# Passive Sonar Flow Monitoring

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## Abstract

The slurry transport of material from the field to the washer is one of the largest processes to occur in mining and certainly, the most power intensive.  Control of this process hinges around knowledge of the volumetric flow; is the volume enough to keep the solids from settling, or too high and wasting energy moving excess water?  Currently, most of the reliable information on flow is from in-line magnetic flux meters located at the end of the slurry lines.  Meter failure requires costly down time while the line is broken for installation of the replacement, or that the operations run blind until repairs can be scheduled.

While researching new technology for the ONA mine, Mosaic found CiDRA Minerals Processing, Inc. offering an alternative reliable non-invasive flow monitoring system with the ability to program for detection of bed settling, air entrainment, and pipeline leaks.  This paper covers Mosaic's extensive acceptance testing of the CiDRA *SONARtrac®* Model VF-100 volumetric flow monitoring system and the technology involved.

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## History

Back in September 2007, Mosaic decided to take a hard look at available and cutting edge technologies to employ in the construction and operation of the new ONA mine. The Technology Selection Team was formed to provide a high level process layout for ONA. From the start, Mosaic knew that mining the ONA property would be a difficult task with many layers of complexities. One of the more troublesome problems Mosaic faced was the probability of using long distance pumping to get the final product to the concentrate plant. Mosaic also understood that anytime work is done on pump settling slurries - the potential of bed settling or deposition exists, so a means of early detection of bed settling was high on Mosaic's list of imperatives. What Mosaic found was an innovative company offering cutting edge technology in bed settling detection, entrained air measurement, and an alternative approach to flow monitoring. The technology was based on the non-intrusive use of passive sonar measurements to determine changes in fluid flow. The decision was made to test the basic flow monitoring technology by comparing CiDRA *SONARtrac* VF-100 against the standard Foxboro 2820 magmeter.

## Initial Test

CiDRA Minerals Processing, Inc. and Mosaic agreed to a 60 day trial of a 20" *SONARtrac* VF-100 Flow Monitoring System, with the understanding that the unit would be purchased by the ONA Group upon the satisfactory completion of the trial. September 2009 - the Unit was installed in a vertical position on the #10 Matrix line at South Fort Meade (SFM). **Figure 1**.


*Figure 1 South Fort Meade Installation*

CIDRA Sales Engineer Joseph Poplawski assisted with the installation and instructed SFM Electricians on the set-up procedure. Installation required only two people and a manlift - there was no need for a crane or downtime. Initial set-up time was two hours due to the training and follow-up installations have taken an hour.

Data was collected in Mosaic's Pi System simultaneously with the Foxboro flow meter readings. In October the unit was moved to a horizontal position approximately 60 feet upstream on the same #10 matrix line using SFM electricians – no adjustments were made to the flow settings. (**Figure 2**)

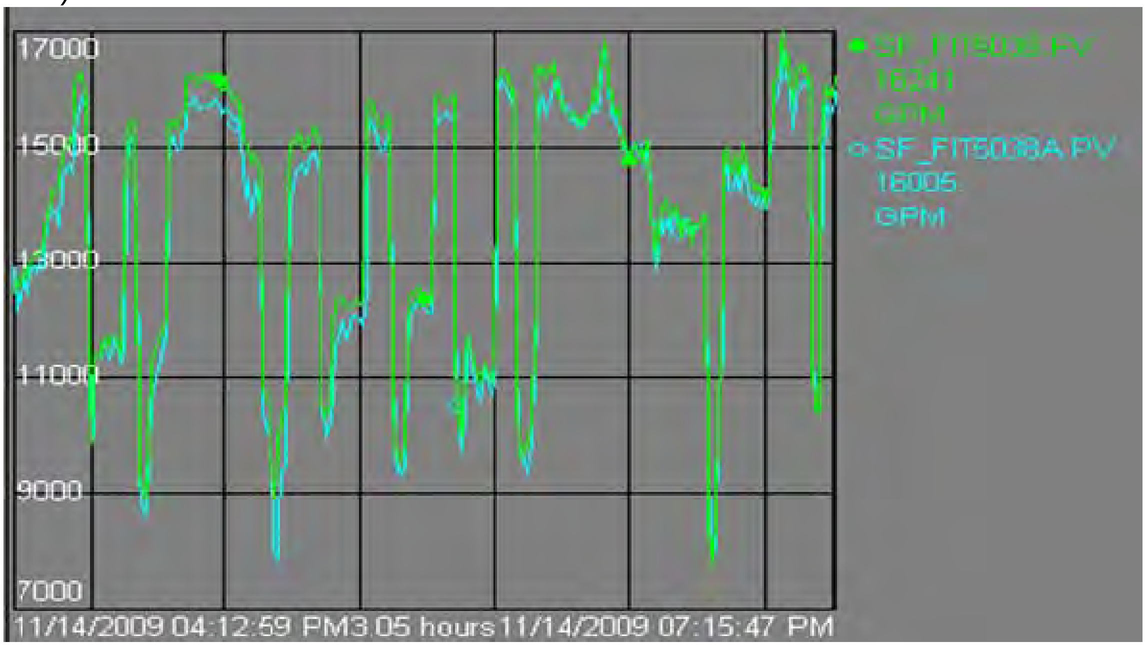


*Figure 2 Comparison Data: Green is the Magmeter and Blue is the CiDRA Flow unit*

The trial concluded at the end of November and the unit was removed from service. Analyses of the data showed the CIDRA unit averaged 14,870 GPM, which tracked the Foxboro unit averaging 15,121 GPM. A 250 GPM difference held steady throughout the test. The standard deviation of the flows for the CIDRA was 1944 GPM compared to 2007 GPM for the Foxboro. ANOVA analyses of the periods where the mine was able to run steady showed the two reading were from the same population. **Figure 3.** Based on this analysis and the economics of the non-intrusive flow-monitoring system, ONA purchased the test unit and George McQuien recommended all Mosaic mines purchase at least one of these units as a back-up system. South Fort Meade mine ordered a replacement for the ONA unit.

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Individual 95% CIs for Mean Based on
Pooled StDev
-----+---------+---------+---------+----
          (-----------*------------)
(-----------*------------)
-----+---------+---------+---------+----
 12480     12560     12640     12720
```

*Figure 3 Results of a typical ANOVA analyses*

## Further Testing

The test at South Fort Meade showed the CiDRA *SONARtrac* volumetric flow monitoring system performed as well as the current standard flow meter. A test series was planned for the ONA unit at each mine location to demonstrate the validity of the initial test.

Hookers Prairie Plant was chosen for the second test, where the unit would be placed in service on a tailing line.  The unit was given to the E&I department and they were instructed on the installation procedures.  The unit was then turned over to the Four Corners Mine Engineer for field testing.

Typically, magnetic flow meters are placed in a protected vertical area at the washer, due to the fragile nature and weight of the meter. A time delay of approximately an hour exists for the long lines between the pit to the washer. Four Corners Field wanted to know how the CiDRA *SONARtrac* volumetric flow monitoring system would perform in the field closer to the pit as an early flow indication to the pit operator. (**Figure 4**)The unit had previously proved itself in a horizontal installation at South Fort Meade.  No formal report was published on the results of the Four Corner Test.  The Process Engineering – Minerals group and Four Corners Operations agreed that the unit performed acceptably and began ordering units.


*Figure 4        Field Installation at FCO*

Following Four Corners, the unit was taken to the Wingate Plant, **Figure 5**; where they were experiencing problems with their tailings line choking.  The line had no flow indication and the GMT amps were used to approximate line performance.  Unfortunately, the range of amps between a good steady flow and choking was 5 amps.  Also the most convenient location for the CiDRA unit was on the tailings down leg.  Conventional wisdom has always been to install a flow meter on an up-leg to insure a full pipe flow condition. The initial installation was met with skepticism, but after a month without choking, the test unit was replaced with a permanent unit.

*Figure 5*　　*Down-leg installation at Wingate*

Lastly, the ONA unit returned to Hookers Prairie and was immediately installed on a matrix line that had recently experienced a flowmeter failure and was running without flow indication, while the magmeter was out for repair. The unit was installed and flow information was restored to the field. The unit stayed in this service until it was replaced with a permanent VF-100. The unit is currently installed on the Hookers Prairie tailing line where it will remain until further notice; **Figure 6**.

*Figure 6*　　*ONA Unit Current Installation*

## Principle of Operation

Sonar array-based flow meters are ideal for tracking and measuring the mean velocities of disturbances traveling in the axial direction of a pipe. These disturbances generally will be conveyed with the flow, propagate in the pipe walls, or propagate in the fluid or slurry. The disturbances that are conveyed with the flow can be density variations, temperature variations or turbulent eddies. The overwhelming majority of industrial flows will have turbulent eddies conveying with the flow, thus providing an excellent means of measuring the flow rate as described below.

## Turbulent Eddies and Flow Velocity

In most mineral processing flow measurement applications, the flow in a pipe is turbulent. Turbulent flow is composed of eddies, also known as vortices or turbulent eddies, which meander and swirl in a random fashion within the pipe but with an overall mean velocity equal to the flow; that is they convect with the flow. An illustration of these turbulent eddies is shown in **Figure 7**. These eddies are being continuously created. As they move with the flow they break down into smaller and smaller vortices, until they become small enough such that they are 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. On the average, these vortices are distributed throughout the cross section of the pipe and therefore across the flow profile. The flow profile itself is a time-averaged axial velocity of the flow that is a function of the radial position in the pipe with zero flow at the pipe wall and the maximum flow at the center as seen in **Figure 7**.

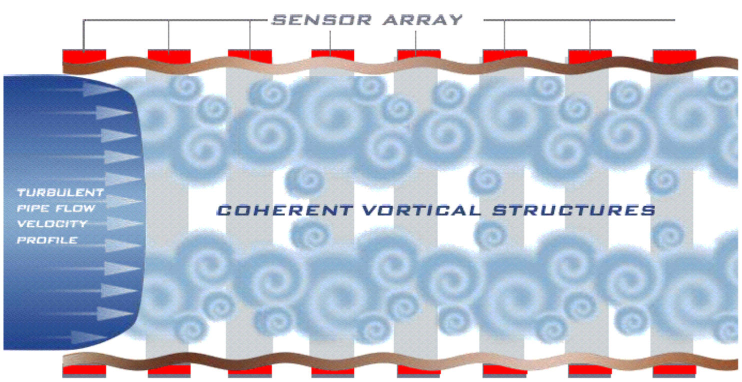


*Figure 7 Diagram of Pipe with Turbulent Flow Showing Fully Developed Flow Profile and Turbulent Eddies*

In turbulent flow, the axial velocity increases rapidly when moving in the radial direction away from the wall, and quickly enters a region with a slowly varying time-averaged axial velocity profile. Thus if one tracks the average axial velocities of the entire collection of vortices, one can obtain a measurement that is close to the average velocity of the fluid flow.

## Array Measurement of Flow Velocity

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

- The movement of the turbulent eddies 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 1 exaggerates)
- The mechanical dynamic strain signal is converted to an electrical signal through a passive sensor wrapped partially or fully around the pipe – no couplant gels or liquids are required
- This electrical signal is detected by each element of the array of sensors. These sensors are spaced a precisely 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 acoustic waves 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.

The challenges of performing this measurement in a practical manner are many. These include the challenges of operating in an environment with large pumps, flow generated acoustics, and vibrations all of which can cause large dynamic straining of the pipe. The impact of these effects is that the dynamic strain due to the passive turbulent eddies is usually much smaller than the dynamic strain arising from pipe vibrations and acoustic waves propagating in the fluid. The strength in the array processing algorithm is its ability to isolate and measure the velocities of these different components, including the weak signal from the convecting turbulent eddies, and the strong signals from the acoustic waves and vibrations. The velocity of the acoustic waves is used to calculate the fluid composition or the amount of entrained air (gas void fraction); this will be discussed in more detail in the section dedicated to **Advances of Sonar Array Technology** in this paper.

Currently this technology can report the volume flow rate on liquids and slurries with flow velocities extending from 3 (0.9 m/s) to several hundred ft/sec. The technology lends itself to measurement on practically any pipe size, as long as the flow is turbulent, and for some non-Newtonian fluids, even without turbulence. The pipe must be full to give an accurate volumetric flow rate but it can have entrained air in the form of well mixed bubbles.

## Calibration

The volume flow measurement provided by tracking the turbulent eddies does require some adjustment or calibration.

In practice the calibration adjusts the reported output by only a few percent, depending on the Reynolds number. Since the flow measurement and hence calibration are not dependent on the absolute values of any analog signals, they will not drift with time or temperature. Calibration accuracy from meter to meter as well as from temperature effects and aging is dependent on maintaining the spacing between the sensor elements and maintaining the stability of the clock used in the digitizer. The spacing between the sensors is fixed when they are bonded to a stainless steel sheet in the manufacturing process, and cannot be adjusted by the customer. Pictures of the sensor band are shown in **Figure 8.**

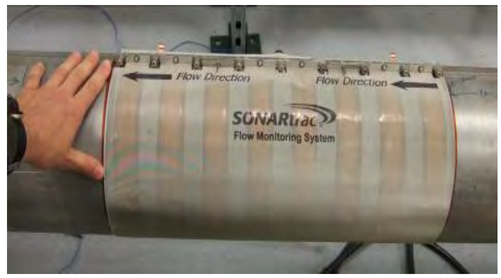


*Figure 8 Pictures of the Sensor Band with Drift-Free Sensor Elements*

The clock stability is better than 0.01% and thus is 50 times better than needed to maintain the flowmeter'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. In **Figure 9** one can see the results from applying the same calibration coefficients to six flowmeters, all of the 6-inch variety and all tested at a NIST traceable calibration facility. As can be seen, the meter to meter variation is quite low, within 0.5%, and with the added advantage that it will not change with time.

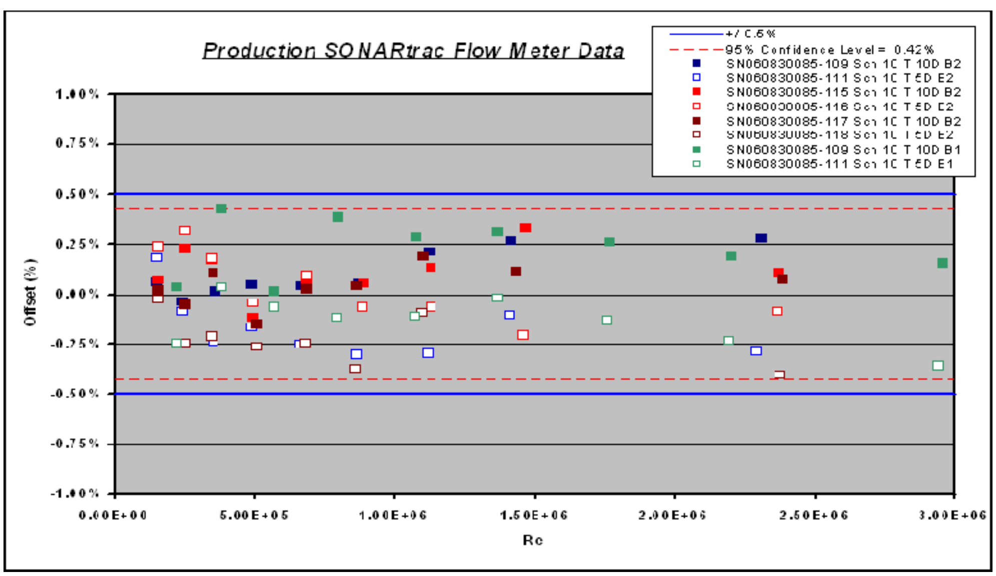


*Figure 9 Illustration of Calibration Consistency from Meter to Meter. All Meters Have Same Calibration Coefficients*

## Advances of Sonar Array Technology

The first part of this paper has illustrated the broad use of the Sonar Array technology with respect to measurements of Volumetric Flow. Specific examples were given of verification tests performed by the Mosaic Company to validate the volumetric flow technology. There are several cases in which the application of the Sonar Array Technology can benefit specific mining operations. Some examples of these cases are:

1. The measurement of entrained air or Gas Void Fraction
2. The detection of sanding
3. Pipeline monitoring

Detailed information for the use of Sonar Array technology in each of these cases follows.

## Gas Void Fraction

As mentioned earlier, the ability to measure Gas Void Fraction (or entrained air), is possible based on the ability of the Sonar array to measure the velocity of sound waves moving in the pipe and the relationship to the speed of sound and the quantity of entrained gas in the solution. It is important to note that the SONARtrac system is capable of making both the volumetric flow measurement and the entrained air measurement independently at the same time.

Acoustic energy is transmitted through pipes in industrial processes from pumps, valves and other devices generating noise. These high speed waves disturb the pipe and can be detected by the Sonar array as they pass by. For the sound speed measurement, the sonar flow meter utilizes similar processing algorithms as those employed for the volumetric flow measurement. As with convective disturbances, the phase and frequency of the acoustic signature from the array of elements is combined to calculate the sound speed velocity. An illustration of the acoustic energy in a pipe is shown in **Figure 10**.

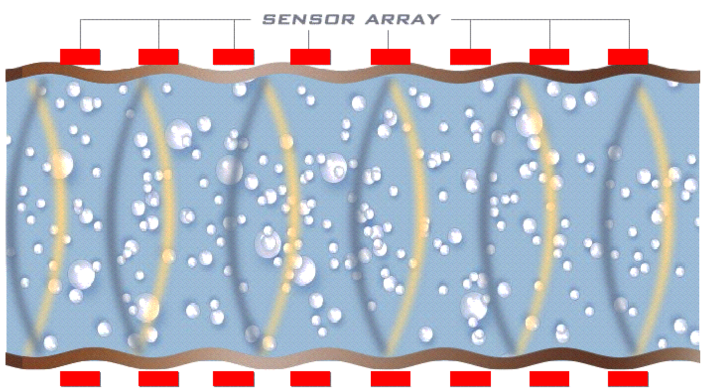


*Figure 10 Acoustic waves propagating in pipe with aerated liquid*

The relationship to the speed of sound and the percentage of air by volume is shown in the chart in **Figure 11**. The entrained air percentage can be obtained based on this relationship.

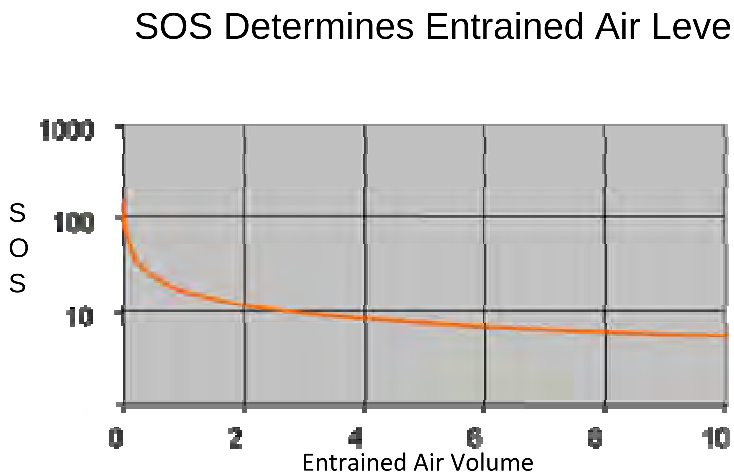


*Figure 11 Graph of Sound Speed vs. Air Volume*

The ability to measure the gas phase of multi-phase liquids is beneficial in mining operations where mass flow measurements are required. Mass flow measurements of slurry are typically obtained by measuring the volumetric flow and the density of the slurry, then computing the mass flow in a particular circuit. Density measurements can accurately measure the three phase mixture density; however, when air is present the mass flow of slurry will be under-reported. This can lead to poor circuit performance and mass balance errors. Because the Sonar array meter can measure the gas fraction in the slurry real time, it is possible to correct the density meter for errors due to aeration. This will improve the mass flow calculations of slurry and improve mass balance calculations across process circuits. The chart in Figure 12 is an example of a corrected density using the Gas Void Fraction meter.

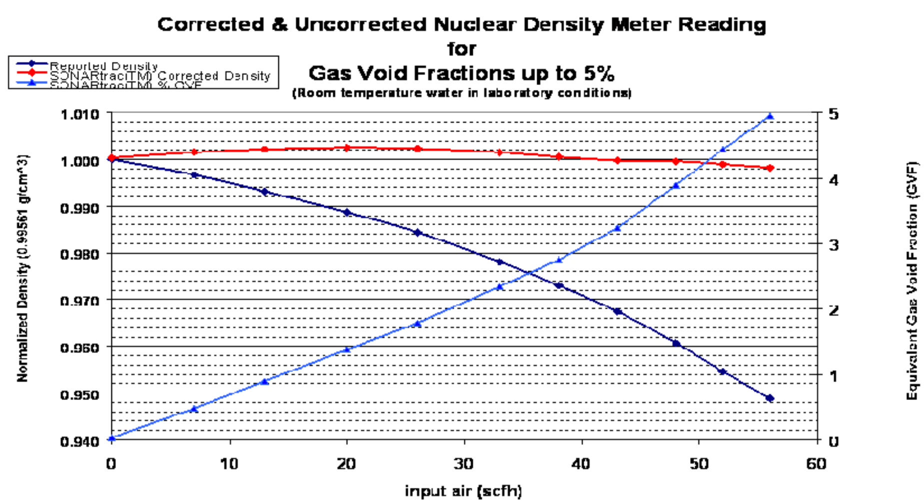


*Figure 12 Graph of corrected nuclear density reading for entrained air*

It is not uncommon for mining processes to have as much as two or three percent air by volume. The chart in **Figure 13** shows the volumetric flow and entrained air measured by the SONARtrac instrument installed on a hydrocyclone feed line at a copper concentrator. It can be seen that the air levels are variable sometimes reaching as high as high as 2.5% by volume. This level of air entrainment can not only cause errors to the mass flow calculation but can also cause poor process conditions and damage to process equipment such as pump impellers that cavitate.

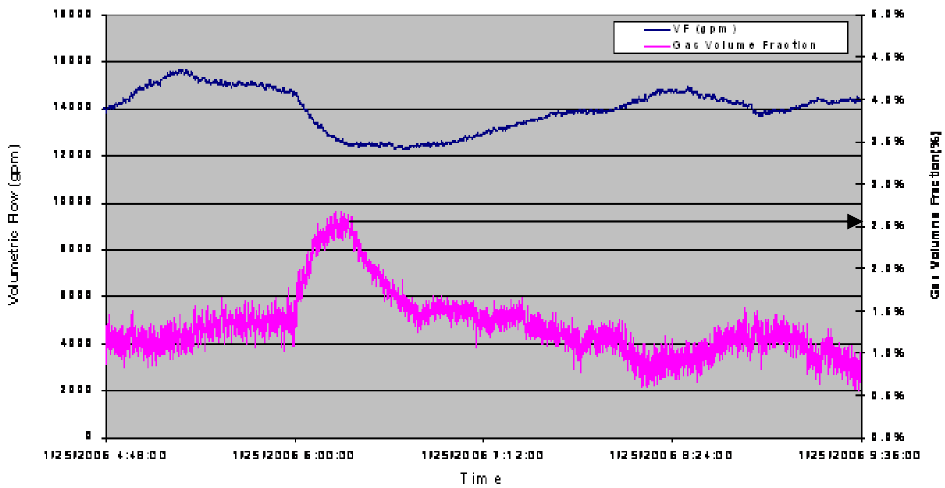


*Figure 13 Volumetric flow and entrained air measured on a hydrocyclone feed line*

The chart in **Figure 14** shows the error in mass flow calculations across a range of slurry densities for varying air fractions. It can be seen that for a slurry density of approximately 1.2 and an entrained air level of approximately 2%; the mass flow calculation error can be as much as 8 or 9 %.

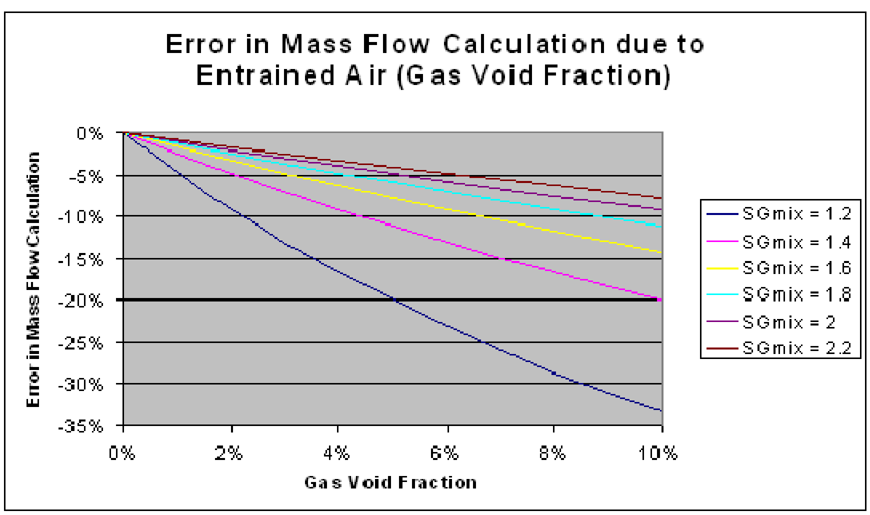


*Figure 14 Error in mass flow calculation due to air entrainment*

## Sanding Detection

Sanding of a horizontal slurry pipeline can occur when flow rates in the pipeline aren't adequate enough to prevent solids in the line from dropping to the bottom of the pipe. The velocity at which this occurs is known as the deposition velocity. There are many factors that impact the deposition velocity, such as; the particle size and distribution, solids density, % solids, and fluid density. It is difficult to maintain the proper flow rate and slurry velocity when these variables are changing. CiDRA has developed a unique system capable of clamping onto the process pipe and measuring the velocity profile of the flow within the pipe at intervals across the height of the pipe. **Figure 15** shows an illustration of the velocity profile of stratified flow in a horizontal pipe.

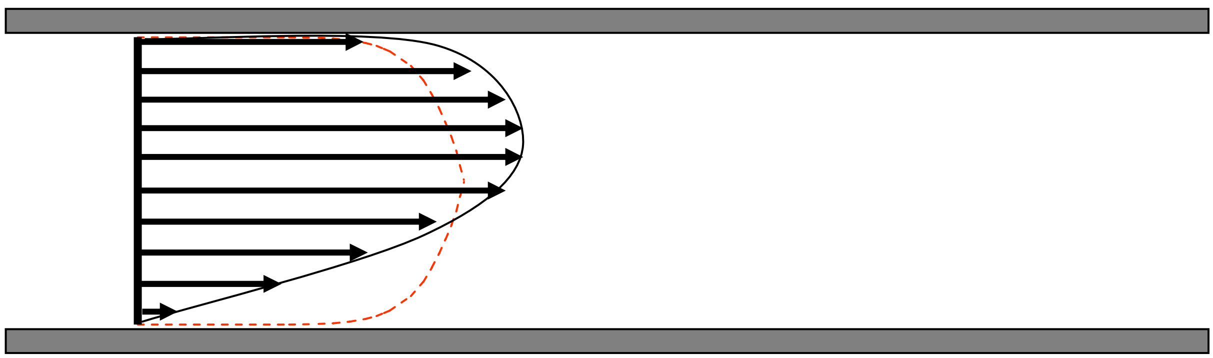

*Figure 15 Velocity Profile of Stratified Flow*

CiDRA has designed a special segmented sensor array to address the problem of sanding. When clamped onto the process pipe the sanding detection meter measures velocities at multiple points across the height of the pipe. These velocities represent the velocity profile inside the pipe. Using this information a control strategy can be put in place to alert operators when flow velocities near the bottom of the pipe are approaching the deposition velocity.

Verification testing of the sanding detection meter was performed on a slurry test loop pumping a 186 um slurry. Data from the verification test is shown in **Figures 16 and 17**.

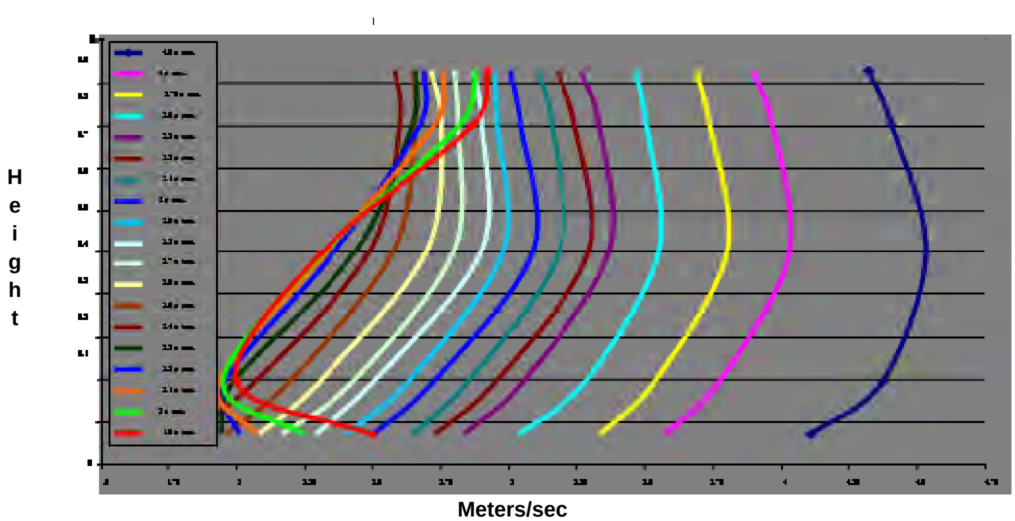


*Figure 16 Velocity profiles from slurry flow loop test*

The data in **Figure 16** shows the varying slope changes to the velocity profile as the flow was stepped down by reducing the speed of the pump. It can be seen that the flow velocities near the bottom of the pipe slow down, relative to the mean flow near the center of the pipe, as the pump speed is reduced. When a stationary bed of sand lies at the bottom of the pipe, the flow velocity of the bottom sensor increases slightly. It is presumed that this effect is due to velocities in the pipe jetting over a sand dune settling at the bottom of the pipe. It is important to point out that this velocity, while slightly increased, is still slower than the fastest flow near the top half of the pipe.

The data in **Figure 17** is the real time velocity data from each sensor segment on the pipe. Once again you can see the trend of the velocities from the bottom sensors slowing down, relative to the velocities of the other sensors, as the speed of the pump is reduced. It should be pointed out that the point at which the velocity increases at the bottom sensor, relative to the nearest sensor above it, correlates well with the increase in density reported from a density gage fixed to the bottom of the pipe. The increase in density is due to the high solids concentrated at the bottom of the pipe (i.e. sand dune).

It is possible, if the sanding detection meter is placed at a location in the pipeline that is prone to sanding, to use the relationship of the bottom sensor relative to the other sensors in the array to develop a control strategy to detect and prevent sanding.

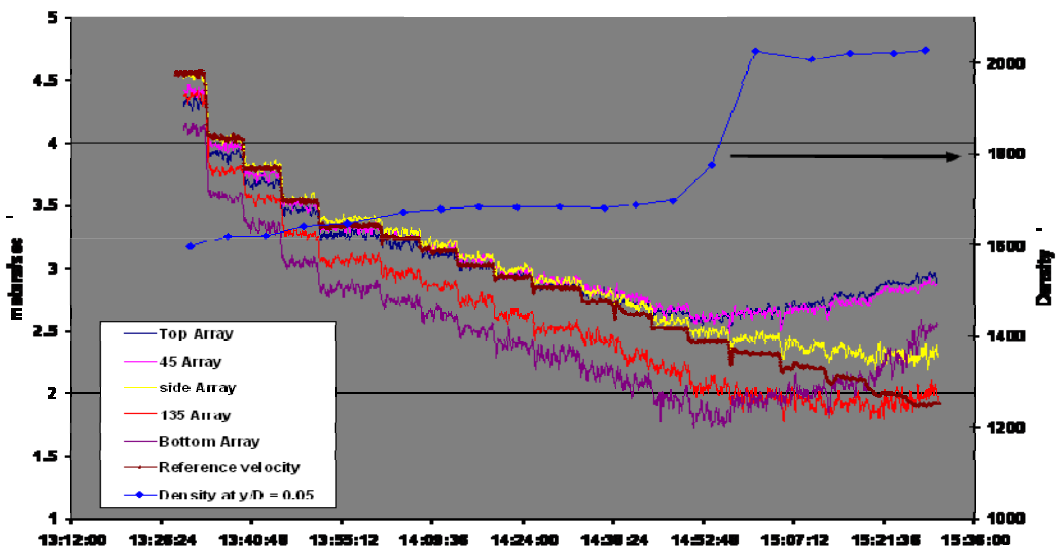


*Figure 17 Flow velocities from slurry flow loop test*

## Pipeline Monitoring

Due to its non-invasive nature and easy installation, the sonar array-based flowmeter is ideally suited for abrasive and/or high pressure applications. As an example, there was a need to have a reliable flowmeter to measure flow at the beginning and end of a >50 km pipeline. The requirement was to accurately measure flow in order to detect any leaks, as well as monitor the load out rate. The challenge for the plant was to do so without breaking into the pipe due to the high pressures (>1000 psi, >70bar) seen on the second flowmeter site. A picture of the high pressure installation in **Figure 18** shows how the external nature of the flowmeter makes for a quick and safe installation, as well as a safe operation.

*Figure 18 SONARtrac installation on a high pressure pipeline*

The resulting flow measurements seen in **Figure 19** clearly show the two flowmeter signals lying on top of each other. The only way to see the small differences between the two readings is by looking at the ratio of the two outputs (red line). Except where transitions cause a difference in flow between the top and bottom meters due to the transit time of the flow change in the pipeline, the averaged ratio is within approximately +/- 1%, which is within the specifications of the meters and the requirements of the plant. Variances between the two flow meters will alert the operators to potential leaks in the pipeline.

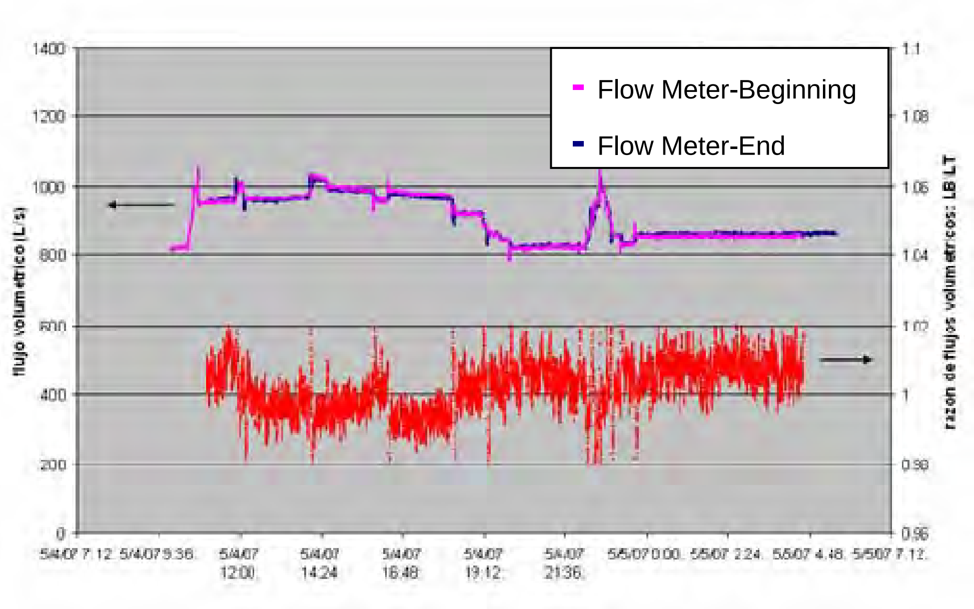


*Figure 19 Data from two SONARtrac flow meters installed near the beginning and end of a 50km long pipeline*

## Summary

Tests were conducted at a variety of Mosaic sites in order to validate the *SONARtrac* VF-100 Volumetric Flow instrument for use on slurry lines in the Phosphate Industry. Data from the *SONARtrac* instrument and magnetic flow meters installed on the same lines were in good agreement with each other.

There are several economic benefits to the clamp-on design and maintenance free operation of the *SONARtrac* system. Other added benefits include the ability to measure Gas Void Fraction, which enables the correction of density gauges when air is present; for improved mass flow measurements. Advances in the passive sonar technology have enabled customers to gain insights into sanding conditions in horizontal slurry lines as well as leak detection monitoring in high pressure pipe lines.

Sonar array based flow meters are installed in a variety of industrial applications world wide and are well suited to meet the needs of the mining industry.

## Authors

### *George E. McQuien, BSChE, PE, Senior Process Engineer – Minerals, Mosaic Phosphate*

**Background:** George McQuien is a native Floridian and has over 30 years experience in the Phosphate Industry. George has worked on both the minerals and concentrate sides, from Laborer to Superintendent of South Pierce's GTSP Plant. For the last six years, George has worked as Mosaic's lead pumping system designer and troubleshooter.

**Qualifications:** George McQuien earned his B.S. in Chemical Engineering from the University of South Florida in 1987. Gained practical engineering experience as Plant Engineer in DAP, Phosphoric Acid, and GTSP production. With the formation of Mosaic, George began specializing in pumps and pumping systems. Having completed GIW slurry transport and pump maintenance classes, George was instrumental in the standardization of pit pumps at Mosaic and has designed multiple systems involving all forms of phosphatic slurries, as well as gypsum and saturated brine solutions. George earned his Professional Engineering License in 2009.

### *Joseph L. Poplawski Regional Sales Engineer – CiDRA Minerals Processing,Inc.*

**Background:** Joseph Poplawski is a native of Connecticut, and has been with CiDRA for 11 years. For the past 6 years, Joe has been with CiDRA Minerals Processing Inc. where he serves as a Regional Sales Engineer. Joe provides sales and technical support to CiDRA's mining customers across the USA and Canada, and has been instrumental in the success of the *SONARtrac* system. Prior to joining CiDRA, Joe worked at United Technologies Research Center in the fields of Laser Diagnostics, Flow, and Acoustics.

**Qualifications:** Joseph Poplawski holds an Industrial Electronics Certificate and an AS in Biomedical Engineering.He has worked on the development of the SONARtrac Flow System and development of optical products for the Telecommunications Industry.

## Acknowledgements

The authors would like to thank the Technicians and Engineers at Mosaic and CiDRA; without whose help the validation test and data presented in this paper would not have been possible.