Early rejection of gangue – How much energy will it cost to save energy?

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ABSTRACT

Comminution accounts for approximately 30 to 40% of the energy consumed on an average mine site (DOE, 2007) and somewhere from 4 to 9% of Australia's total energy consumption (Tromans, 2008). Additionally, if one includes the energy embodied in steel grinding consumables, this may increase comminution energy by more than 50% (Musa and Morrison, 2009). Energy savings of up to 50% are theoretically possible by employing novel circuit designs and using smart separation techniques, which reject coarse liberated gangue. A range of different strategies such as selective mining, screening, ore sorting, coarse flotation and dielectrophoresis can be used to reject the coarse liberated gangue at different particle sizes. These technological advances have the potential to increase the throughput in the comminution circuit, while decreasing the energy consumed per tonne or ounce of metal produced. This paper investigates the energy consumed through sorting, and the optimum position of these technologies in the flow sheet, in terms of energy, cost and risk. The findings form the basis of a methodology that can identify the potential upgrades/changes required to obtain a positive return from these sorting and coarse separation techniques.

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Introduction

Early rejection of gangue, also known as pre-concentration or removal of coarse liberated gangue, is a concept that has gained attention in recent times. It has the potential to provide a step change reduction in comminution energy consumption. It requires a change in priority from the old approach of concentrating the liberated valuable mineral after grinding to the newer approach of rejecting gangue early—essentially as soon as it is liberated. Note the change in the conventional process of liberation to now cover both the liberation of gangue, not just the liberation of the valuable mineral. Removing a portion of waste before milling has the potential to not only reduce the energy intensity per unit of metal produced, but also to increase the grade of the feed going to the concentrator. Interestingly, increasing the feed grade generally results in a higher recovery, which may compensate for the inevitable loss of some of the valuable mineral during the pre-concentration stage. This effect can be explained by using a simple mass balance approach—if the tail and concentrate grade remain constant, the total recovery increases with the feed grade.

The increase in recovery with pre-concentration is epitomised by the results observed at Castlemaine Goldfield's plant (Grigg, 2011). In this example 48% of the feed was rejected as gangue, thus almost doubling the grade sent to the processing plant. Although only 92.6% of gold was recovered in pre-concentration, the overall recovery increased by 3.8% because of the increased grade. Therefore, due to the gangue rejection and the increased recovery, the energy consumption for the gold produced (MWh/oz) decreased by 30% with pre-concentration. As a side note; the reporting of energy consumption as a function of throughput (kWh/t) does not take into account increases in efficiency that are attributable to improved recovery. To include the effect of recovery, the energy consumption must be reported per unit of metal product.

Hand sorting is the oldest form of gangue rejection in mineral processing but one that would be extremely out of place in modern, high throughput plants. Automatic sorting, with the exception of radiometric machine sorting, is a viewed as a relatively new technology within the minerals industry. This advancement in technology allows minerals to be efficiently separated at a coarse size before grinding. Removing a portion of the non-valuable component at these coarse size ranges has the potential to dramatically reduce the energy consumption per unit of metal. However, one potential limitation of pneumatic sorting is the amount of energy consumed through compressed air supplied to the ejector valves. A number of factors influence the air consumption in a sorter. This work aims to gain a better understanding of how these parameters affect the air consumption and the overall energy balance.

Automatic sorting

Automatic sorting is an extremely versatile separation technique that can be adapted to various ore types and positions in the flowsheet. The versatility is achieved by using air jets to eject particles, thus allowing the use of any number of front-end measurement techniques to determine which particles will be ejected. Carrasco (2012) lists the current types of sensors available to be used in sorting devices:

- Optical sensors for visible light
- Optical sensors for fluorescent minerals
- Infrared sensors to detect the thermal response from sulphides and carbonaceous species
- X-ray sensors, specifically dual energy x-ray transmission
- Conductivity and magnetic susceptibility (metal) detectors
- Laser inducted fluorescence and breakdown spectrometry
- Micro Wave/InfraRed (MW/IR) sensors based on induced thermal responses

Unfortunately, sorting alone has not proved to be the silver bullet required for mineral processing, as it has several limitations. Because particles are detected and ejected individually, they need to be presented in a monolayer to both the detector and the ejector. The particles must also be stable after detection to enable a prediction of their positions at the point of ejection. These two limitations control the design of the separator and limit the achievable throughput. The presentation belt is generally curved to stabilise the particles and it is also sped up to high velocities to allow a higher monolayer throughput (see Figure 1).

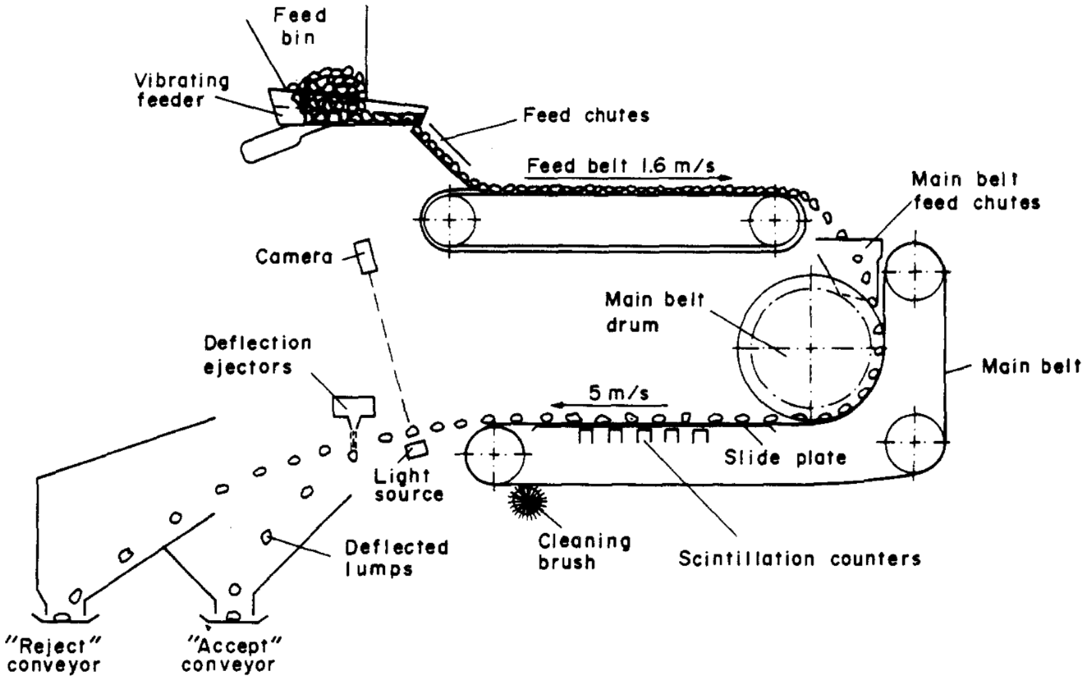

Figure 1 - Diagrammatic cross section through a radiometric sorting machine (Wheeler, 1989).

The maximum practical capacity of an automatic sorter is limited by its ability to provide a mono-layer in the detection and ejection zones. Data processing capabilities are sufficiently advanced that they do not restrict maximum capacity and can allow rates in excess of 2000 particles per second (de Jong and Harbeck, 2005). Figure 2 shows the geometric maximum monolayer throughput achievable for different particle sizes, as well as the achievable throughput, when percent occupancy is used to control the throughput. In this example the percent occupancy is defined as the fraction of the belt area covered by rocks. In each case the throughput is directly proportional to the particle size. This is easily explained mathematically because in the calculations, the volume of the particle is divided by the cross-sectional area.

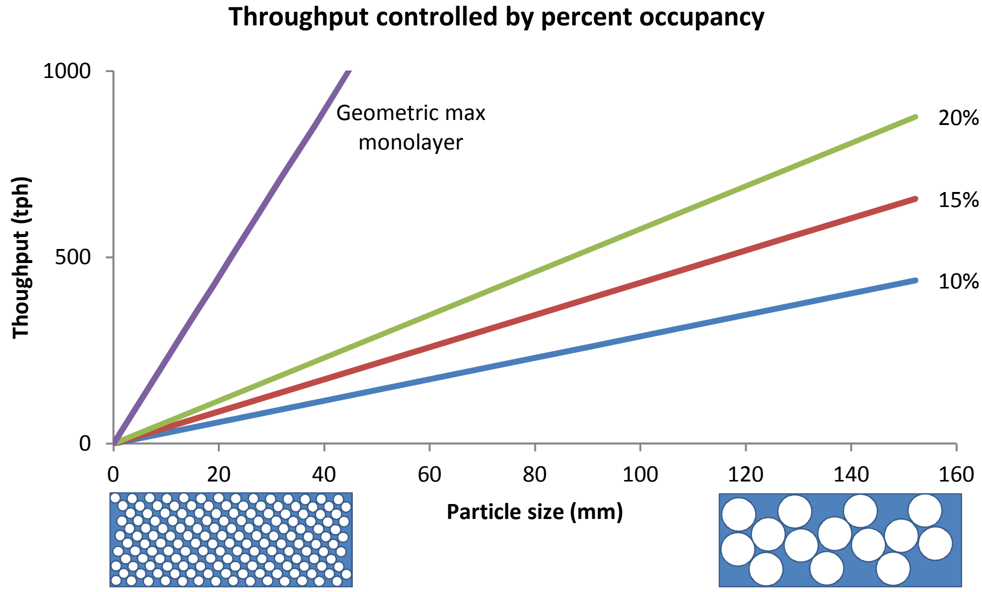

Figure 2 - Maximum throughput calculated for spheres with a density of $3 g/cm^3$ on a 1m wide conveyer running at 4m/s as it varies with percent occupancy.

Air consumption

The most expensive operating cost and the most energy intensive component of the sorter is the air compressor (Schapper, 1977). The supply of compressed air for the ejectors potentially accounts for between 85% and 95% of the electrical energy consumed through sorting. In addition to this direct machine energy consumption, sorting also introduces indirect energy consumption through additional conveyor systems and the bulk handling of the rejected stockpiles. Accounting for this indirect energy is outside of the scope of the current investigation. The research question for this paper is: when does the energy consumed through the compressed air supply to the ejector valves increase beyond the energy saved by removing the material from milling?

To determine the energy required, the size of the compressor has to be determined. Different air compressors have different maximum air flowrates and pressures. These two parameters determine the size of the engine required to do the work (see Figure 3). Equation 1 describes the relationship between pressure, air flowrate and motor power.

$$\frac{\textbf{\textit{Motor power}}\ (\textbf{\textit{kW}})}{\textbf{\textit{Air flowrate}}\ (\textbf{\textit{L/s}})} = \mathbf{0.0225} \times \textbf{\textit{Pressure}}\ (\textbf{\textit{bar}}) + \mathbf{0.1768} \qquad \textbf{[1]}$$

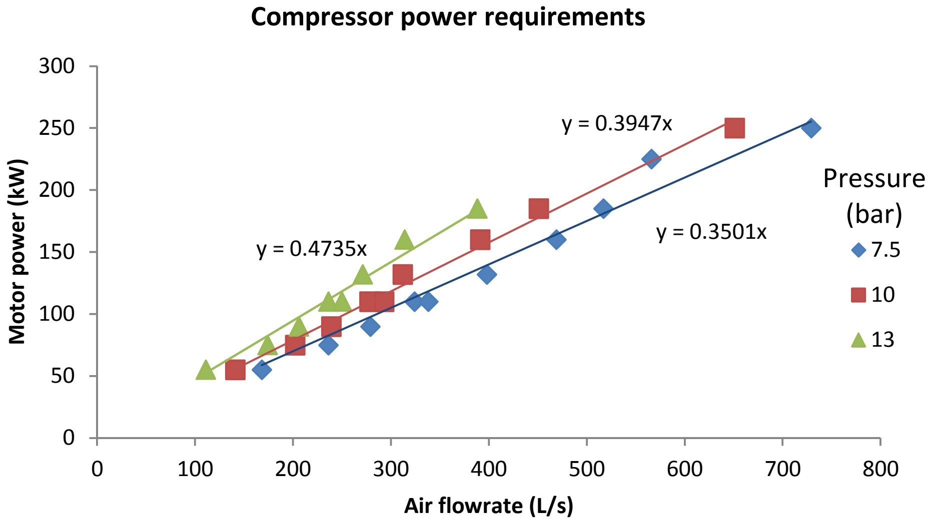

Figure 3 - Relationship between motor power, air flowrate and required pressure taken from the compressor equipment supplier technical data (Sullair, 2012).

The air flowrate per tonne of ejected rock was calculated as a function of particle size. It was assumed that the force of the air-blast was sufficient for ejection, when the cross-section of the air blast equalled the projected area of the rock. The number of ejectors was determined by their horizontal resolution, and the particle size of the rock requiring ejection. And assuming that the rocks travel across the path of the ejectors, the length of time required for the ejector blast was calculated using the particle size and speed (as determined by the conveyer). The Hagen-Poiseuille equation was used to calculate the volumetric flowrate (L) of air out of the nozzle (see Equation 2). The flowrate is dependent on the upstream and downstream pressure difference ($p_u - p_d$), the diameter (d) and length (l) of the nozzle, and the viscosity of the fluid (μ) (Bomelburg, 1977).

$$L = 1.23 \times 10^6 \frac{d^4}{\mu l}(p_u^2 - p_d^2) \qquad [2]$$

Figure 4 displays the relationship between the required power and the particle size. As explained in the previous paragraph, the air flowrate required from the ejector is proportional to the cross-sectional area of the particle requiring ejection. In addition, the required power for the air compressor is linearly proportional to the air flowrate. Therefore, the specific power (kWh/t) required to power the air compressor is inversely proportional to the particle size. The nozzle dimensions were fitted to obtain air flowrates consistent with industrial units. To obtain normal volumetric flowrates of $10Nm^3/t$ for 40-80mm rocks and $40Nm^3/t$ for 10-20mm rocks, 5mm long nozzles were required with a diameter of 6.1mm. Although the air blast required for a small rock is less than that required for a large rock, the mass ejected per blast is much smaller. Therefore, the power required to eject a tonne of rock increases exponentially for smaller particle sizes. This result, when combined with the throughput relationship shows why sorting is better applied to coarser rocks. However, liberation is much lower for larger rocks and consequently the risk of rejecting valuable material increases at coarser sizes.

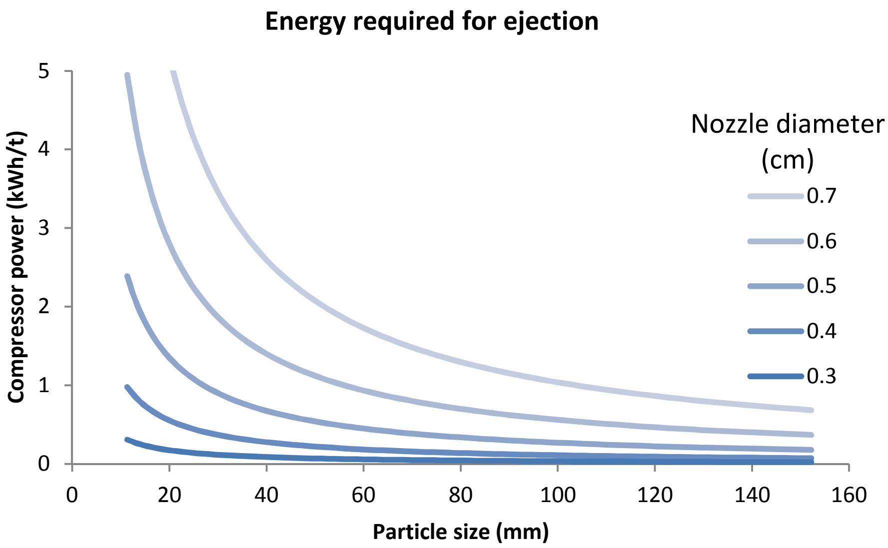

Figure 4 - Compressor power required per ejected tonne as a function of particle size

Virtual liberation

The associated risk of using sorting is the potential rejection of the valuable component with the gangue due to the low degree of liberation. This risk is controlled by the efficiency of the detection and ejection processes, and is dependent upon the degree of liberation of the gangue phases. As discussed earlier, the stability and overlap of the rocks influence the efficiency of detection and ejection, which is controlled by the throughput and mechanical design of the sorting machine. On the other hand, the liberation of the gangue phase is controlled by the rock properties and particle size. The liberation of the gangue material is more important at these coarse sizes than the liberation of the valuable ore. Therefore, for this study a virtual broken rock was required to quantify the effect of liberation on sorting. A one metre block was virtually sampled using a number of randomly generated cubes to assess the effect of size on liberation. A simple binary aggregate was created by randomly populating the block with 19mm cubes—representing the higher-grade, valuable component (see Figure 5). These cubes were restricted to occupying 75% of the block, with an overall volumetric concentration of 10%. Although this is a relatively simple model, not specifically based on any particular real ore, it provides a realistic progression in liberation across the size ranges (see Figure 6).

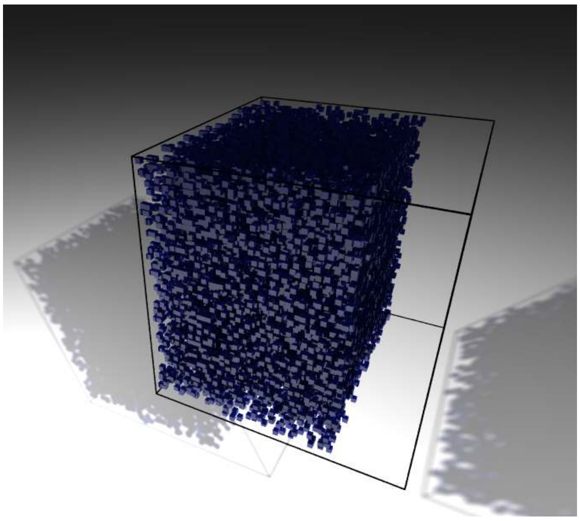

Figure 5 - Three dimensional visualisation of virtual unbroken aggregate.

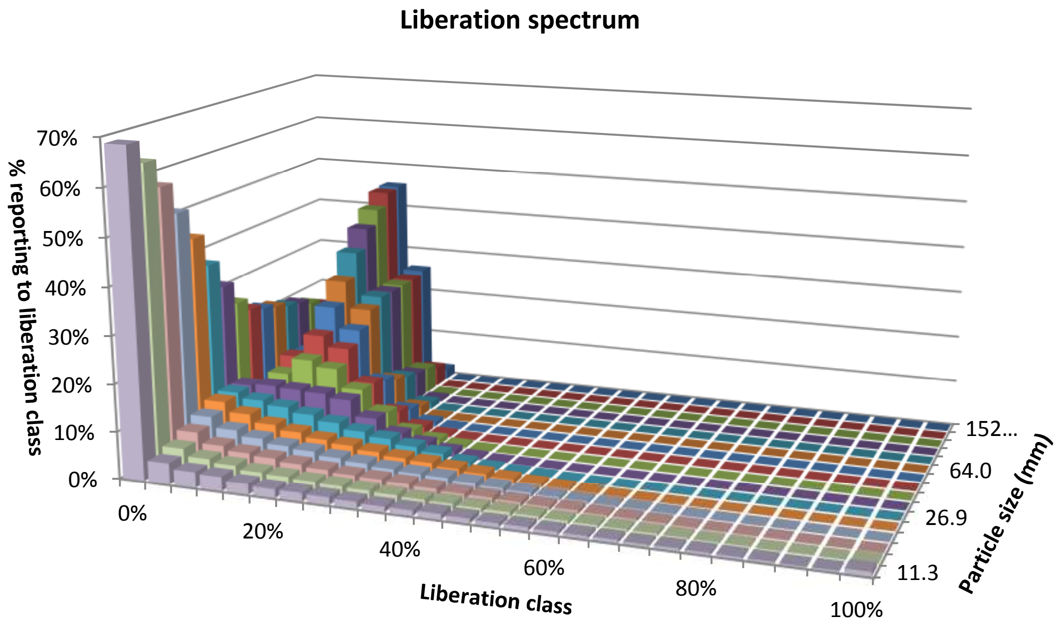

Figure 6 - Virtual liberation spectrum for a block populated randomly by 19mm cubes.

Electromagnetic and x-ray sorting is able to separate particles based on their three dimensional liberation. For the simple binary liberation spectrum shown above, the effective recovery and grade was calculated by using the liberation class as the separation cut-point. For different classes, the cut-point was calculated so that the separation reached a target recovery of 98%. Although there are inefficiencies within the detection and ejection processes, the decision whether to accept or reject a particle was assumed to be ideal. This separation simulation effectively measured the liberation-limited maximum rejection rate.

The maximum energy benefit, attributable to sorting, was calculated by multiplying the maximum throughput by the net energy savings and the maximum rejection rate. The maximum throughput was calculated based on a 15% belt occupancy. The net energy savings for sorting was calculated from the difference between the compressor energy requirements and the energy saved by removing a portion of the stream from milling. Finally, the maximum rejection rate was found from the liberation modelling, and by setting a target recovery of 98%. Figure 7 shows that the maximum theoretical power savings are achievable at the coarser size ranges for this sample ore structure and grade. The energy savings and value increase with more competent ores (those ores with a higher Bond Work Index) due to their increasing impact on the energy-intensive milling process.

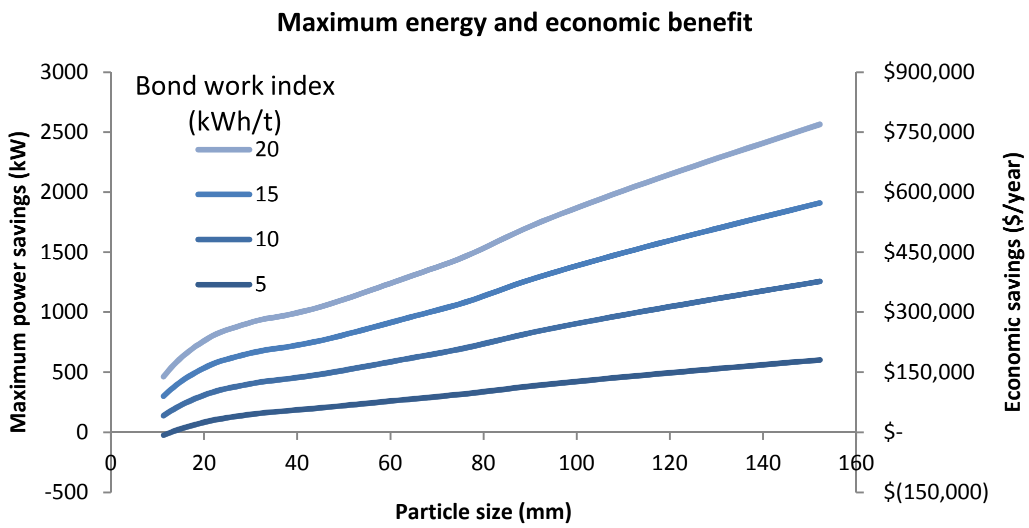

Figure 7 - Maximum energy and economic benefit of sorting for a range of ore competencies, as indicated by the Bond Work index.

The real impact of coarse rejection of gangue using sorting is best displayed in terms of the economics, because this enables the impact on recovery to be included in the calculation. The average cost of electricity provided to industry in Australia was $29.45/MWh in 2011/2012 (AEMO, 2012). This value was used in the calculations. However, since there was no information on the change in flotation recovery, the economic savings were linearly related to the power savings.

Both the calculated values for power saving and economic saving will depend entirely on the operating methodology of the site concerned. It can be reasonably assumed that mining operations would prefer to mine at a higher rate and fully utilise existing equipment rather than make savings in power consumption and accept a reduced plant throughput. Therefore, it may be more appropriate to identify the power and economic savings, either in terms of mining throughput or metal produced. However, these calculations would require specific information on the feed grade and processing recovery.

Conclusions

This paper describes a holistic methodology for calculating the net energy around a sorter. The results obtained depend on a number of assumptions; therefore the absolute values may deviate from reality. This paper signals a need to investigate the factors that influence the profitability of a sorter: for example, the ejector dimensions and resolution, and the coarse liberation of gangue. Researchers within CRC ORE are currently working on a technique for quantifying liberation at these coarse size ranges.

The energy required to supply compressed air for the ejectors was found to be inversely proportional to the particle size. Also, in order to maintain a monolayer, the limiting throughput increased linearly with particle size. The practicable maximum rejection rate for a certain size is controlled by the target rejection grade or recovery, and the liberation spectrum. Therefore, with an operation strategy to maintain the grade of the reject stream, the maximum rejection rate increases for larger rocks. All these factors combined show that for the simple structure used in this study, the energy savings were larger when sorting coarser rocks. However, the risk of rejecting the valuable component also increases for coarser rocks. Therefore, the optimum size for sorting should be calculated on a situational basis.

This study supports the approach of using a sorter on a middlings stream as opposed to the whole stream. For instance, if there is deportment of the valuable component in the finer sizes, a double deck screen could hypothetically be used to remove the coarse gangue and concentrate the fine valuable ore. The intermediate size range could then be sorted to obtain a sharp separation. This has two positive effects: the challenges involved with fine particles are eliminated, and the volume of fully liberated rocks requiring ejection is reduced because they report to either the top screen oversize or bottom screen undersize. This has the potential of increasing the throughput and decreasing the compressed air consumption required by a coarse feed with less fully liberated gangue and valuable components. The implementation of sorting on a middlings stream is also being investigated by the team at CRC ORE.

Any new technology that claims to reduce energy must be tested using a holistic energy balance approach. The energy used by ancillary equipment, the consumption of energy intensive materials (embodied energy), and the energy required in the decommissioning process must all be incorporated into the calculation. This kind of life cycle analysis is important for energy related projects, as they have the potential to claim energy efficiency when in fact the energy consumption has merely been shifted to another region of the mine. For instance, the ancillary power requirements for sorting may indeed be larger than the energy savings in grinding, or the accept stream may be harder than the accept stream, thereby increasing milling energy.

This study will continue with a range of mineral structures and grades to assess the impact of sorting on energy consumption and will incorporate more realistic sorting efficiencies to better assess grade loss to the reject stream.

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