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# Coarser Grinding: Economic Benefits and Enabling Technologies

**Robert Maron[1]*, Jaime Sepulveda[2], Adam Jordens[1], Christian O'Keefe[1], Henry Walqui[1]**

1. *CiDRA Minerals Processing, USA*
2. *J-Consultants, Ltd.*

## ABSTRACT

Coarser grinding and coarse particle recovery are receiving increased attention as a potential strategy for overcoming the multiple challenges that face the mining industry now and into the foreseeable future. Lower grade – normally harder – ores require the processing of larger ore quantities to achieve even the same production rate; necessarily increasing production costs.

As dictated by the well known Comminution Laws, coarsening the final ground product size significantly increases throughput and reduces specific energy consumption and production cost. However, implementation of this coarser grinding strategy could be hindered by two key limitations.

The first limitation is adequately controlling the final product size to enable more closely approaching process barriers in a safe manner. This requires an advanced process control system that can achieve the desired target size with low size variability. Lack of reliable online real-time particle size measurement has been a key limiting factor to achieving this goal. A new measurement technology developed by CiDRA overcomes this, making the grinding circuit better suited to implement a coarser grinding strategy.

The second limitation is the potentially lower metal recovery in conventional froth flotation due to its limited ability to recover coarse particles. Although studies show that this recovery loss is often more than compensated for by increased throughput, operations have traditionally been averse to accept recovery loss. Along these lines, CiDRA is in the final stages of development of a radically innovative "bubble-less" separation technology – therefore very distinct from conventional flotation – with the capability of recovering particles across the entire size distribution, as produced by a grinding circuit operating in a "coarse grind" mode.

This paper primarily addresses the first limitation. It presents a methodology for estimating the benefits of coarser grinding by using advanced process control enabled by a reliable online particle size measurement. Case studies and high-level control strategy are presented.

***Corresponding author**: CiDRA Mineral Processing Inc., Managing Director Latin America, 50 Barnes Park North, Wallingford, CT 06492. Phone: +1 860 638 9928. Email: rmaron@cidra.com.

## INTRODUCTION

The mining industry has long realized that coarser grinding could bring significant benefits due to increased throughput (Giblet et.al. 2016, Burger et.al. 2011), but it has been unable to take full advantage of this benefit primarily due to the limitation of froth flotation to recover coarse particles. New separation technologies for coarse particle recovey have begun to address this limitation, causing major mining companies to seriously evaluate the benefits of coarse grinding strategies that are estimated to produce up to 15% cash flow gains with lower capital expenditure, lower risk, and shorter implementation time compared to greenfield projects.

Achieving the full benefits of a coarser grinding strategy requires overcoming two challenges: grinding coarser and recovering the coarser particles. By initially addressing the first challenge, some of the potential benefits, typically 2% to 6%, can be obtained quickly and at relatively low cost. Through implementation of improved measurement and control of the final ground product size its variability can be reduced thus permitting coarsening the size up to the limits of the existing installed process technologies, essentially increasing the effectiveness of the ball mills operating in closed circuit with the hydrocyclone classifiers.

Later, coarse particle recovery technology can be implemented and the grind size can be further coarsened past the operational limits of conventional flotation technology. Resultant losses from the conventional flotation technology primarily in coarser size fractions, are now recovered so that throughput can be maximized with minimal sacrifices in plant recovery. CiDRA is now developing a coarse particle recovery technology platform that addresses this application.

The near-term ability to successfully implement a coarser grinding strategy, the primary focus of this paper, involves the use of a novel acoustic impact-based particle size measurement technology developed by CiDRA Minerals Processing under the commercial name CYCLONEtrac Particle Size Tracking (PST). It is being utilized in commercial operations throughout the world, delivering increased throughput and recovery, with near 100% availability, and minimal maintenance. It overcomes the limitations of older 'near-line' technologies, often due to problems with slurry sampling and transport systems required to deliver samples to measurement instruments located remotely from the process stream. This reliable real-time particle size measurement on every hydrocyclone overflow stream, when incorporated into a control strategy, enables operators to coarsen the product size and more confidently closely approach the downstream process limits.

## METHODOLOGY FOR ESTIMATING THE BENEFITS OF COARSER GRINDING

The first step to evaluate a potential coarse grind strategy in an existing operation is to assess the potential benefits. Three methods have typically been used: changing the grind size in a full-scale plant and observing the effects, using simulator programs for both grinding and flotation, and laboratory testing using industrial circuit samples. All three methods are useful but involve considerable time and expense. The authors have developed a simple methodology using historical plant data over a long time period to assess current performance, and predict the improvement that may be possible by successfully coarsening the grind size (Maron et.al. 2017, 2018).

This methodology uses daily data from a concentrator over a long enough time period (ideally over 1 year or more) to obtain a high-level assessment of the general plant operating performance, mainly focusing on throughput (T), and recovery (R) which are used to calculate the net metal production (NMP) – the primary cash flow generator – giving the final objective function for process optimization purposes, as determined by the simple expression:

$$NMP = h\ T\ R$$

**Equation 1** Objective funcion for calculating Net Metal Production (NMP)

Where h represents the head grade of valuable metal being recovered.

Implicit in this methodology is the typical observation that throughput (T) and recovery (R) are strong functions of product size, consequently product size is chosen as the independent variable. Therefore NMP should also be a strong function of product size, so there should exist an optimal product size that maximizes NMP and cash flow.

The typical unfiltered data set shown in Figure 1 left reveals a centrally weighted data cloud that makes trend detection unreliable so a data binning technique is used that results in the filtered data set shown in Figure 1 right. This data set shows that a ~2.5% increase in NMP is possible by coarsening the final product size. Other potential benefits due to improved process control and reduced size variability are discussed in a later section.

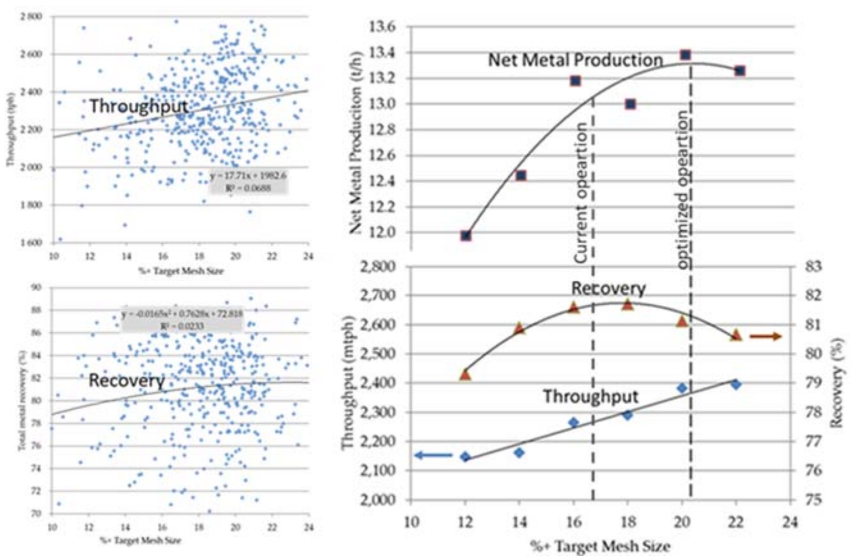


**Figure 1** Throughput & Recovery unfiltered (left), with data binning (right) with Net Metal Production (NMP) objective function per Equation 1

## GRINDING COARSER: MEASURING, CONTROLLING, OPTIMIZING

Selecting a coarse grind strategy involves determining the operator imposed conditions that maximize throughput of the grinding line at a larger final product size while confidently closely approaching the downstream process limits. For a grinding line consisting of a SAG mill followed by conventional ball mills, this optimization strategy involves maximizing SAG mill fresh feed tonnage while respecting the ability and limitations of the downstream ball mill – classification circuit to produce the desired coarser final product size.

### Secondary Grinding: Ball Mill - Classification Circuit Optimization

In conventional ball milling, the so called Comminution Laws, and in particular Bond's Law, highlight the importance of specific energy consumption as the most determining operating condition affecting the resulting product size in a grinding/classification system. As presented in Equation 2 it shows that throughput (T) is fundamentally related to the ratio of power (P) consumed in grinding to the specific energy consumption (E). Furthermore, when Bond's Law is restated below, it shows that we can mazimize throughput (T) by relaxing the Grinding Task ($F_{80}$, $P_{80}$), maximizing the mill Power draw (P), and reducing the Operational Work Index ($W_{io}$).

In that form it is clear that there are three paths available to increase throughput.

First, the input power drawn by the mill should be maximized by adjusting mill speed and charge level whenever possible. Second, the grinding task should be reduced (relaxed) which is most effectively accomplished by coarsening the P80 which is our main goal. Third the classification effectiveness should be increased, which is a measure of how effectively the energy of the mill is being directed to grind the coarse particles that have not yet been reduced to their target size.

$$T = \frac{P}{E} = \frac{\overbrace{(1/W_{io})}^{\text{Classification "Effectiveness"}} \bullet \overbrace{P}^{\text{Input}}}{\underbrace{10\,(1/P_{80}^{0.5} - 1/F_{80}^{0.5})}_{\text{Grinding Task}}}$$

**Equation 2** Bond's Law showing opportunities to maximizing throughput (T)

Importantly, the classification effictiveness is determined by $W_{io}$ which appears as a reciprocal in Equation 2, and represents how the hydrocyclone classifiers contribute to reduce the tons processed per unit of energy consumed. This means that for optimal energy efficiency and increased throughput, the content of fine particles in the mill charge should be as low as possible for a given grinding task. This can be achieved by operating the circuit under the following three conditions, which are sometimes referred to as the "Fourth Law" criterion and are graphically summarized in Figure 2.

- Minimum % Solids Overflow, only limited by the total water availability,

- Maximum % Solids Underflow, only limited by the undesirable hydrocylone 'roping' condition,
- Maximum Circulating Load, only limited by the capacity of both the pump(s) and the mill itself to transport the required volume of slurry.

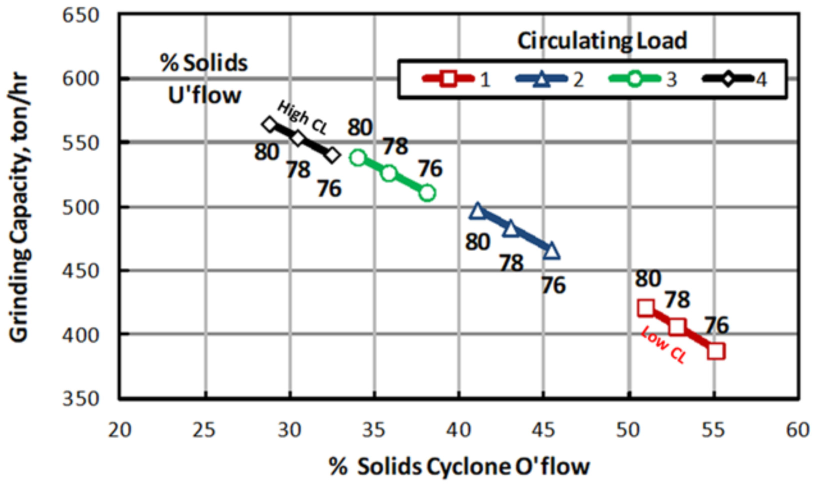


**Figure 2** Exploratory simulations of comminution "4th Law" criterion; P80 is constant, cyclone number and geometry adjusted to maintain constant pressure drop

## Primary grinding:

For the SAG mill, optimization involves finding the operating conditions that would maximize the fresh feed tonnage to satisfy the demand of the ball mill. The same theoretical considerations used for conventional ball milling systems are also applicable to SAG systems, providing it is recognized that for SAG milling there exists two types of grinding media: balls and rocks, each acting independently with their own effectiveness. SAG mill optimization has recently been explored in detail showing that optimizing the operator imposed conditions of Load Cell (% charge filling), bearing pressure, mill speed and mill discharge density (% solids) can result in very significant tonnage improvements of over 13% in one case (Sepulveda et.al 2018). For the case where the newer technology of High Pressure Grinding Rolls (HPGR) are used in place of SAG mills, it is much simpler to grind coarser and gain tonnage since it is enough to increase the opening of the product size controlling screen.

## Grinding Coarser: How to Control the Grinding Circuit

It is well known that measurement is essential to effective control. Reliable real-time measurement of the final ground product size has historically been a significant challenge due to the limitations of older technologies, but has now been overcome by employing a new technology specifically designed for this demanding and important application.

## Impact-Based Real-Time Size Measurement on Individual Cyclone Overflow Streams

Acoustic impact-based particle size tracking is a unique method for measuring and controlling a reference product mesh size in cyclone overflow streams. The implementation of this technology is centered upon a sensor probe that is inserted into the overflow slurry stream via a two-inch (50 mm) hole in the overflow pipe. Particles within the slurry stream impact the surface of the probe generating travelling stress waves within the probe. A sensor converts these travelling stress waves into an electrical signal and proprietary signal processing techniques convert these signals into a particle size measurement that is output every four seconds. The sensor is constantly in contact with many particles in the slurry stream, thus obtaining information from orders of magnitude more particles than traditional sample based technologies. Also, because of the location of the sensor downstream of the hydrocyclone and the presence of an air core at that point, the sensor produces no change in the back pressure seen by the hydrocyclone and thus does not affect hydrocyclone performance. The probe has a useful life of approximately 18 months due to the abrasive wear caused by the direct slurry impact. The probe life is related to the particle hardness and size which is obviously finer in the overflow stream compared to the feed stream, thus enabling an acceptable probe life. Currently the software provides up to five reference mesh sizes to be incorporated into a process control strategy. Figure 3 shows the main components of the PST system.

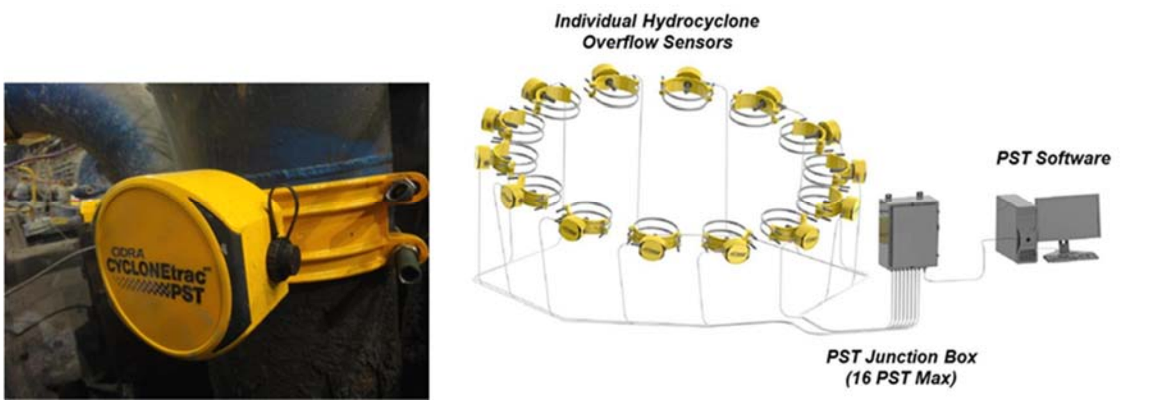


**Figure 3** PST mounted sensor head (left), and system with interconnections (right)

## Coarser Grinding Control Philisophy Using PST Real-Time Particle Size Measurement

The PST system enables two levels of control strategy.

The first strategy is based on using a single size measurement for the entire battery based on a composite of the individual PST signals. The median signal is often used because it is less sensitive to very large or small values comared to the mean signal, which can improve control stability. This single composite size is then used in the usual way to command the circuit to produce a coarser or finer size if it is not already within the desired range.

The second strategy is a novel one enabled by PST, which monitors the signal from individual cyclones and identifies cylcones that are classifying outside the desired range – too coarse or too fine – and enables correcting this condition by closing the out-of-class cyclone and opening another. This strategy is particularly important because as the control circuit commands the circuit to grind coarser, the cyclones can deviate from their normal operating range and enter into a pre-roping or roping condition. PST enables immediate detection of excessive coarsening of the particle size which enables corrective action such as closing the cyclone.

The P80 value (or a reference mesh size) is provided by the PST system. The sump level is controlled by the pump velocity. When the composite P80 from all cyclones in a battery is too fine and the ball mill is not able to increase it to the desired coarser target size, then the system releases the SAG mill by increasing the load cell set point thus increasing the throughput. When the composite P80 from all cyclones is too coarse and the ball mill is not able to reduce it to the desired range, then the system puts the SAG mill into a restricted mode by reducing the load cell set point thus reducing the throughput. The second strategy described above is always monitoring the individual cyclones so that if an individual cyclone PST signal indicates that the overflow size is too coarse then that cyclone is closed and replaced by another.

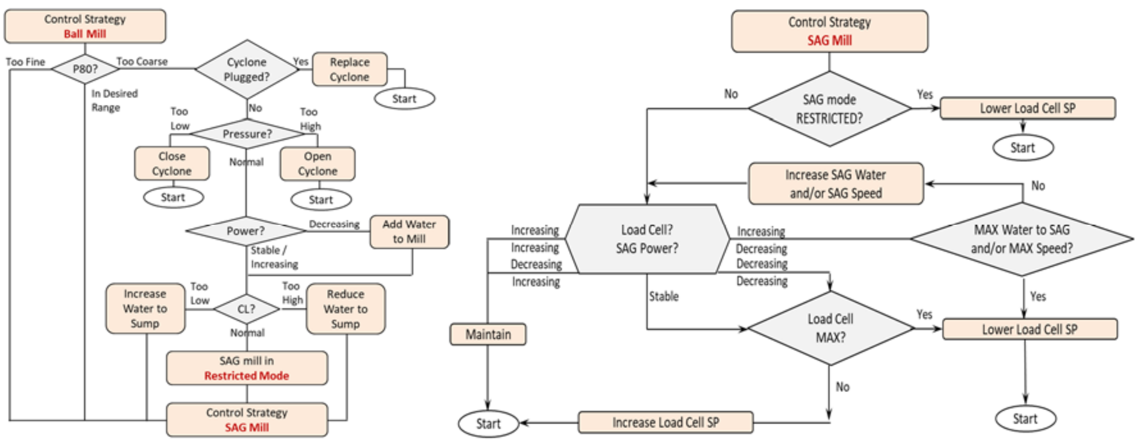


**Figure 4** Control philosophy for control of SAG and ball mill grinding circuit to implement coarser grinding to increase throughput and NMP

## COARSE PARTICLE RECOVERY

The preceding sections have discussed the importance of high availability, high-resolution real-time particle size tracking for the effective control of primary grinding circuits. Regardless of the control and operating philosophy adopted to achieve a coarsened grind it is inevitable that the particle size distribution produced from this coarsened grind will still contain a large amount of value copper minerals in the finer size classes. So regardless of how coarse the ground product could be, the downstream recovery technology must also provide acceptable fine particle recovery. Figure 5 shows the variation of particle size and copper distributions for the same porphyry copper feed ore ground to three different grind sizes in a batch rod mill. Even when the primary grind size is coarsened from $P_{80}$ = 280 μm to $P_{80}$ = 520 μm (an increase of 86%), over 50% of the copper will still deport to the -150 μm size class. This example is not meant to be indicative of anticipated plant shifts in value mineral distributions as a function of primary grind size, merely to reinforce the concept that coarsened grind sizes in operating copper flotation plants will still produce a flotation feed with copper minerals distributed across a wide array of size classes. This means that the oft-cited limitations of traditional flotation technologies to recover both very fine and coarse particles will still apply.

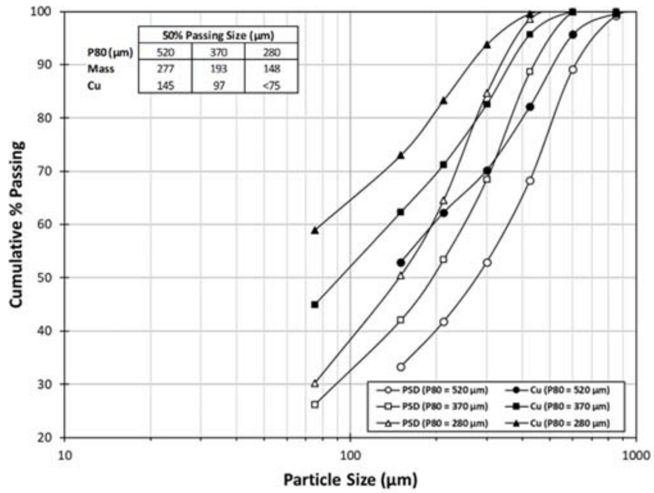


**Figure 5** Particle size and copper distributions for a North American porphyry copper ore ground to three different grind sizes in a laboratory batch rod mill

The conceptual argument for coarse particle recovery technologies as part of a coarse grind plant strategy then must include unit operations to recover both the coarser value mineral particles which result from adoption of a coarse grind strategy, as well as the fine value mineral particles which will still be present in the flotation feed stream. The primary approach is to rely on existing flotation technologies to recover particles below a "coarse particle recovery limit", which is itself a function of the installed flotation technology, value mineral grain size and association, as well as the degree of mineral liberation produced from the installed comminution technology. The value minerals present in particles coarser than this "coarse particle recovery limit" are then targeted using a coarse particle flotation technology which has been specifically tailored to the recovery of coarse, marginally-liberated particles. The coarse particle flotation technology often requires a narrow operating size distribution which may be achieved using multiple stages of pre-classification. An example of such an arrangement is shown in Figure 6. In this configuration the rougher tails are classified by a cyclone with the underflow sent to a screening stage to produce a narrow size distribution for the coarse particle flotation technology. The screen undersize and cyclone overflow are then directed to final plant tails. The coarse flotation concentrate, with a mass pull of approximately 10-25% and concentrate grade approximately equal to the mill feed head grade, is sent to a separate closed circuit regrind stage complete with a cleaner flotation step. The tails of the cleaner flotation step are then directed to final tails.

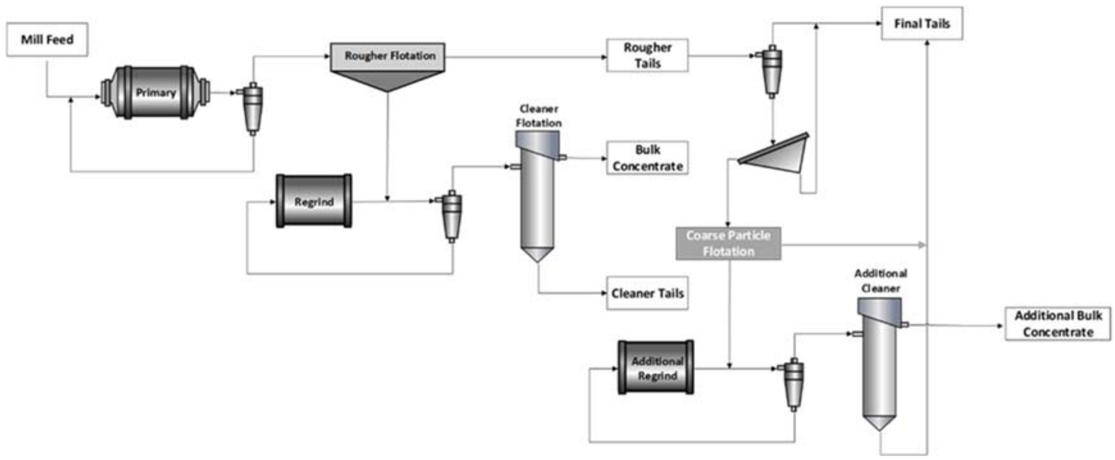


**Figure 6** Simplified conceptual flowsheet for a coarse particle flotation technology requiring two stages of upfront classification as well as additional regrind and cleaner circuit capacity to handle the resultant coarse particle concentrate

The advantages of any coarse particle flotation technology are significant in that it can mitigate coarse particle losses as the primary grinding circuit is shifted to a coarser primary grind size. This enables an increase in net metal production with coarser grind size and increased throughput. The primary disadvantages of the circuit arrangement in Figure 6 are the degree of flowsheet complexity and additional slurry classification required. Dependent on mass pull from the coarse particle flotation step, the additional regrind and cleaner flotation circuit may also present significant additional investment costs to realize the gains in net metal production from a coarsened primary grind. Finally, the coarse particle flotation stage is not able to address any value mineral losses present in the cleaner tails or the fine size fractions of the rougher tails.

To address the deficiencies of the described coarse particle flotation circuit in Figure 6 an alternative brownfield approach to value mineral recovery when employing a coarsened primary grind is shown in Figure 7. In this configuration the whole plant tails, including both rougher and cleaner tails is directed to a conceptual coarse particle recovery unit operation which is capable of directly handling the entire size distribution of the incoming tailings stream. This recovery technology also has very high selectivity such that the resultant mass recovery is as low as 1-3 % with a concentrate grade equal or greater than the plant's rougher flotation concentrate grade. Thanks to the low mass of this concentrate stream it is then possible to direct this stream to the plant's existing regrind circuit with minimal modifications required to accommodate this increased concentrate mass flow.

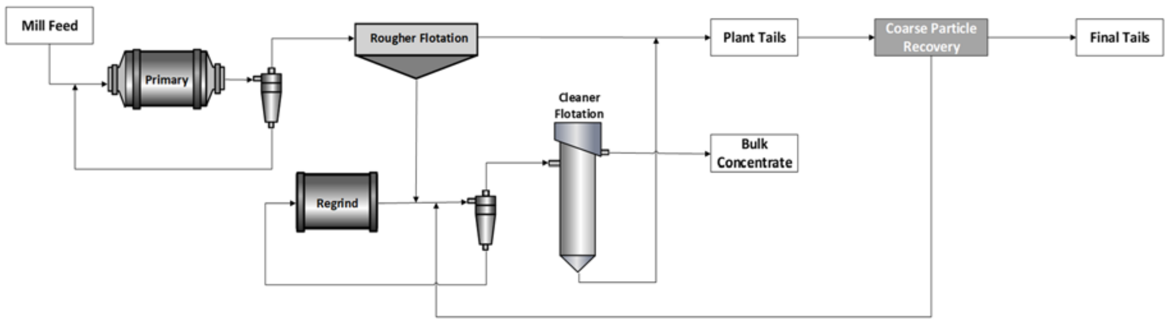


**Figure 7** Simplified conceptual flowsheet for a coarse particle recovery technology capable of treating the whole plant tails stream with sufficient upgrade ratios to direct the resultant concentrate directly to the existing plant regrind and cleaner circuit

CiDRA is in the process of commercializing this novel separation technology, distinct from flotation, with the ability to extend recovery-by-size relationships with very high selectivity. Flotation fundamentals dictate that bubble particle interation (capture, transport, and release) are a tradeoff largely driven by kinetics and pulp chemistry. Under this new paradigm, the optimized process can recover particles across a wide size range with high selectivity.

## FINAL REMARKS

The mining industry is moving towards coarse particle processing. This paper has presented the plant operator with tools to justify a coarser grinding strategy in operating plants including:

- a methodology to estimate the potential economic benefits of coarser grinding
- commercially adopted impact-based technology offering real-time particle size tracking to enable improved measurement and control of coarser grinding
- potential control schemes to integrate real-time particle size measurement and effectively realize a coarsened grind
- flowsheet considerations for supplemental coarse particle recovery technology

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