sound and gas void fraction (entrained air bubbles) measurement

The sonar array based technology may also be used to track acoustic waves traveling in the fluid. In most mineral processing plant there is an abundance of acoustic waves propagating within the process pipes. These acoustic waves are generated naturally from a variety of sources. These sources include pumps, the flow through pipe geometry changes and bubbles within the fluid that generate acoustic waves through their natural oscillations. These acoustic waves are low frequency (in the audible range), and travel in the pipe's axial direction, with wavelengths much longer than the entrained gas bubbles. An illustration of these acoustic waves in a pipe is shown in Figure 3 and, as can been seen in the figure, they can propagate in either direction down the pipe or in both directions.

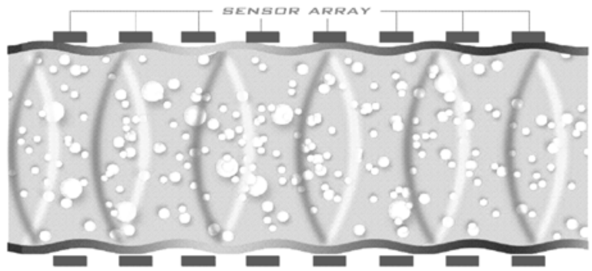

Figure 3: Illustration of naturally occurring acoustic waves propagating in pipe under the array of sensors

Through the same array of passive sensors used to measure the flow velocity and similar sonar array processing algorithms, the average axial velocities of a collection of acoustic waves is obtained. Since acoustic waves are traveling pressure waves, they introduce localized pressure changes on the inside of the pipe walls during the course of cycling from compression to rarefaction and back. These pressure changes strain the pipe wall and are tracked in a similar manner as for the turbulent eddies or density variations. The process fluid can be multiphase, or multi-component single phase. In a multi-component single phase fluid, the acoustic velocity is a function of the ratio and acoustic properties of the two fluids, thus this measurement can be used to determine mixture ratios through application of the simple mixing rule (volume average of velocity).

In multiphase fluids that consist of a gas mixed with a liquid or slurry, the acoustic velocity can be used to determine the amount of entrained gas (gas void fraction) when the gas is in the form of bubbles that are well mixed within the liquid or slurry. Since the wavelengths of the acoustic waves are much larger than the bubble size, a complex interaction takes place that sets the acoustic velocity to be a strong function of the gas void fraction. The speed of sound is proportional to the square root of the ratio of the compressibility and the density, both of which are heavily influenced by air content. An example of the resulting relationship is shown in Figure 4. The particular values outlined by the curve in this figure are influenced by other factors, particularly pressure. Thus pressure at the location of the array based instrument must be measured or calculated. Once pressure is determined, the array based instrument is used to accurately measure the speed of sound, and the relationship between speed of sound and entrained air content is used to accurately quantify the amount of entrained air.

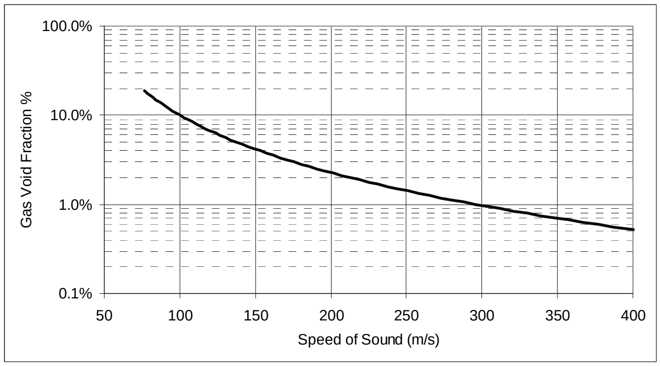

Figure 4: Example of relationship between gas void fraction (entrained air bubbles) and speed of sound

The gas void fraction measurement is used in a variety of different industries and applications. Within mineral processing, it is used for nuclear density gauge correction, flowmeter correction to provide true volume flow, diagnosis of pumping issues, detection of flashing, and air injection applications. It is being successfully used for entrained air applications ranging from 0.01% to 20% gas void fractions with an accuracy of 5% of the reading. An area of particular interest is the real time measurement of gas holdup with in the collection zone of a flotation cell. Field trials in this area are presently on going.

Physical embodiment of flow monitoring instrumentation based on sonar array

In a commercial embodiment of this measurement principle, 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 no ultrasonic waves are used. The sensor band is always 50 cm long in the axial direction of the pipe and equal to the circumference of the pipe in the orthogonal dimension. The typical installation procedure and hardware embodiment is outlined in Figure 5. First the pipe is wiped down and any high points are sanded or filed away. Second, the flexible sensor band is wrapped around the pipe and a series of captive screws on the sensor band are 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 ensure a set clamping force. Third, 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. Fourth, the cable from the sensor head to the transmitter is installed and wired to the transmitter. Fifth, the easy to use front panel menu on the transmitter is used to configure the transmitter.

Figure 5: Installation procedure from (top-left) pipe preparation through cleaning and light sanding of pipe to (top-middle and top-right) mounting of the flexible, lightweight sensor band to (bottom-left) installation of the sensor cover and to (bottom-middle and bottom-right) connection of sensor cover to transmitter via water tight cable

Calibration and long term stability

The flow measurement technique is not dependent on the absolute value of any analog signal. All the strain measurements are taken dynamically. Therefore the calibration of the meter will not drift with time or temperature. The only two absolute measurements are the sensor spacing and the transmitter clock. The spacing between the sensors is set in the factory where they are bonded to a stainless steel sheet and cannot be adjusted by the customer. Pictures of the lightweight sensor band are shown in Figure 5.

The clock stability is better than 0.01% and thus is 50 times better than needed to maintain the flow meter's typical accuracy of +/- 1% in the field; and +/- 0.5% under reference conditions or after in-field supplemental calibration. As a result, the impact of clock stability can be neglected.

Most flowmeters will inherently demonstrate drift mechanisms due to temperature effects, aging (time) effects, or process effects. In many cases, these changes in reported flow will not be noticed or cannot be verified through an accurate gold standard test such as a tank fill or draw down calibration. The accuracy of an electromagnetic flowmeter depends on many factors. Those factors are the stability of analog electronics (prone to drift with time and temperature), the absence of magnetic particles in the ore, and/or clean and uncompromised electrodes. Any one of these factors can impact the electromagnetc flow meter performance. Frequently an operator is not aware that an error has taken place unless the electromagnetic flowmeter is compared to another flowmeter or other process measurements, or is recalibrated via a gold standard test.

As an example, data is shown in Figure 6 from two 8-inch electromagnetic flowmeters placed in series and in close proximity to each other at a gold and copper concentrator in the United States. In that figure, the two black lines are the electromagnetic flowmeter outputs, while the gray line between the two black lines is the sonar array flowmeter. The sonar array flowmeter was configured using the universal calibration coefficients used for this size meter. In this example, the two electromagnetic flowmeters differ on the average by over 12%. The data from the sonar array flowmeter is seen to provide a flow reading that is approximately an average of the two electromagnetic flowmeters but with the confidence that it will not drift with time. Verification of the performance of the sonar array flowmeter can be performed without stopping the process by moving the flowmeter to a location where a tank test can be accomplished.

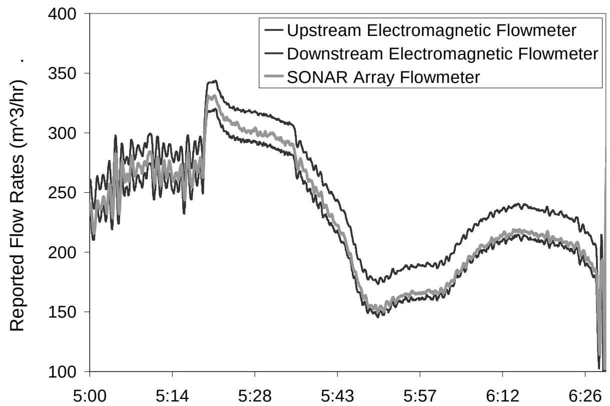

Figure 6: Two electromagnetic flowmeters in series with sonar array flowmeter showing offsets greater than 12% between the two electromagnetic flowmeters and the drift of the electromagnetic flowmeters relative to the drift-free sonar array flowmeter

One other feature of the sonar array flowmeter design is that there is no need for a meter to meter or serial number based calibration. Figure 7 demonstrates the results from applying the same calibration coefficients to six flowmeters tested at a NIST traceable calibration facility. The meter to meter variation is within 0.5%, and it will not change with time.

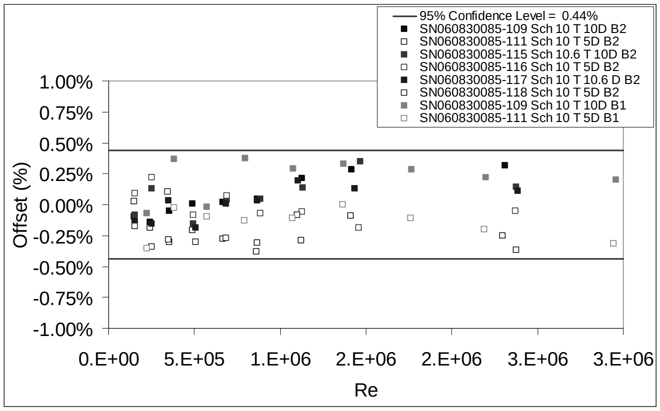

Figure 7: Illustration of Calibration Consistency from Meter to Meter. All Meters Have Same Calibration Coefficients

APPLICATION OF SONAR ARRAY BASED TECHNOLOGY

In the minerals processing industry there are many critical multiphase flow measurement applications in grinding, classification, flotation, tailings management, hydro-transport, thickening, tailings management, leaching, and refining. These applications include hydrocyclone feed lines, hydrocyclone overflow lines, mill water feed lines, mill discharge lines, flotation feed lines, concentrate lines, thickener underflow lines, final concentrate lines, tailings lines, organic lines, pregnant leach solution lines, raffinate lines, acid lines, scrubber water lines, red mud lines, bauxite slurry lines, and bauxite green liquor lines.

In many cases the success of a control and optimization strategy is dependent on the quality of the feedback parameters. Traditional flow measurement technologies have been used to provide this feedback. The application of these technologies has presented the industry with long standing problems. These problems include measurement point high life cycle cost, process down time, calibration drift, repeatability, sensitivity to pipe scale build-up, sensitivity to entrained air, sensitivity to percent solids, and sensitivity to magnetic ore.

Over the past five years the sonar array based technology has been successfully applied to all the above mentioned applications in over 140 concentrators in 21 countries. Outlined in this section are selected case studies demonstrating the benefits of the technology.

Reliable and repeatable volumetric flow measurement in a hydrocyclone feed application

Control of the hydrocyclone and hence classification performance leading to greater throughput and efficiency is dependent on an accurate flow measurement. A comparison of the sonar array flowmeter to a ceramic lined electromagnetic flowmeter was performed on a 900mm hydrocyclone feed line in a copper concentrator in Chile. This environment poses particular issues for flowmeters since it is typically a high pipe wear rate environment, thus the interest in the non-intrusive sonar array flowmeter. In this test a performance evaluation of the two flowmeters was performed by comparing their outputs to the pump power. Even though the pump power is a non-linear indication of flow rate, it exhibits a strong linear component if operational conditions such as slurry density, viscosity, and sump level are kept constant. A comparison of the two flowmeter technologies relative to pump power can be seen in Figure 8. In that figure, the pump power is represented by the gray solid line, which is closely matched by the dark solid line outlining the sonar array flowmeter measurement. The electromagnetic flowmeter output, represented by the dark dash lined, differs significantly from both the pump power and the sonar array flowmeter output.

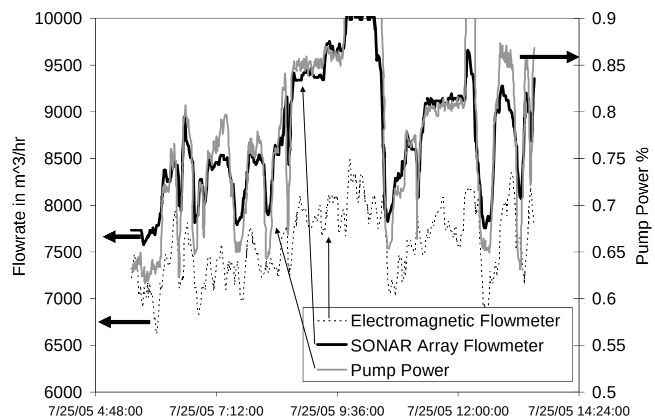

Figure 8: Comparison of sonar array flowmeter and electromagnetic flowmeter to pump power on hydrocyclone feed line

A quantitative analysis of the performance of the flowmeters can be obtained by comparing their outputs against the pump power. First by graphing the flowmeter outputs on the ordinate axis and the pump power on the abscissa axis, one can see the spread of flow measurements at different levels of pump power as seen in Figure 9. In that figure, the electromagnetic flowmeter output is shown by the dark points, whereas the sonar array based flowmeter output is shown by the gray points. If certain key process parameters are kept constant, then for the same pump power, the flow rates reported should have a minimal spread along the ordinate axis at each level of pump power. Assuming a quasi-linear response of flow rate with pump power, a linear regression model can be applied to each flowmeter measurement, along with a quantitative indication of the fit and inversely the spread in reported flow by calculating the coefficient of determination (R^2) which can range from 0 to 1.0. In this case, a higher R^2 indicates better performance.

This calculation was performed on the data in Figure 9, resulting in a R^2 of 0.58 for the electromagnetic flowmeter and a R^2 of 0.90 for the sonar array flowmeter. Another indication of performance can be obtained by comparing the pump power to the outputs of the flowmeters during periods of relatively stable pump power and hence assumed relatively stable flow.

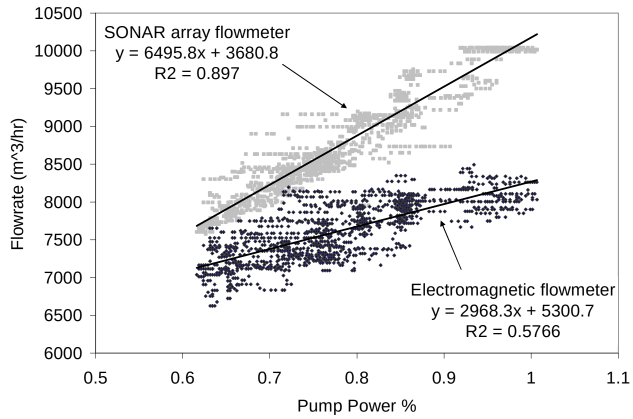

Figure 9: Flow rate reported by sonar array based flowmeter and electromagnetic flowmeter relative to pump power (as percentage of maximum power)

The results of this comparison are shown in Table 1. In this table the standard deviation of the two flowmeters are divided by their respective means during the two selected time periods to provide a normalized standard deviation of the reported flow. The electromagnetic flowmeter demonstrated a normalized standard deviation more than four times greater than the sonar array flowmeter. A visual examination of the outputs in Figure 9 indicates that these differences in standard deviation are low frequency variations and hence minimally impacted by filtering.

Table 1: Comparison of sonar array and electromagnetic flowmeter performance during periods of relatively stable flow

Start Time	End Time	Electromagnetic Meter Normalized Standard Deviation	Sonar-Array Flowmeter Normalized Standard Deviation
8:48	9:19	1.37%	0.40%
11:26	12:07	1.80%	0.38%
Note: Pump power and hence assumed flow rate exhibited some fluctuations during these periods.			

The more accurate and repeatable flow reading from the sonar array flowmeter enables operators to maintain the optimum circulating load ratio (McIvor, 2009). The combination of flow rate, pressure and specific gravity is used in many operations to control the number of hydrocyclones that are activated in a hydrocyclone battery. This control is essential for the optimization of the separation process in order to obtain the correct particle size distribution needed in the flotation, leaching or magnetic separation steps, while maximizing throughput in the mills by minimizing overgrinding. “Poor cyclone operation is the commonest cause of grinding inefficiencies.” (Napier-Munn et al, 2005)

Volumetric flow and entrained air for maximizing milling circuit throughput

An industry alumina refinery uses the classifier underflow (circulating load) as a limiter in the overall mill circuit controller. Classifier feed flow is used for control with the aim of managing circulating load so as to ensure optimum mill feed rate, while avoiding overload and maximizing throughput. The 400mm feed line has been instrumented with an electromagnetic flowmeter and a sonar array flowmeter.

At high mill feed rates the electromagnetic flowmeter is prone to spiking and noise due to entrained air and solids impact on the electrodes. The noisy flow measurement causes the control system to react, reducing the linearity between mill feed and circulating load. The result is circulating load can not be used as the mill limiter and throughput is subsequently reduced.

By applying the sonar array technology to the mill classifier feed line to measure volumetric flow and entrained air, an effective control strategy has been implemented to maintain linearity between circulating load and mill feed. Figure 10 is a plot of the circulating load versus mill feed rate as measure by the electromagnetic flow meter. A linear fit of this data yields an R^2 of 0.53.

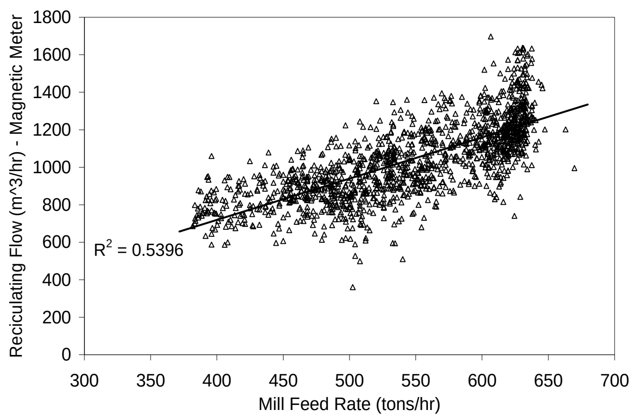

Figure 10: Circulating flow rate versus mill feed rate as measured by the electromagnetic flowmeter.

Figure 11 is a plot of the circulating load versus mill feed rate as measure by the sonar array flowmeter. A linear fit of this data yields an R^2 of 0.72.

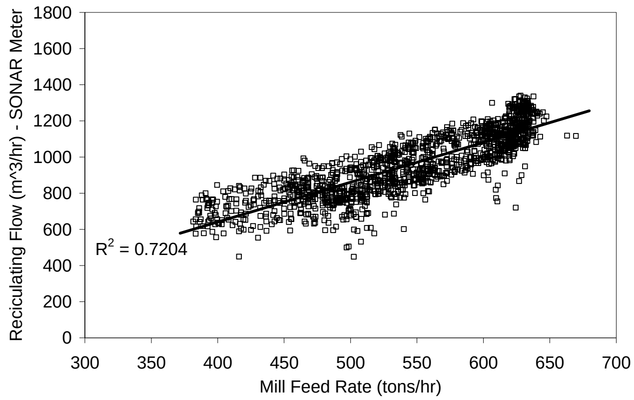

Figure 11: Circulating flow rate versus mill feed rate as measured by the sonar array flowmeter.

The sonar array technology and fundamental measurement principal makes it insensitive to high solids content and entrained air within the process stream. This enables the operator to maximize grind circuit throughput. In addition to milling circuit throughput control, the classifier performance may also be optimized. This is accomplished by using the entrained air reading to correct the density measurement on the feed to the classifier. This will be discussed in detail in a subsequent section of the paper.

Measuring volumetric flow in the presence of ferromagnetic ore such as magnetite or pyrrhotite

Magnetic ore in a slurry line, whether intentional in an iron ore mill or whether unintentional in mills concentrating other metals, poses a potential problem for electromagnetic flowmeter measurements. Many locations mining copper, gold or other non-ferrous metals have magnetic ore in or near their ore body. The magnetic ore, even in small quantities, creates both short term and long term changes in the outputs of electromagnetic flowmeters. Short term changes result from perturbations of the magnetic field induced by the magnetic ore within the electromagnetic flowmeter resulting in over reporting of flow or the introduction of noise in the output. Long term changes result from an attraction of the ferromagnetic ore to the electromagnetic flowmeter elements resulting in a reduction of the pipe cross section, thus increasing the over reporting of volumetric flow rates. Electromagnetic flowmeter manufacturers have attempted to circumvent the impact of magnetic ore with a third coil, with magnetic field measurements, and with manual offset adjustments based on laboratory samples of the typical slurry. These methods have resulted in mixed results. Many times the calibration or offset changes depending on the quantity of magnetite present.

A more robust solution is to use a flowmeter technology that is not impacted by the presence of magnetic ore. The sonar array flow monitoring system does not rely on the use of any magnetic fields. It is totally impervious to the effects of magnetic ore. An example of this is illustrated in Figure 12 in which a sonar array flowmeter is compared to an electromagnetic flowmeter. In the figure, one can see that during a period of constant flow rate as the amount of the magnetic ore in the slurry increases, the electromagnetic flowmeter erroneously reports a higher flow rate, whereas the sonar array flowmeter correctly continues reporting no change in the flow rate.

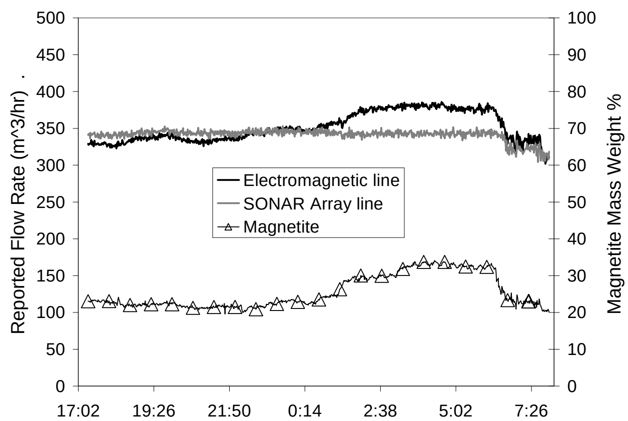

Figure 12: Electromagnetic flowmeter erroneously respond to magnetite while sonar array flowmeter accurately reports flow

Correction of volumetric flow due to entrained air bubbles

To achieve a stable processing system with higher levels of efficiencies, accurate and repeatable volumetric flow measurement of the liquid or liquid/solids (slurry) phases is necessary. Slurries tend to entrain air bubbles. Most traditional flowmeter technologies cannot perform an accurate flow measurement in the presence of air bubbles. In addition, the older generation of flowmeter technologies do not have the ability to compensate for the air content. The sonar array based technology robustly measures flow in the presence of entrained air and quantitatively determines the amount of entrained air.

Entrained air bubbles can come about from a myriad of sources including low sump levels, flotation processes, pump leaks, flashing, and others. The ability to measure the entrained air levels results in two major benefits. These benefits include the identification of process and equipment problems, early warning of potential safety issues, and the ability to determine the true volumetric flow of the process fluid/solid phase. Some of these benefits can be seen in the example in Figure 13. In this figure, the dark trace with the triangles is the volumetric flow of all three phases. The three phases consist of solid, liquid, and gas bubbles measured on a concentrate line at a copper/gold/molybdenum concentrator. The dark trace at the bottom of the graph is a measurement of the gas void fraction or percentage of volume occupied by the gas bubbles, as measured by the sonar array based instrument. In this case, air has become entrained in the final concentrate slurry which can lead to a metallurgical balance calculation error. The gray trace with the open circles between the other two traces is the true volumetric flow rate of the slurry as calculated from the total volumetric flow (black trace with triangles) and the gas void fraction via a simple linear correction (Equation 1).

Adjusted Volumetric Flow = Volumetric Flow * (1 – Gas Void Fraction %)   (1)

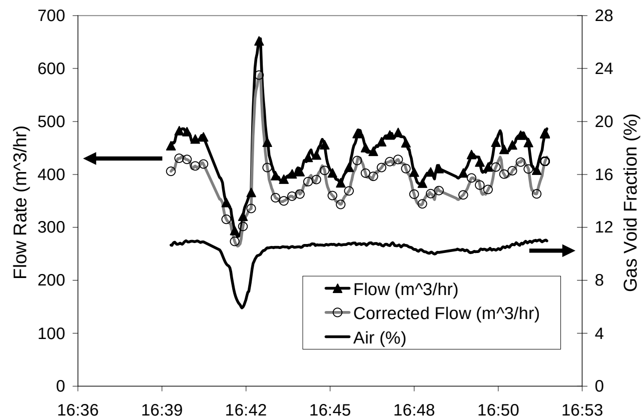

Figure 13: Detection of entrained air bubbles and compensation of flow measurement

Correction of nuclear density gauges due to entrained air bubbles

Nuclear density gauges are commonly used to determine the specific gravity of the bulk fluid which in turn is used to calculate the concentration of the solids phase. The presence of entrained air bubbles or gas void content will directly reduce the specific gravity reported by a nuclear density gauge. In order to obtain the correct density measurement of the slurry itself, the gas void fraction must be measured and used as a correction factor. To validate this approach, a test was performed in which varying levels of air were introduced into a water flow loop containing a nuclear density gauge and a sonar array Gas Void Fraction (GVF) meter. Figure 14 shows that when the air injection rate was increased the nuclear density gauge output decreases proportionally (reported density line). The sonar array instrument on the same line accurately measured the resulting air content (sonar %GVF line). Using this measurement a simple linear correction was applied to the nuclear density gauge output (corrected density line). As a result the error has been reduced from 5% to +/- 0.25%.

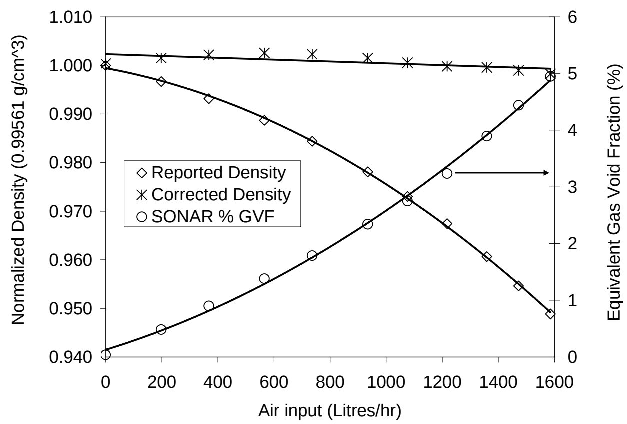

Figure 14: Sonar array flow meter used to correct nuclear density gage for entrained air induced errors.

Mass balance calculation improvements with sonar array technology

In a previous section Figure 13 shows how entrained air can cause errors in density measurement if a correction is not made. The extent of the error is dependent on two variables, the amount of entrained air and the relative specific gravity of the slurry. The relative specific gravity is the specific gravity of the slurry divided by the specific gravity of the liquid component. Typically the liquid phase is water so in those cases the relative specific gravity is the same as the slurry specific gravity. If the carrier fluid is a brine solution then the relative specific gravity will be lower than the slurry specific gravity. As the relative specific gravity approaches one, the resulting mass flow calculation error will increase in the presence of entrained air. Figure 15 shows the errors in the mass flow rate as a function of the relative specific gravity and percentage of entrained air (gas void fraction). The resulting negative impact on mass balance calculations, recovery calculations, as well as process improvement initiatives can be significant.

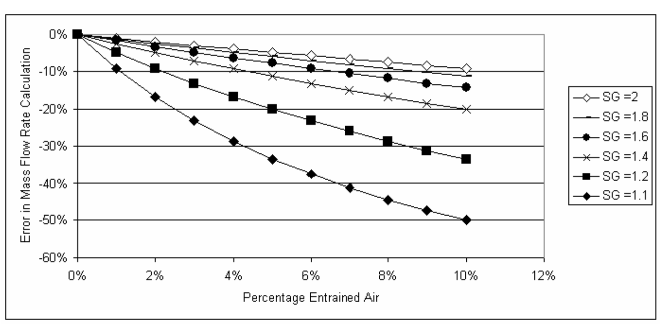

Figure 15: Error introduced by entrained air in mass flow rate calculations as a function of slurry relative specific gravity (SG)

Flow measurement with buildup of scale on interior pipe walls

A common situation in process streams containing hard water, scrubber water, bauxite liquor, and lime slurry is the buildup of scale on the interior of the pipe walls. This scale buildup can vary from a thin layer to several inches thick, depending on the pipe material and lining, the fluid composition, the flow rate, and the time intervals between maintenance actions performed to remove the scale. The impact of this scale build up on most flowmeters varies. There may be a small impact such as an increase in noise or large impact such as a drift in the reported flow measurement. In some cases a complete failure of the flowmeter will be reported at any flow rate. No flowmeter is truly immune to the effects of scale buildup but flowmeters commonly used in mineral processing, such as electromagnetic meters and ultrasonic flowmeters, are particularly sensitive to scale.

Impact of scale buildup on ultrasonic and electromagnetic flowmeters

In the case of transit time ultrasonic flowmeters, an ultrasonic wave injected into the fluid has to travel between two transducers using known bending or refraction of the ultrasonic wave at the pipe to fluid interface. The impact of scale on such a meter involves three effects: 1) attenuation of the ultrasonic signal in the scale, 2) scattering of the ultrasonic signal at the scale to fluid interface, and 3) change in the refraction angle at the scale to fluid interface.

Ultrasonic doppler flowmeters operate on a different principle than transit time flowmeters and their transducer arrangement differs as well. They also suffer from similar problems induced by scale. Whereas the change in refraction angle may not necessarily cause the ultrasonic signal from one transducer to miss the second transducer, it certainly will change the reported flow. The conversion of the doppler frequency shift to a flow reading requires that the instrument know the angle between the ultrasonic wave propagation direction and the axial direction of the pipe. Scale will change this angle thus producing an erroneous flow reading.

Electromagnetic flowmeters operate by using the interaction of a magnetic field with a flowing conductive fluid to create an electric field within the fluid. The electric field is in turn detected and measured by a pair of electrodes placed on opposite sides of the interior of the pipe. Scale buildup on the electrodes serves to electrically isolate the electrodes preventing the flowmeter from measuring the flow induced voltage. The only recourse is to stop the process or divert the flow, remove the electromagnetic flowmeter, and remove the scale.

Impact of scale buildup on sonar array flowmeter

The passive sonar array technology does not rely on the contact of any electrodes with the fluid, nor does it rely on the injection and retrieval of a signal into the fluid. The turbulent eddy induced pressure signals simply strain the scale which in turn strains the pipe wall and then the sensors. The impact of scale buildup is that the effective stiffness of the pipe may increase which will reduce the magnitude of the strain. Since the absolute magnitude is not used in the flow calculation, there is no change in the measurement of the flow velocity. Like most velocity meters, the sonar array-based flowmeter uses the effective inner cross-sectional area of the pipe to convert the velocity to a volumetric flow. Scale buildup will decrease this inner cross-section area thus requiring some adjustment of the inner diameter entered into the transmitter. The difference is that, unlike traditional flowmeters such as electromagnetic meters, ultrasonic meters, differential pressure based meters, etc., the sonar array-based flowmeter will continue to operate thus eliminating periods of time in which the operator is "operating blindly" at those measurement points.

This technology has been proved on a variety of pipes with scale buildup from scrubber water, bauxite green liquor, and lime. The first example is 450mm ball mill water feed line in a copper concentrator grind operation. In this case the pipe is estimated to have about 50mm of lime scale on the inner diameter of the pipe. Downstream of the sonar array flowmeter is an electromagnetic flowmeter that is cleaned out every few months to remove the scale from the electrodes. This maintenance practice is necessary in order for the electromagnetic flowmeter to continue operation. The maintenance is labor intensive, it results in the loss of flow measurements, and it relies on a bypass system to prevent a process shut down. The valve used to divert the flow is developing problems from the same scale build up and the bypass system has a limited life. As can be seen in Figure 16, both flowmeters have similar noise levels, flow rate changes responses, and outputs. The electromagnetic flow meter has been cleaned and the sonar array flow meter is measuring flow rate through the scale buildup. It has been demonstrated that the sonar array flowmeter may be used in place of the electromagnetic flow meter. This will eliminate the capital cost of the bypass loop as well as the annual maintenance costs associated with the electromagnetic flowmeter cleaning.

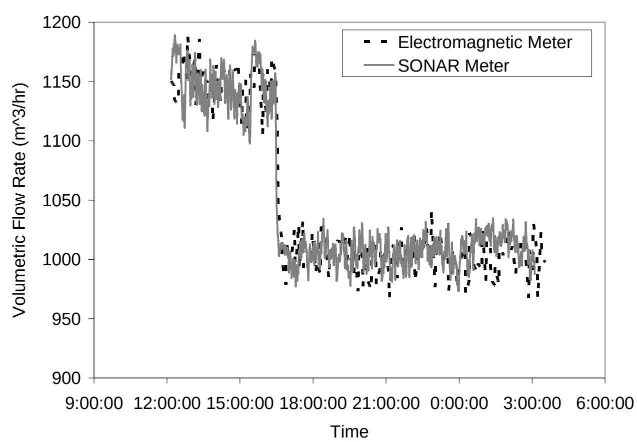

Figure 16: Sonar array flowmeter operation on a water pipe with two inches of scale buildup compared to a recently cleaned electromagnetic flowmeter.

The second example is a 300mm bauxite green liquor line located on the red side of the process. In this application the scale buildup is very aggressive. The rate of scale buildup may be as high as 5mm per month. Upstream of the sonar array flowmeter is an electromagnetic flowmeter that is cleaned out during the regular annual process shutdowns. The electromagnetic flowmeter will typically operate for about three to six months and then fail due to the scale buildup on the electrodes. The sonar array flow meter operates continuously regardless of the scale. Figure 17 demonstrates the uninterrupted performance of the sonar array flowmeters at the time of the electromagnetic flowmeter failure. It has been demonstrated that the sonar array flowmeter may be used in place of the electromagnetic flow meter. This will eliminate the annual maintenance costs associated with the electromagnetic flowmeter cleaning. More importantly the sonar array flowmeter will provide a reliable flow reading for the entire operational cycle of the plant.

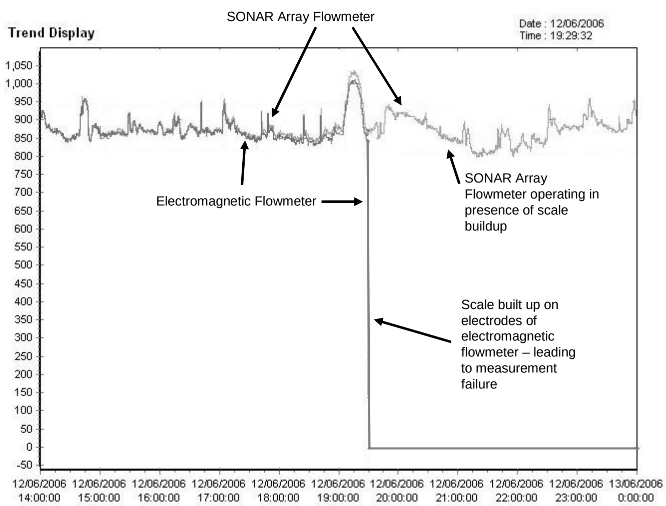

Figure 17: Sonar flowmeter operation on a bauxite green liquor line with scale buildup during an electromagnetic meter failure.

ADDITIONAL MEASUREMENT CAPABILITY

The sonar array technology has led to the development of a hardware platform that supports many other measurement capabilities. These include the acoustic monitoring of pipelines and equipment, as well as determination of the stratification of slurries and the onset of sanding.

Valve actuation monitoring on a high pressure concentrate pipeline

During the course of measuring flow, the sonar array based flowmeter detects the acoustic levels within the pipe. A test was conducted on a 600mm copper concentrate pipeline in Chile. By monitoring these acoustic levels over selected frequencies, additional information about events occurring in a pipeline can be obtained. As an example, valve movement in a pressure reduction choke station corresponds with changes in the acoustic levels during the movement, as well as before and after the movement as the flow is diverted through a different pipe. The flow, shown as the dark line in Figure 18, changes by about 8% due to a change in the valve position which directs the flow through a different path in the choke station. The acoustic level changes by a factor of three to four (200% to 300%) during the valve movement and by a factor of three (200%) between valve positions. The combination of the flow measurement and acoustic level provides the necessary information to monitor the valve. Therefore the meter provides not only the flow rate of the slurry, but it also provides verification that the valves have changed position. This is particularly important in situations requiring remote monitoring and verification of critical events.

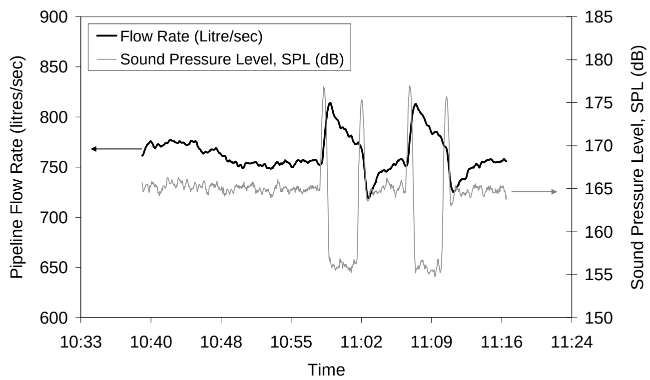

Figure 18: Flow measurement and acoustic level measurement of a choke station while the valves are actuated.

Velocity profile and sanding detection

A common concern for operators of hydrotransport pipelines is the possibility that solids material will settle to the bottom of the pipe and lead to a blockage in the pipe. Operators strive to avoid this "sanding out" condition by keeping flow rate above a certain empirically determined or calculated value deposition velocity. Unfortunately, incomplete models and changes in the slurry properties including viscosity, fines content, and changes in particle size distribution make it difficult to determine the exact deposition velocity. Therefore pipelines are commonly run at higher than needed velocities to avoid a pipeline blockage. A better solution is to actively monitor the flow profile in the pipe. As the average flow velocity drops the larger denser particles settle to the bottom of the pipe. During this condition the flow velocity at the bottom of the pipe is slower than the volumetrically averaged flow rate as shown in Figure 19. Through a different instrument, including a specially engineered sensor and multiple processing units, the flow at different heights in the pipe can be measured.

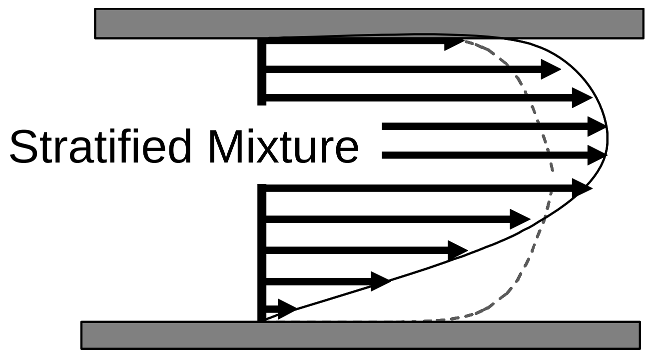

Figure 19: Illustration of flow profile change that occurs during onset of "sanding out"

Field test results are shown in Figure 20. Here, the change in the flow profile due to the stratification of particles is evident in the lower velocities seen near the bottom of the pipe as the “sanding out” condition is approached. By processing some characteristic features of the flow profile, an alarm condition can be generated.

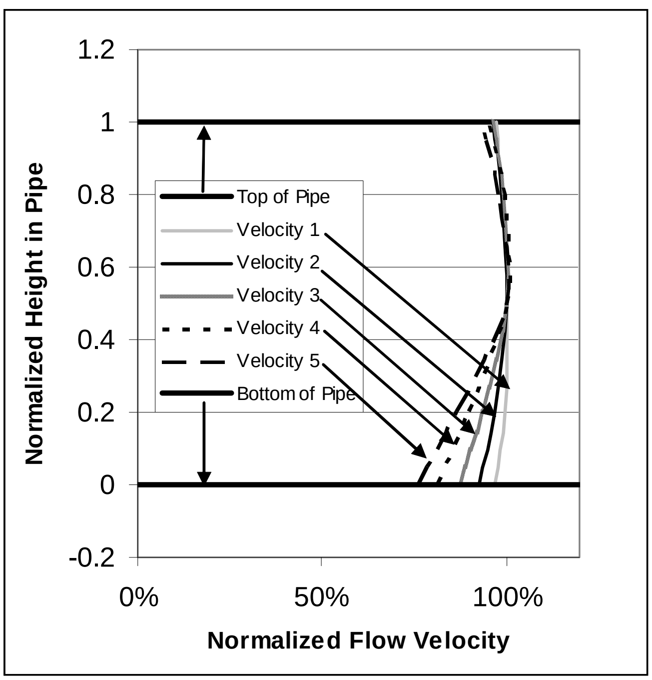

Figure 20: Velocity profiles at different flow rates. Note the drop in velocity at the bottom of the pipe at the lower flow rates

By extending this processing to examine not only the condition where a small level of "sanding out" has occurred but has now reached a higher level in the pipe (>25% of the pipe height) we can set a higher level in the alarm. This is illustrated in Figure 21.

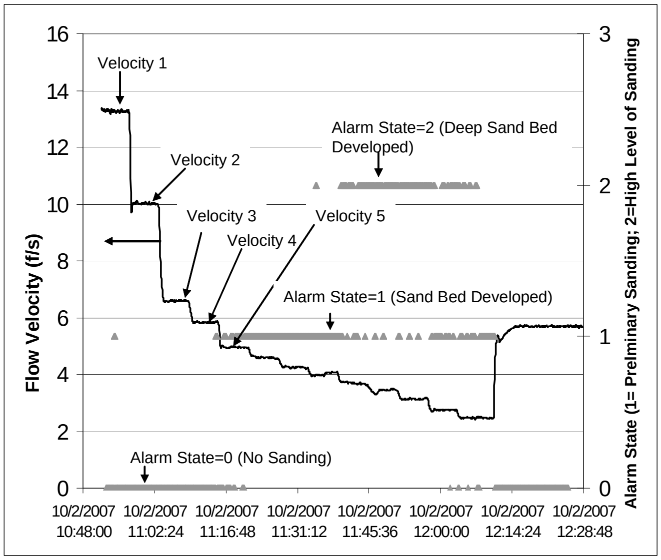

Figure 21: Flow velocity and alarm condition for low levels of sanding (alarm level=1) and high levels of sanding (alarm level=2)

SUMMARY

Sonar array flow and entrained air measurement instruments are a new class of industrial flow and compositional analyzers leveraging over 60 years of sonar development and utilization. These instruments have been specifically designed for multiphase flow applications and are well suited for a wide range of minerals processing applications. The technology is field proven and has years of operational experience in concentrators around the world. The use of this technology solves long standing performance and maintenance flow measurement problems within concentrators. Such problems include reliable and repeatable flow measurement in the presence of abrasive slurries, slurries with continuously changing solids content, pipes with scale buildup, magnetic ores, and highly aerated concentrate streams. This enhanced flow measurement capability enables operators to more accurately control critical process. Such processes include grinding mill throughput by controlling circulating load, flotation circuit mass balance and final concentrate accounting by measuring flow and correcting density measurement, and tailings management through robust flow measurement.

The sonar array technology is a scalable platform that is more than just a flow technology. It has the ability and capability to provide several other value added measurements and information such as speed of sound, entrained air/gas, gas hold-up, and acoustic levels.

ACKNOWLEDGEMENTS

The authors wish to thank our customers for adopting the SONARtrac® process monitoring equipment, providing plant data, and other technical support. The authors also acknowledge the efforts of the dedicated minerals processing team at CiDRA .

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