GRINDING CIRCUIT FINAL GRIND CONTROL AT AGNICO EAGLE MEADOWBANK MINE

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ABSTRACT

Continuous control of the final grinding product size is important to optimize gold liberation for Gold Milling operations. At Meadowbank Mine an on-line Particle Size Monitor has been employed successfully to achieve the targeted final grind which leads to optimizing the gold recovery at maximum grinding circuit throughput. The live monitoring of the final product particle size leads to a maximum grinding circuit throughput every minute during the process. This paper discusses the optimal utilization of the Particle Size Monitor to assist the Mill operator to maximize the grinding circuit throughput as the milling conditions change due to variable ore processed at Meadowbank Mine. Also the paper includes the usage of the Particle Size Monitor to guarantee the final grind target at each instant of the process.

KEYWORDS

Agnico-Eagle, Meadowbank, Grind control, PSM-400MPX, Particle size analysis, Sampling, Gold

INTRODUCTION

Agnico-Eagle is a Canadian-based company that Trades on the TSX & NYSE (AEM). It owns eight mines (8) operating in Nunavut, Quebec, Finland and Mexico and has more than 7,500 employees (Figure 1). 1.6 M ounces of gold were produced in 2015 and the annual average annual production from 2016 to 2018 is forecast to be approximately 1.53 million ounces of gold.

Figure 1 – Location of Agnico-Eagle mining operations

The Meadowbank Mine is located in Nunavut, Canada (Figure 2). The mine opened in 2010 and from 2010 to 2014 a total of 1.8M oz of gold was produced. The milling rate is 4.2 Mt per year with an average mill throughput of 11,900 tpd or 496 tph. Average annual gold production over life of mine is expected to be 450,000 ounces. Meadowbank has 775 employees, of which 265 are Inuit or 36% of the total workforce. Estimated life of mine is 2010 to 2018. Gold production in 2015 was 381,804 oz. Meadowbank was Agnico-Eagle's largest Gold producer in 2015.
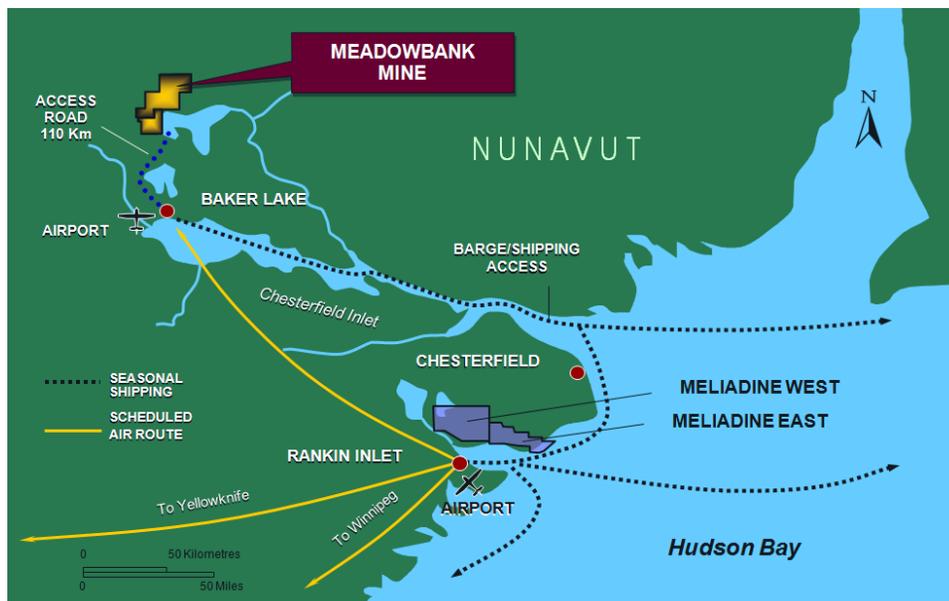

Figure 2 – Location of Meadowbank Mine in Nunavut, Canada

Access to the mine is by road from the community of Baker Lake and via air charter flights. Heavy equipment and supplies for the entire year are transported to Baker Lake during the summer by barge and then trucked to the site along the 100 km all weather road. The camp is operated on a fly in fly out (FIFO) basis with a schedule of 14 days on 14 days off for most employees. The Meadowbank mining operations include three (3) open pits; Portage, Goose and Vault. Currently only Portage and Vault pit ores are processed as production from Goose ended in May 2014.

Metallurgical Plant details

The Meadowbank milling flowsheet is shown in Figure 3. Samplers are indicated by an "S" inside a yellow circle. A total of 5 process streams are sampled for metallurgical accounting and process control.

Crushing Circuit

Run of Mine ore is fed to a primary gyratory crusher with a throughput capacity of 625-850 tph at a design utilization of 75%, which feeds a vibrating screen deck. The oversize material reports to a secondary cone crusher which reduces the 4 - 4½" gyratory crusher product to 0.675" -1½" final product size depending on the required mill feed rate and ore hardness.

Figure 3 – Meadowbank milling flowsheet

Crushed ore is conveyed to a covered stockpile with an 8,500 t live capacity. Two variable frequency drive apron feeders reclaim the stockpiled material to a conveyer belt feeding the SAG mill in the primary grinding circuit. SAG Mill feed size is ¾ to 1 inch.

Grinding Circuit

The grinding circuit consists of a conventional SAB circuit with a 7.93m x 3.73 m 3,356 kW SAG mill and a 5.49 m x 8.84 m 4,474 kW ball mill in closed circuit with 6 hydrocyclones (4 operating and 2 on standby). SAG mill throughput typically ranges from 473 - 515 tph depending on the ore type being processed. The cyclone overflow is the grinding circuit final product and the target 80% passing size (p80) varies from 75 to 110 microns.

Part of the cyclone underflow reports to a gravity recovery circuit which consists of a scalping screen and a single Falcon centrifugal concentrator. The concentrate reports to an Intensive Cyanidation Unit where it is leached and the gold in the pregnant solution is recovered in a dedicated electrowinning cell. The gravity circuit rejects return to the grinding circuit. Gravity gold recovery ranges from 6 – 30% depending on the type of material being processed.

The grinding circuit final product is sampled with a Thermo Scientific SamStat-20 where a sample is acquired for the Thermo Scientific PSM-400MPX particle size analyzer. The PSM continuously measures 5 cumulative size fractions across the full particle size distribution along with the percent solids by weight.

Gold Recovery Circuit

The cyclone overflow goes to a trash screen and then to a hi-rate thickener to provide density control ahead of cyanidation. Thickener underflow reports to the leaching circuit which consists of two pre-aeration tanks in parallel followed by seven cyanidation tanks.
Dissolved gold is recovered on activated carbon in a Carbon-In-Pulp (CIP) circuit consisting of 7 tanks with Kemix pumpcells in a carrousel configuration. Gold is eluted using a pressure Zadra process and then plated onto steel wool cathodes in two parallel electrowinning cells. The gold sludge is smelted in an induction furnace to produce Dore bars.

Following CIP a portion of the cyanide is recycled to the process with a hi-rate thickener and the remaining cyanide is destroyed using a standard SO_2 / air process before sending the slurry to the tailings storage facility.

The process plant availability is 95% with a global gold recovery of 90.5 to 95.5% depending on the ore type.

Samplers and Analyzers

The plant was designed and built with Thermo Scientific samplers (see Figure 4.) for composite sampling and a PSM-400MPX on-line particle size analyzer for the grinding circuit final product. Composite samplers include the SamStat-20 automatic sampler which is located at the cyclone overflow, pre-aeration feed (grinding thickener underflow), CIP tails and cyanide destruction (final) tails.
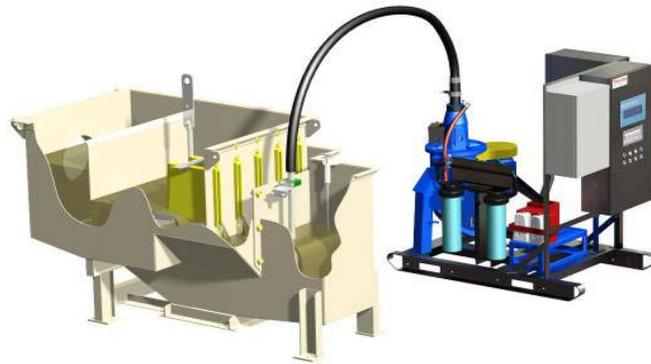
Figure 4 – Thermo Scientific Samstat-30R and PSM-400MPX

There is also a gravity static cutter followed by a linear cutter in order to obtain a composite sample of the leach tails. Since commissioning the plant throughput has increased from 350 tph to the current throughput of 473 - 515 tph following modifications to the original plant design. The resulting increase in cyclone overflow volume exceeded the design specifications of the cyclone overflow sampler rendering its composite sampling function inoperative. The unit has been highly modified to manage the large flow volume and has since been used as the primary sampler for the PSM.

Ore processing challenges in the Grinding Circuit

As is typical in gravity-cyanidation processing plants, when the target grind is not achieved (under-grinding) this results in more unliberated gold particles and therefore a loss in gold recovery. Over-grinding does not have a significant benefit to gold recovery but adversely affects the mill throughput and results in higher unit costs in terms of energy and grinding media consumption.

At Meadowbank frequent changes in ore hardness affect the grinding circuit performance and pose challenges for the control room operator to maintain the target particle size. Furthermore, metallurgical testing has shown that the optimal grind targets are different for each ore type which provides an additional challenge since the mill feed can consist of either ore type or a blend and can change quickly depending on mining operations.

The grind target is set by the metallurgical team based on the desired p80 and the control room operator is required to maintain the cyclone overflow particle size within +/- 1 % of the target percent passing 200 mesh as reported continuously by the PSM-400MPX.

Property	Portage	Goose	Vault	Vault Porphyry	Portage Pit E
A x b	40.7	42.3	40.9	**35.9**	**29.3**
Bwi (kWh/t)	10.7	11.4	**13.9**	**16.7**	11.3
Rwi (kWh/t)	15.1	14.3		16.7	17.1
Ai (g)	**0.540**	**0.517**	0.234	**0.610**	**0.583**
% Pyrrhotite	**3.6**	0.1	-	-	**3.6**
% Magnetite	**22.2**	3.0	-	-	**22.2**
% S	1.63	**11.21**	1.71	1.71	1.63
% Fe	**24.50**	**23.30**	4.87	**4.87**	**24.5**
% Quartz	45.5	49.7	33.0	33.0	45.5
% Muscovite	3.0	3.5	21.5	21.5	3.0
% Pyrite	0.5	**20.7**	**3.8**	**3.8**	0.5
% Arsenopyrite	0.1	0.7	-	-	0.1
Final Grind (microns)	75.0	63.0	**106**	**106**	75
Gold Recovery (%)	**95.0**	**95.0**	91.0	91.0	**95**
CN cons. (kg/t)	0.12	0.18	0.25	0.25	0.12
Lime cons. (kg/t)	1.4	1.7	0.5	0.5	1.4

Figure 5 – Meadowbank mine ore characteristics

Figure 5 compares the various Meadowbank ore types for the three different pits and it can be seen that the A x b and Bwi vary significantly and this affects the grinding circuit operation. It should also be noted that the desired final grind p80 varies from 75 microns for Portage to 106 microns for Vault, which is a significant change in product size and it is a challenge to optimize both throughput and grind on a continuous basis. As a result the importance of the PSM as a critical tool to manage the process has been recognized and resources have therefore been allotted for its operation and maintenance. This has allowed the implementation of the best known practices for daily and preventative maintenance, calibration and technical support as recommended by Thermo Fisher.

An example of the process control trend at Meadowbank is included in Figure 6, which shows the PSM providing real time information regarding the cyclone overflow percent solids and percent passing 200 mesh. The control room operator will make adjustments to the mill throughput and other grinding circuit parameters based on whether the grind is on target or not.
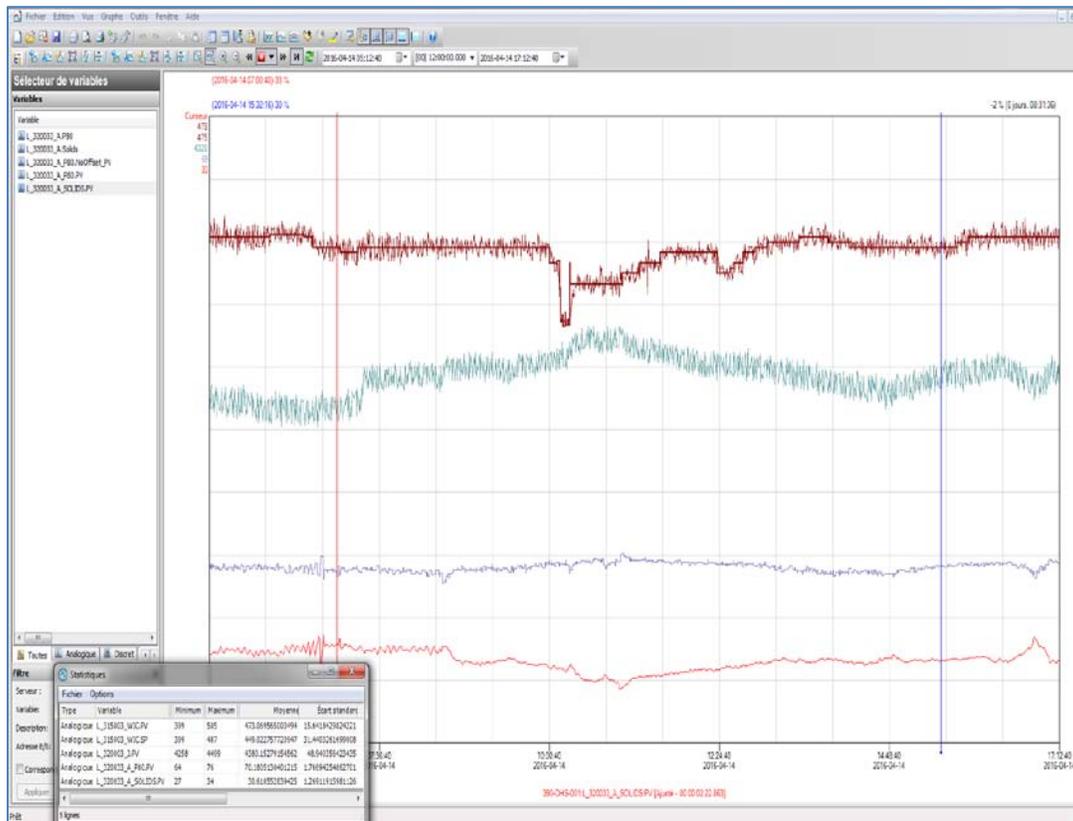
Figure 6 – Example of the control room process trend showing SAG mill feed tonnage (maroon), SAG power (teal) and cyclone overflow percent passing 200 mesh (blue) and percent solids (red)

Meadowbank is a remote mine site with a rotating crew which poses specific challenges. To ensure reliable operation of the PSM-400MPX Meadowbank has invested in yearly training and support contracts with Thermo Fisher Scientific that include periodic site visits. Initially the credibility of the PSM was low due to reliability issues but over time the metallurgical team has been trained in its operation and maintenance to the point where the control room operators have complete trust in this instrument. Metallurgical technicians handle routine activities such as flushing and cleaning as well as basic troubleshooting, and calibration updates are managed by the metallurgists. Daily verification samples are taken from the PSM calibration sampler and compared against the PSM size and percent solids readings to validate the PSM accuracy. The differences are tracked and if a trend emerges then the calibration regressions are updated.

One significant challenge for the PSM operation was dealing with scale build up in the PSM sample conditioner and Flowcell internals, as well as on the ultrasonic sensors. The scale causes erroneous readings and flow problems, which is not surprising because scale issues had previously been encountered elsewhere in the plant. In order to mitigate the issues related to the scaling of the PSM it was decided to try adding the same anti-scale that is used in the plant water systems to the sample conditioner using a small metering pump. The amount of reagent required was relatively small due to the small flow of pulp through the PSM (48 lpm), but it had a dramatic effect in suppressing scale build up in the sample conditioner and on the sensor faces. The net result was a reduction in the time spent cleaning the PSM each day and the accuracy of the verification samples against the PSM also improved. This lead to even greater availability for the PSM (consistently above 96%) with less effort expended to achieve this result.

PSM-400MPX AT MEADOWBANK

PSM-400MPX Technology

The PSM uses scattering of ultrasonic energy in a continuously flowing sample across a range of frequencies to determine the particle size for five cumulative size fractions and percent solids. The relationship of the ultrasonic pressure wavelength to particle size is exploited to determine the coarseness and fineness of the particle size distribution along with the concentration of particles. This relationship is shown in Figure 7.

The scattered signal intensities across multiple frequencies are measured as signal loss (attenuation) in slurry compared to signal intensity in water. The signal loss is reported in Decibels (dB) and normalized to dB/in to account for the different spacing between the ultrasonic sensor transmitter-receiver pairs. The dB/in is determined by an electronic calibration from a known calibration reference built into the PSM electronics. To determine each reading the flowing slurry sample is measured for about 6 seconds during which particle size information is derived by scattering from millions of particle contained in 8 liters of slurry at full percent solids of the process stream. For this reason the fundamental statistics of the ultrasonic method are exceedingly robust. The PSM size and solids outputs are responsive, accurate and stable all of which are essential characteristics for reliable grinding circuit control

The dB/in for each operating frequency are used as inputs to a set of calibration equations to compute the five size fractions and percent solids. The metallurgical calibration is determined by taking a suite of up to 30 slurry samples that span the process operating conditions for both particle size and percent solids.
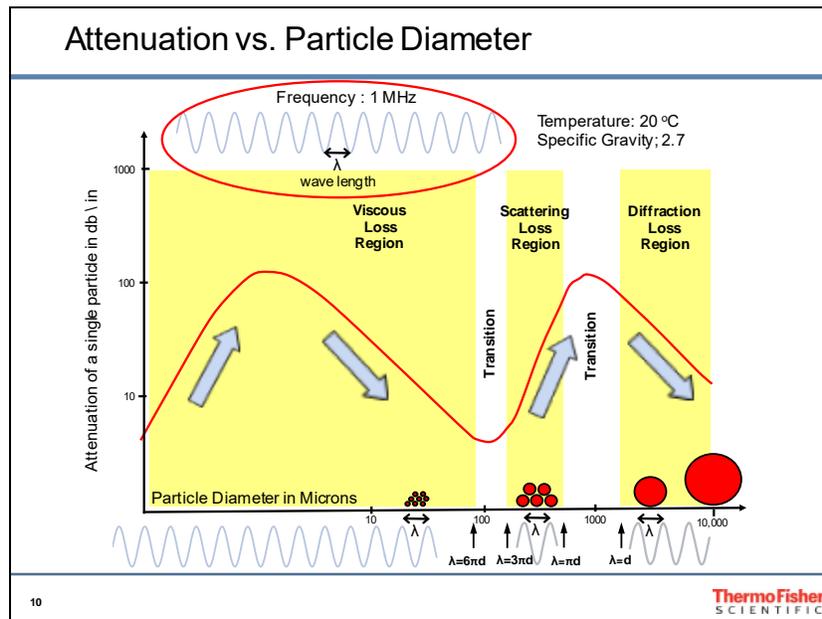

Figure 7 – Loss mechanisms from scattering of ultrasonic pressure waves by a particle in water

The slurry calibration samples are weighed, wet sieved, dried and dry sieved to obtain an accurate determination of the cumulative size fractions and percent solids. This data is entered into a calibration database and regression software tool (Modeler) supplied with the PSM and installed on its central server. Once the calibration coefficients are determined they are saved into the PSM in the field. Using this calibration model the PSM computes and displays the five size fractions and solids results locally. It also sends the data to the plant control system through a network connection. Figure 8 shows an example of a calibration regression in Modeler.
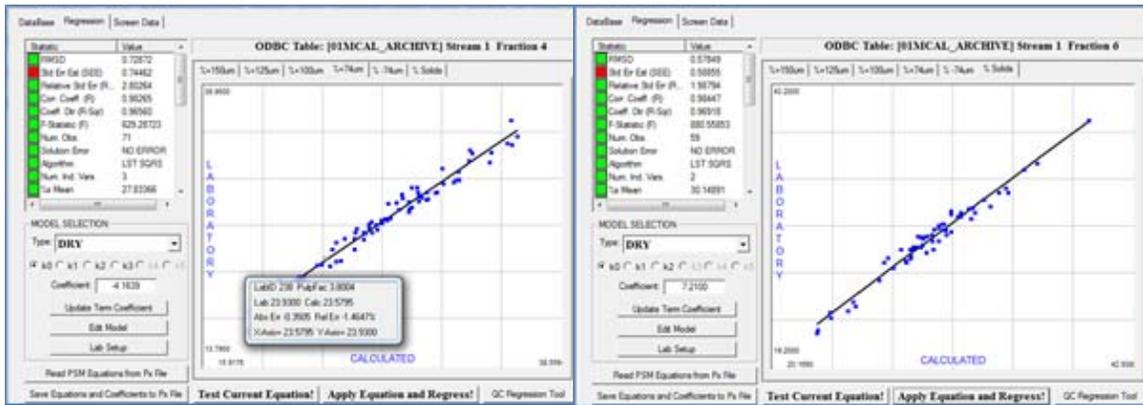
Figure 8 – Calibration regression graph %+74µm (200#) left, %solids(wt) right.

The data in Table 1 and 2 summarize the goodness of fit and calibration sample range for the multi-linear regressions created using Modeler. The goodness of fit and correlation along with other statistical parameters not shown here that are used to build the calibration models show the PSM accuracy is within expectations. The samples used were taken over many months from January 2015 to March 2016 an indication of long term robustness. Samples taken during periods when there was heavy scale present on the sensor faces or obviously bad sieve data were disabled from the regression.

Table 1 – Summary goodness of fit for PSM calibration

Meadowbank PSM 18 April 2016	Error			R	R²	Samples 1/6/15 to 3/20/16	
Fraction	RMSD	SEE	Rel. %			Used	Total
%+150µm	0.57	0.58	8.1	0.983	0.965	72	88
%+125µm	0.82	0.83	6.3	0.972	0.945	73	88
%+100µm	0.82	0.84	4.9	0.978	0.958	71	88
%+74µm	0.73	0.74	2.8	0.982	0.965	71	88
%-74µm	0.57	0.74	1.0	0.982	0.965	71	88
%Solids (wt)	0.58	0.59	1.9	0.984	0.969	59	88

Table 2 – Calibration sample range

Meadowbank Size/Solids	PSM-400MPX Cumulative %	Calibration Samples Range	
Fraction	Mean	Min	Max
%+150µm	9.2	2.0	16.5
%+125µm	14.1	5.2	21.2
%+100µm	18.4	8.3	27.5
%+74µm	27.8	17.0	36.7
%-74µm	72.16	63.3	82.9
%Solids	30.14	22.2	40.2

To measure ultrasonic attenuation accurately in slurry the entrained air must be removed from the sample. This is done in the Sample Conditioner portion of the PSM as shown in both Figure 9 and 10. The Sample Conditioner is a specialized vacuum assisted centrifuge that acquires the sample by aspirating from the process sampler, de-airing it in the centrifuge under vacuum and then stabilizes the flow for measurement. Entrained air is present in all slurries to varying amounts and is created via tumbling in the mills and pumping.
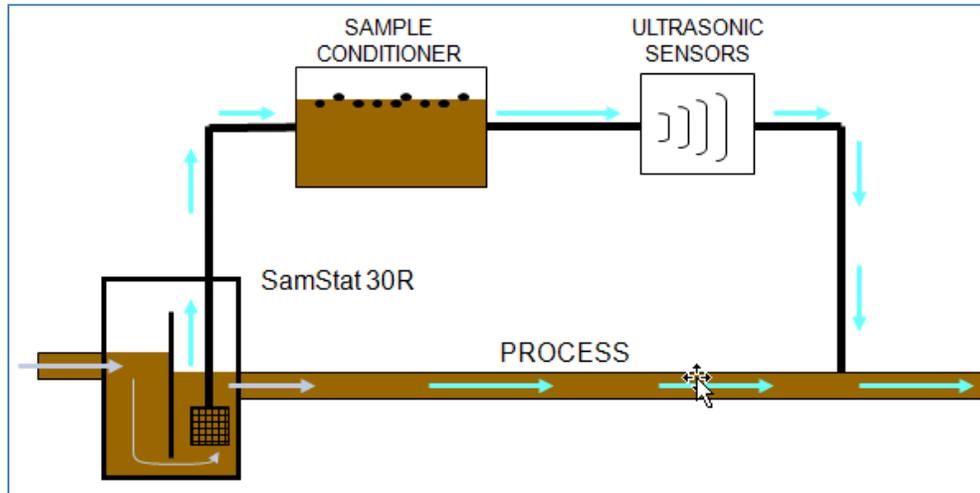
Figure 9 - PSM sample flow path

As shown in Figure 9, the sample conditioner not only de-airs and stabilizes the flow to the sensors but also aspirates the sample from the process which allows reliable continuous flow and gravity return to the process eliminating the need for additional pumping and simplifying the sample transport path. The resulting installation provides ease of maintenance and maximum reliability with minimal measurement lag since sample transport lines are kept very short and direct.
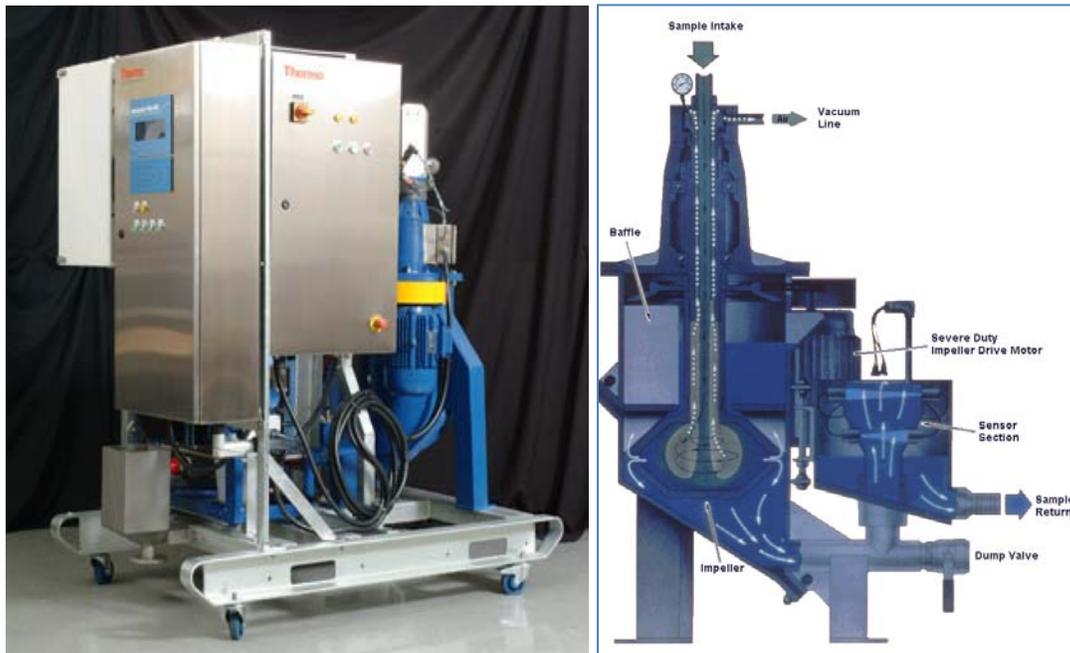

Figure 10 – Skid mounted PSM-400MPX and sample conditioner operation

Installation

To measure particle size accurately on-line in real time the sample must be acquired from a point in the process and in a way where the particle size meaningfully represents the mill classifier product. The sampler should not only allow an accurate sample to be acquired across all size fractions but should be in a location that is as close as possible to the cyclone overflow collection launder. Ideally there should be a

plug-flow regime from the classifiers through the sampler to the PSM and the sample should not be pumped. Previous experience shows that sampling well downstream from the classifiers and especially after sumps and pumps includes excessive measurement lag and process noise into the particle size distribution (PSD). Such samples can have PSDs that over a few seconds are wildly different that what is being produced at the cyclone overflow spout making the data difficult if not impossible to use for process control.

The sample for the PSM must be acquired in a way that does not bias the particle size. This is done by observing iso-kinetic principles in the sampler and the PSM sample acquisition designs. The SamStat uses a reverse flow principle to create an upwelling flow regime which is representative of the process flow. Depending on flow volume this may be a multi-stage device. The PSM aspirates the sample from the sampling zone in the upward direction so that no component of the slurry is required to change direction to enter the PSM sample intake. Proper sampling to obtain the most reliable and reproducible size analysis for grinding control has evolved since the early days of the PSM (1970s) and is based on experience gained from installations in many different wet grinding circuits around the world. The evolution of PSM samplers is shown in Figure 11. The invention of the reverse flow sampler (RFS) in 1983 resolved the inconsistencies and maintenance issues with weir boxes and has been used successfully since. In 2003 the SamStat was employed to provide the PSM sample. This enables proper multi-stage sampling for large process flows along with improved access and simplified maintenance of the intake filter.
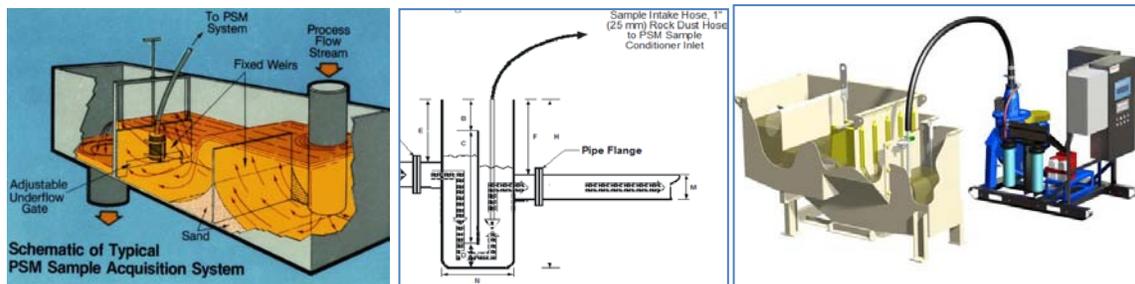

Figure 11 – Samplers for the PSM through the years. Left to right, an early COF collection launder modified into a weir box 1972-1982, the Armco/Denver Autometrics Reverse Flow Sampler 1983-2003 and the Thermo Scientific SamStat-20/30R 2003 to present

Operation and Maintenance

Daily maintenance consists of routine flushing and cleaning with water once per shift. This takes about 10 minutes and is a simple task that is easy for technicians to learn. Frequent checks are made of the operational condition of the sample conditioner as well as the water pressure and vacuum gauges and anti-scale reagent feeding system. Metallurgical personnel take a verification sample once per day from the PSM which is sieved in the lab and compared to the PSM results.

Along with training on various topics such as calibration and troubleshooting, proactive scheduled replacement of wear items and moving parts (ex: drive belts, bearings and impeller) is coordinated through the Thermo Fisher Field Engineer as part of the product support contract. This has contributed to the current high availability and reliability of the PSM.

Accuracy and Availability

Accuracy is tracked by comparing the lab sieve results of a daily verification sample against the PSM reading using the installed calibration. The sample is processed as a normal calibration sample and can be used to update the calibration model using the Modeler regression tool in the PSM central server. If the difference between the daily sample and the PSM reading is considered excessive an offset can be entered in the plant control system to correct the readings displayed in the control room. This is not

statistically robust because it is just one sample and can include sieving errors of as much as 1% or more, but it nonetheless provides a consistent and easy to perform procedure to verify the results. Due to the high accuracy of the PSM this offset function does not need to be used very frequently. If necessary, the accumulated verification sample results can be used to update the calibration model using a more statistically robust set of data spanning a greater range of process conditions over time.

The data can be plotted over time as shown in Figure 12 below. In addition to validating the accuracy trends this also provides a useful diagnostic tool to monitor the maintenance procedures for the PSM. Note the larger errors occurring in October and November 2015 in the chart on the left, which were found to be the result of inadequate Flowcell sensor cleaning. The chart on the right with more recent data shows that the bias has been removed from the error as a result of the anti-scale reagent addition, refining the validation sampling procedure and elimination of a 1% calculation error of %Solids in the lab sieve data spreadsheet.
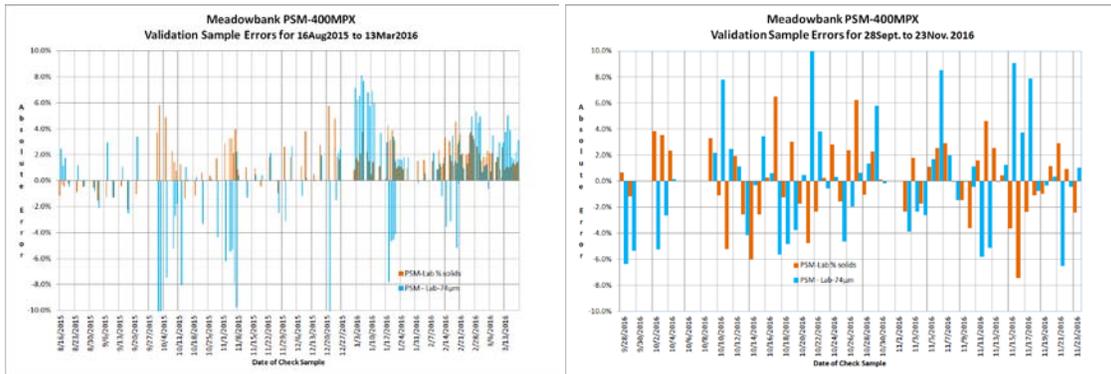

Figure 12 – PSM vs daily verification sample offset for passing 200 mesh and percent solids

The cleaning practice was being carried out as before but it was not sufficient to deal with the additional scale created by the combination of ore types being treated at that time. This finding led to developing a better cleaning practice. Eventually a less labor intensive solution was found by automating the addition an anti-scaling reagent into the PSM sample conditioner.
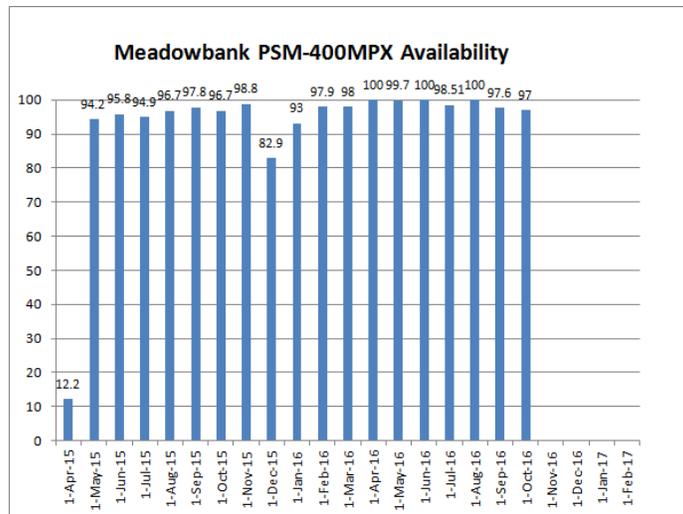

Figure 13 – Meadowbank PSM-400MPX monthly availability with respect to plant availability

The PSM availability with respect to plant availability shown in Figure 13 is determined by calculating the time that the passing 200 mesh parameter falls within a defined range each day and

comparing that with the plant operating time. This range is determined based on the experience of knowing the expected range of the grind and that values outside this range indicate a problem such as a sanded sample line or flushing with water during the daily maintenance routine.

Payback Study

An internal payback study was carried out by the Meadowbank metallurgical team to determine the benefits of using the PSM for grinding control. The analysis was based on comparing the mill performance during periods when the PSM was not available with periods when the PSM was operating reliably. In the study two periods when the PSM was not operating were considered: prior to commissioning in September 2013 and the period from December 2014 to April 2015 when the Flowcell failed and the PSM was not available while waiting for a replacement part.

Figure 14 shows the achieved versus target grind for periods when the PSM was available compared to when it was not operating. Similarly, the actual versus modeled gold recovery for periods with the PSM and without the PSM is presented in Figure 15. As is expected the main impact of the PSM is on grind size and on average the grind size was 6.1 microns coarser than the target without the PSM compared to 1.7 microns coarser when the PSM was available. As can be seen below, the better grind control when using the PSM leads to a gold recovery that is on average better than the model then when the PSM is not available.
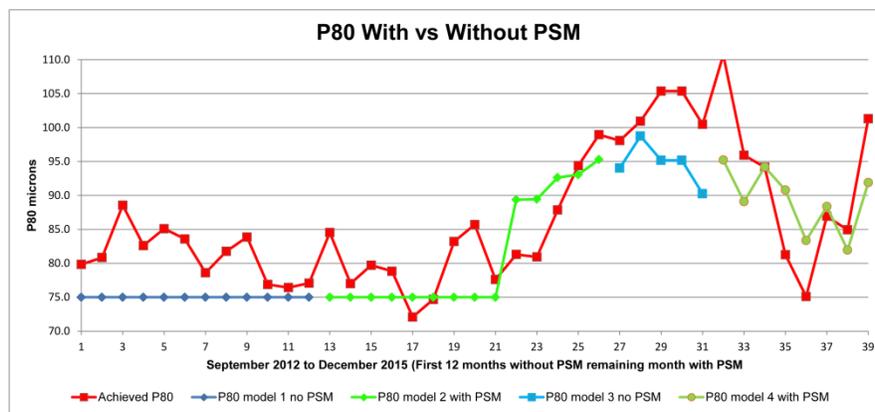

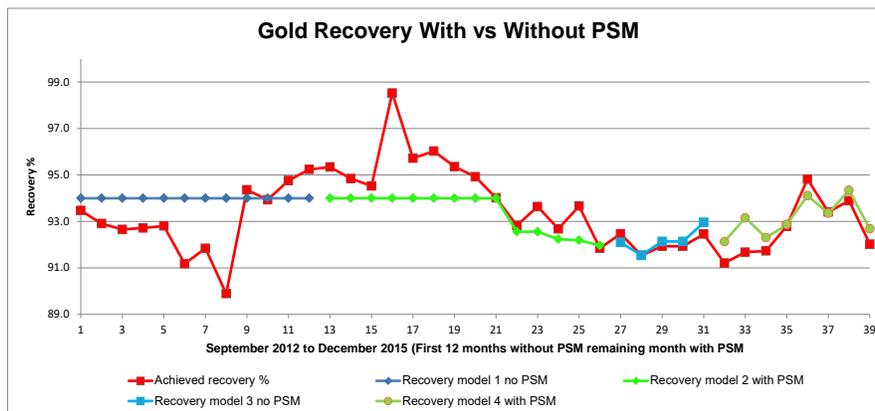Figure 14 – Achieved versus modeled p80 with and without the PSM

Figure 15 – Achieved versus modeled gold recovery with and without the PSM

The differences between achieved grind size, throughput and recovery versus the respective models are summarized in the Table 3 for periods with and without the PSM, respectively.

Table 3 – Summary of internal grind control payback study: achieved vs. modeled

Meadowbank	PSM-400MPX	Payback Study	
Achieved v.s. modeled	Δ grind size	Δ Throughput	Δ Recovery
Operating condition	Microns	TPH	%
Without PSM	6.10	-15.94	-0.70
With PSM (Combine)	1.70	-9.02	0.59
Recovery PSM Gain (50%)	-4.40	6.92	0.64

An economic analysis was performed based only on the gains in recovery and not due to any improvement in mill throughput. Also, the gain in recovery could be partly attributed to other factors such as better budgeting practices so the analysis assumed that only 50% of the gain in recovery found could be attributed to the better grind control. Based on these assumptions it was estimated that the improvement in grind control due to the PSM resulted in the production of an additional 249 ounces per month.

CONCLUSIONS

The grinding circuit control strategy to produce a stable and optimal grind at a target size depending on ore type or blend has resulted in measureable increases in gold recovery and more stable operation of the mill to optimize the grinding circuit throughput at each instant of the process. The achieved Mill throughput and gold recovery performs more predictably to the Meadowbank models increasing their value to the business as an operational planning tool.

The Thermo Scientific PSM-400MPX has proven to be a reliable tool for control of the final grind product and is a prime enabler for the above mentioned improvements in final grind size stability and recovery of Gold. The increased recovery of gold reported in the internal study attributed to the PSM is significant and returns additional revenues and cost savings which more than justify the purchase and ongoing investment in operating, maintaining and servicing of the PSM.

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REFERENCES

Agnico Eagle Website – Operations page – Meadowbank
   http://www.agnicoeagle.com/en/Operations/Northern-Operations/Meadowbank/Pages/default.aspx