SIZE DISTRIBUTION CONTROL

WITH THE PSM-400

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ABSTRACT

For many years, the PSM system has been available as an on-line instrument capable of producing an output representative of a single point on the size distribution. Often overlooked, however, is the PSM's sensitivity to the grind size distribution. Utilizing this inherent distribution sensitivity of the PSM to control the cumulative distribution delivered to subsequent processes can yield benefits many times the initial cost. Benefits can also be realized in the added circuit insight and troubleshooting potential of the instrument. Extraction of MAXIMUM potential requires proper application of the instrument as a measuring device and normally necessitates some type of grinding circuit control. An understanding of some statistical process control principles and applying these principles in control of the grinding circuit can help to yield improvements in overall efficiency in the plant. Payoff of initial investment can be realized either through increased throughput, better recovery, or some balanced combination of the two for maximum revenue yield. This treatise explains PSM operation and sensitivity to size distribution and why that sensitivity can be implemented to maximize plant efficiency.

INTRODUCTION

Since 1969, Denver Autometrics has been installing on-line particle size monitors in concentrators around the world. This continued affiliation with numerous grinding applications has qualified us as experts in the field of on-line particle size measurement and its application to various types of comminution circuits.

Due to the need for on-site calibration of each instrument, we have been present for the commissioning of over 400 instruments. Ongoing field service operations have kept us in continued contact with most of these installations on a technical level. We have thus been able to attain a high sensitivity to the general level of acceptance of our product, and the perception of its value to our customers.

Since its introduction, the PSM has been through three design revisions. These revisions were largely a reaction to marketplace demands to extend measurement range, increase reliability and offer an instrument which makes use of state-of-the-art in microprocessor technology. The original physical principals of operation have been retained throughout these revisions. As our understanding of these principals has grown, we have continued to improve the quality and expand the capabilities of the instrument. With the PSM-400, and the extremely high level of reliability it has exhibited, we offer an instrument which places results directly in the hands of operations personnel without regular intervention from
maintenance and instrumentation professionals. Most PSM-400's are calibrated and utilized directly by plant metallurgists and operators.

The PSM is accepted as an instrument capable of producing an output representing a single point on the grind distribution. This output has often been put to use in automatic control of grinding circuits to realize maximum process optimization. However, it has not been fully appreciated that this instrument output is actually representative of the entire grind distribution. Nor has the statistical necessity of controlling this distribution at the earliest possible point in the circuit been appreciated.

OPERATING PRINCIPLES OF THE PSM-400 SYSTEM

The PSM-400 is a rugged, on-line instrument which pulls its own sample at approximately 20 GPM (75 LPM). It then deaerates the sample and passes the deaerated sample through diametrically opposed ultrasonic sensors. Deaeration is necessary due to the undesirable effects of air upon ultrasonic transmittance. Size and % solids readings are produced at a rate of approximately 20 readings per second, and the sample is returned back to the process. The PSM's only requirements for operation are 3 phase power to the air eliminator motor to drive the vacuum-assisted centrifuge and power the electronics; approximately 12.5 GPM (47 LPM) of water at 60 psi (450 kPa) to create the vacuum necessary to remove air and supply seal coolant water; and representative sample point located somewhere below the instrument. Experience shows that an upward-flowing, well-mixed, continuous flowing sample is best. On-site calibration to the preferred lab standard is performed to present particle size in a universally accepted form. This also allows for occasional accuracy checks to the preferred standard.

Two sets of ultrasonic sensors are utilized to accomplish the size measurement. Each is a matched set of transmitting and receiving transducers which operate at discrete frequencies, these transducers being diametrically opposed across the slurry sample flow stream. Loss of energy from transmit to receive is measured in decibels of attenuation:

\[ dB = -20 \log \left( \frac{V_{out}}{V_{in}} \right) \]  

(eq. 1)

where \( V_{out} \) is voltage at the receive transducer and \( V_{in} \) is voltage at the transmit transducer. This is commonly represented as alpha (\( \alpha \)), units of dB per inch for a single particle. Attenuation change is linearly affected by sensor spacing.
One set of these transducers is selected to operate at a unique frequency such that only changes in the amount of solids present in the slurry, and not particle sizes, affect the total amount of ultrasound energy lost (attenuation) as it travels from transmit to receive transducer. Attenuation of the ultrasonic signal increases with increased solids content. This set of sensors is referred to as SOLIDS (Fs) sensors. Please refer to the following figure.

![Figure 1](image)

At any other frequency, attenuation losses will be affected by both changes in the amount of solids and particle size distribution. Higher frequencies produce greater initial attenuation and greater attenuation changes as particle size changes \((A_{b} > A_{a})\). The operating frequency of the second transducer pair is therefore chosen so that at maximum coarseness and maximum percent solids of the slurry, the instrument does not overrange \((a_{max})\), and yet creates enough attenuation change from fine to coarse particle size to yield maximum sensitivity to grind size changes. At this second frequency, larger sizes produce larger losses at constant percent solids. This set of sensors is referred to as SIZE sensors.

The output of these two sensor sets is then mathematically compared to yield a parameter which changes directly with changes in size and yet remains constant with changes in percent solids of the slurry. This size-depndant parameter is referred to as GAMMA \((\gamma)\). The result of attenuation changes from the SOLIDS sensors directly yields a parameter which changes with percent solids. This parameter is referred to as ASN. These two parameters are then calibrated to a lab standard to output continuous size and percent solids information. On-site calibration is necessary to account for site specific differences in distributions, sampling,
and lab technique. This further guarantees that the user is presented with an output identical to that which he has learned to use to evaluate circuit performance. Typically, percent passing (or retained) on a Tyler screen is selected.

**DISTRIBUTION EFFECTS UPON PSM MEASUREMENT**

Theoretically, once the proper particle size for the process in question has been identified, it would be desirable to produce all particles at that given size. Some distribution may, of course be necessary for material handling purposes and to maintain an efficient viscosity in the mill, but mono-sized particles would increase the efficiency of most size-dependent processes. This is, unfortunately, impossible due to the breakage function of materials and the inability to remove properly sized material still in the grinding process. It is thus an unavoidable necessity that a size distribution be produced.

The classification characteristic of the classifier is typically represented by a reduced efficiency curve.

![Reduced Classifier Efficiency Curve](image)

The x-axis of this graph indicates particle size. The y-axis indicates the percent of that size reporting to classifier output. Theoretically, this curve could be a vertical line (infinite slope) at some size separation point, with all other sizes at 0 and 100% (curve C1). This would mean that all sizes above a given size were returned to the ball mill for further grinding and all sizes below a certain size were immediately removed before being ground too.
fine. Recognize that this is not necessarily desirable from a grinding efficiency viewpoint, as fines are necessary to control mill viscosity. It is the characteristic of a classifier that such a fine cut cannot be performed. There is thus an inherent S-shape and slope to the typical curve (curve C2). The slope of the curve is generally an indication of classifier efficiency, greater slopes indicating higher efficiencies.

The classifier efficiency curve indicates the ability of the classifier to act upon the size distribution which is delivered to it. Viewed as a frequency probability density function, that distribution may look as follows:

![Size Density Function](image)

The x-axis represents particle size and the y-axis is a number of particles at each size. Note that the differences between this curve and the classifier efficiency curve tell two entirely different stories. The classifier efficiency curve represents the percent of WEIGHT fraction smaller (or larger) than a given size which is to be classified. The frequency probability density curve indicates total particle SIZE amounts. The area under the curve up to a given size relative to the total area is representative of the percent less than that size fraction.

Consider the effect of a complete distribution of particle sizes upon the ultrasonic signal being transmitted through the slurry. Each particle will produce a loss dependant upon its size; smaller particles producing smaller losses and larger particles larger losses. The net effect is that total attenuation is a function of the attenuation of each particle present. This is illustrated in the graph on the following page:
Figure 4a represents the attenuation as a result of particle size at a given frequency. The x-axis is in units of microns and represents increasing particle size to the right. The y-axis is in units of dB per inch (or α) and represents increasing attenuation for a single particle. Multiplying alpha times spacing (constant) yields attenuation.

Figure 4b represents the frequency probability function for a normally distributed grind size range. Few, if any grind size distributions are normally distributed, but a normal distribution is shown here for simplicity. (The principles to be discussed could be applied to any distribution shape.) See Figure 2 for an explanation of the axes of this graph.
The effect of individual particle sizes upon total attenuation can then be readily recognized as:

$$A_{\text{total}} = \sum_{i=1}^{n} N_i A_i$$

Where:

- $A_{\text{total}}$ is the total amount of attenuation caused by the particular sample distribution in question.
- $N_i$ is the number of particles present at the $i$'th size interval.
- $A_i$ is the attenuation of each particle at the particular size. It is alpha times spacing at each interval, spacing being constant.

Note that this could just as easily be written as the integral of particle size times characteristic attenuation with respect to particle size.

It becomes obvious that any changes in particle size distribution will cause a net change in total attenuation and therefore a change in output from the instrument. However, it is the characteristic of a grinding and classifying operation that although the distribution may not maintain continuous shape as nominal (or mean) grind size changes, the shape is constant within any specific size interval. Therefore, although the nominal grind size may be changing, whenever the circuit is outputting a specific nominal size distribution, the distribution shape will be the same, or exhibit only minor variance. Note that this is true only for samples taken under identical sampling circumstances and from the same point in the circuit. Samples taken from different points in the circuit or using a different or unrepeatable sampling method may show variance and lead to conclusions that distribution variance is occurring. At this point it is important to note that extremely wide variations in the ore being milled, operation of the grinding circuit outside of its normal operational range, or changes in equipment within the circuit may in fact produce distribution shifts.

These observations of the lack of distribution variance have been proven to be true in all installations in which PSM's have been involved. If this were not the case, it would be impossible to calibrate a PSM. These facts have been independently reported and
verified unofficially by many others. Keeping in mind the method by which $A_{\text{total}}$ is obtained in equation 2 above, consider the following comparison of two different distributions:

![Size Distributions With Common Mean and Number](image)

Figure 5

Referring to the figure above, it can be seen that although these two distributions have the same nominal (or mean) particle size, total attenuation for them would be markedly different. Had the instrument been calibrated using D1, the instrument would have shown a large difference between instrument output and lab results when a check sample was taken with sample D2.

Knowing that the PSM is sensitive to the complete distribution of particle sizes, valuable information can be obtained from the initial calibration of the instrument. Providing a sufficient stack of screens is used to perform the initial calibration, information of the interdependence of coarse and fine materials can be quantified. The following is a graph from a PSM calibration illustrating this:
The gamma output shown on the x-axis is the instrument output which corresponds to size changes as shown in the preceding section. Since gamma is constant for any particular distribution, we can use the graph above to extrapolate grind at any given mesh size so long as the value is known at any other mesh size. In the installation depicted above, the metallurgists used the 100 mesh readings for daily operations.

CONTROLLING THE GRIND DISTRIBUTION

With the introduction of the PSM, grinding circuits once thought to be fairly stable were seen to be quite dynamic. Since the stability of a mill/classifier combination was a widely accepted assumption, this caused some concern at the earliest installations. As the reasons for these upsets were investigated, however, considerable faith was instilled in the PSM’s ability to precisely monitor grind variations. The following diagram illustrates some of the variables which can have an effect upon the grind distribution at the cyclone overflow in a particular circuit. Fortunately, with an on-line particle size monitor, the net effect of all these can be reduced to a single variable.
The product of the grinding circuit is generally considered to be the output of the cyclone overflow or other classifier. It is the function of the classifier to remove sufficiently fine product from the circuit so that the full capacity of the mill can be used to grind more product. Further, the classifier must deliver the proper size particles to subsequent processing to ensure that liberation or reaction kinetics are satisfied. The classifier is thus the heart of the grinding circuit, and its control governs the efficiency of the entire circuit. Classifier product output is therefore the typical location of a PSM.

Let us consider the uncontrolled output of a grinding circuit during some period of time. As the distribution mean shifts with normal changes in feed size and grindability, and as densities and flow rates change in the circuit, this distribution mean and distribution shape may change between two finite endpoints. The resultant net distribution as delivered to subsequent processes will be a composite of all distributions which have taken place over the period of time in consideration. This is illustrated in Figure 8 below:
A shift composite sample, compiled on a regular basis will reflect this composite distribution. Operators may take advantage of this by allowing the circuit to run coarse during times of hard ore and make up for it during times of soft ore, thus "balancing" the composite grind. Note also that it is the tendency of the grinding circuit to perform this same task if it is allowed to run freely at constant feed rate and classifier feed percent solids. Therefore, on a metallurgical basis, the composite sample may meet the required grind, and yet results are still not what had been hoped for! The reason for this is that there is too much coarse or fine (or both) product. Even though on a percentage basis the required criterion is satisfied, excess coarse material has been allowed which is out of specification and is made up for by producing excess fine material, which is also out of specification. Both excesses will probably cause efficiency problems in subsequent processes.

Also note what this does to the "apparent" classifier efficiency curve. The curve tends to flatten out and exhibit a larger size spread and thus a resultant decrease in slope. This appears as decreased overall classifier efficiency.
During a period of operation in which changes in ore are not so drastic, however, the proper grind may be attained without having produced so much coarse product and so much fine product - the composite grind therefore exhibiting less variance then that shown in Figure 8. That is to say that the STANDARD DEVIATION of the grind was not quite so large. Operations which judge efficiency by composite grind comparison usually report that they see no grind dependency in subsequent operations. It is, in fact, standard procedure in operations which use large collecting tanks that product specifications are met by "balancing" the grind as mentioned above.

Examine in Figure 10 on the following page the results of controlling the same grinding circuit output distribution within specific limits. Typically, the mean size can be controlled within 1% absolute (referring to amount retained or passing a given mesh).
The resulting composite distribution is very "peaky" compared to the previous ones, exhibiting a much lower STANDARD DEVIATION. Total amount of coarse and fine particles would be much less. The resulting product delivered to subsequent operations would be closer to an ideal mono-sized particle distribution, which would allow greater control of material handling, recoveries, and process efficiencies.

**MAXIMIZING CIRCUITS WITH SIZE DISTRIBUTION CONTROL**

The ability to control the grind distribution at the classifier allows you to control the standard deviation of the overall (or composite) grind distribution which is delivered to downstream processing. This means that a very peaky distribution is produced with very little "tail" intruding into either the coarse or the fine size fractions.

If the aim of a circuit is to accomplish greater throughput, that circuit will typically have a coarse grind constraint. Beyond this coarse constraint, either recoveries drop, classifier efficiency is lost (roping cyclones, etc.), or mills overload. Typically, an operation looking for throughput will therefore operate at an "average" grind which, with changing ore conditions, allows the grind to only occasionally bump against this coarse grind.
constraint. The operation is therefore losing tonnage during those periods when ore is softer and thus ground finer than necessary.

The opposite is true of a mill with a recovery goal (usually one of limited mine life). There will be a fine grind constraint beyond which recovery is lost. Classifiers and flotation operate inefficiently and excess power usage results. In this operation, they operate at an "average" grind which, with changing ore conditions, only occasionally bumps against this fine constraint. Recovery is therefore lost during periods when ore is harder and grind is excessively coarser.

The PSM allows such operations – throughput or recovery dependent to "butt" the size distribution up against this size constraint either through a control system or via operator interaction. The lowering of standard deviation means you can hold the grind at that point and reap the resultant gain in profits (See Fig. 11, Fig. 12). One operation has quoted a reduction in grind standard deviation (SD) from 10% to 2% (on 100 mesh screen) and as a result increased nominal grind coarseness by four percent, thus gaining the additional throughput which this allows. Others have quoted increases in both throughput and recovery as a result of reduced SD.
Although not currently widespread practice, the addition of an on-stream analyzer, such as our own XRA-1600 allows a base metal operation to accurately establish the real-time relationship between grind and recovery for different grades and hardnesses of ore. Having established the dynamics of this relationship, they can then set grind size for maximum total profit based upon the prevailing metal prices, grind costs and other constraints. (See Fig. 13)
The PSM has been used successfully in over 400 installations since 1969 to accomplish the above-mentioned goals. Additionally, it has been used as a troubleshooting and training tool, both for plant commissioning, and ongoing operations. A gold mine started recently commissioned in one week with the help of a PSM. They mention that they saved their original investment during start-up alone. For them, it continues to be a circuit control tool, as well as a training tool for new operators and a troubleshooting guide which gives them early warning of equipment problems.

PROPER USE OF A PSM

As mentioned, large standard deviation in the distribution curve may lead to the belief that there is no grind dependency in subsequent operations due to inefficiencies experienced in both the fine and coarse fractions of the distribution. Also, a large standard deviation in the composite grinding circuit output may occur even with a circuit under tight grind control, IF THE PARTICLE SIZE MONITOR IS IMPROPERLY APPLIED WITHIN THE CIRCUIT. It is extremely important that particular attention be paid to the installation location and sampling system prior to initial installation. Considering the cost savings to be expected (properly applied PSM's typically pay back their investment many times in the first year), a little time and money spent on the front end can ensure that these cost savings are realized. It is therefore of utmost importance that the PSM obtain its sample AS CLOSE BEHIND THE CLASSIFIER AS IS PRACTICABLY POSSIBLE. Some things to be avoided in installations which may lead to problems with cumulative distribution control are as follows:

1. SAMPLING FROM OR AFTER A LARGE VOLUME. The net effect of any incoming (small) volume distribution upon the existing distribution of the larger volume is not enough to change the net output of overall distribution reading. For example, a relatively large volume coarse distribution which is fed a relatively small volume fine distribution being fed to it will still seem to be a coarse distribution and no control action will be taken to rectify the situation. Thus, numerous fines which cannot be efficiently processed may be delivered to the ensuing process and mill capacity will have been wasted.

2. SAMPLING A COMBINATION OF PRODUCT LINES. The net effect of one line's distribution upon the other's may be enough to offset any changes which may be occurring. The problem is compounded as the number of lines grows.

3. SAMPLING TOO FAR AWAY FROM CLASSIFIERS. The effect of this is somewhat less than those above, but could become considerably dependant upon line size and velocity and the distance involved. The problem is that particles are
being delivered to a line mix with particles already existing in the line. Responsiveness is therefore sacrificed.

4. MULTIPLEXING A SINGLE PSM BETWEEN LINES. Multiplexing systems offer many possibilities for distribution effects. Components used may produce effects similar to any others listed here due to residence times and volumes. Additionally, the factor of uncontrolled distributions created during periods of non-monitoring compound the effects.

5. SLOW REACTION TIME TO PARTICLE SIZE CHANGES. It is for this reason that the greatest savings realized from a PSM come from using it in an automated control scheme. Operators simply cannot react quickly enough to make the proper changes in the circuit to keep the circuit at optimum conditions. Note also that extremely dampened instrument or controller response may exhibit the same effect.

Facilities which have incorporated size-based control schemes have generally gone to a coarser grind and maintained previous recovery rates. This is because the composite distribution is controlled, producing a lower standard deviation and thus less coarse and fine product to be dealt with in subsequent operations. These facilities were also able to reap the benefits of the resultant increase in throughput.

THE PSM AS AN ANALYTICAL TOOL

Improper analysis of distribution effects upon the process has led to many false conclusions with respect to the dependency of grind distribution upon the efficiency of an operation. Proper scientific procedure dictates that in order to evaluate any process and the effect of any variable upon that process, it is necessary to hold all other variables constant while evaluating the net effect of the variable in question. It stands to reason that if one of the most important variables in a grinding circuit is not controlled, virtually any test results compiled from such a circuit and their effects on subsequent operations should be suspect.

Referring back to Figure 7, which shows those factors which may affect particle size, it can be seen that any gains or losses witnessed in associated tests may have been a direct result of particle size changes, and not necessarily the parameter under test. Keeping in mind the fact that a complete distribution is being produced, it should also be noted that any tests which do not evaluate the exact same distribution as the classifier or other operation in question may produce erroneous or misleading results. Such erroneous results can lead to the selection of an improper
target grind for new operations, improper selection and sizing of circuit components, poor or extended start-ups and inaccurate estimations of results.

The PSM can thus be seen as an important tool necessary for comprehensive evaluation of any grinding circuit test results. The exact circuit parameters in a new plant cannot be evaluated until all equipment is on line and actual circuit samples are available. The PSM has, in this context, been used as a valuable tool in the commissioning of numerous plants. Reductions in commissioning time have been noted. Other plants have used the PSM as a troubleshooting tool and learning aid for their operators. PSM output has been used as an indicator for all of the following:

- Change in pH at cyclone causing viscosity changes.
- Cyclone plugging, roping or extensive wear.
- Cyclone surging.
- Effect of extra cyclones valved in.
- Correct sizing of cyclone vortex/apex.
- Effect of rod/double ball split.
- Mill grate blinding.
- Mill liner wear.
- Proper control concepts for different grinds.
- ACTUAL size operating range of circuit.
- Size setpoints for different ores.
- Effect of floor wash sump water.
- Start-up parameters during commissioning.
- Assurance of product quality in iron ore pelletizing.
- Potential sanding of lines or thickeners.
- Determination of ball charge resulting in least power and steel consumption at highest throughput.

CONCLUSION

The effects of fine particles or coarse particles in a given circuit are generally apparent from laboratory studies performed on the particular processes involved. Usually, an ideal particle size is determined for process efficiency, and stated as a percent retention at a given mesh or micron size. The normally overlooked factor of such studies is the desired distribution, and its exact point of measurement. It is not sufficient to merely state that greatest occurs at 80 percent passing 200 mesh. How much coarse material is acceptable? How much fine material is acceptable?

As a general rule, once maximum grind capability of a circuit has been reached (within the limitations of the equipment involved), that particular operation is "strapped" with whatever distribution it is capable of producing. The ultimate goal is then to squeeze maximum efficiency out of that particular distribution no matter how inherently good or bad it may be. With the availability of a
particle size monitor which is sensitive to the entire slurry distribution, and with proper application of that monitor within the circuit, it is possible to fine-tune any grinding circuit to obtain maximum efficiency in subsequent operations.

Due to Denver Autometrics' sensitivity to customers' problems, we have reacted to supply the tools which can be used to realize the benefits available through size-based control. With our proven experience in process control, and the availability of process sensors such as the PSM-400 Particle Size Analyzer, and the XRA-1600 On-Stream Analyzer, many of our customers are now realizing the additional benefits of continuous monitoring and control of grinding, flotation and other mineral recovery operations. Recent successful applications of advanced flotation devices (i.e.: column cells, flash flotation, large volume cells, etc.) will further highlight the need not only for size-based control, but integrated plant-wide control.

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