

**DEVELOPMENT OF ECONOMIC EVALUATION METHODS OF COARSE  
ORE UPGRADING OPPORTUNITIES INCLUDING INTEGRATION OF CUT-  
OFF GRADE BASED MINING STRATEGIES**

by

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## **Abstract**

Coarse ore upgrading opportunities, involving a mix of new and traditional technologies, are gaining momentum in the mining industry as a tool to improve the economics of resource extraction while lowering the energy and water footprint of the extraction process.

Documented attempts to quantify the value of coarse ore upgrading opportunities have focused on the incremental change in processing costs of a static ore stream. In reality, the inclusion of a coarse ore upgrading step will inherently change the key value drivers of the mining operation. For example, with lower processing costs the cut-off grade (lowest grade that can be mined profitably) can be materially reduced, impacting the mine plan and the amount of deposit material classified as ore.

This paper provides a framework to integrate cut-of grade based analysis into the evaluation of coarse ore upgrading opportunities from an economic perspective.

**Keywords:** ore-sorting, ore sorting, coarse ore upgrading, cut-off grade, sensor-based ore sorting

## **Executive Summary**

A methodology for incorporating variable cut-off grade analysis, common in mining engineering, has been developed for a group of mineral processing technologies that are rapidly emerging in the mining industry. These technologies, collectively known as “Coarse Ore Upgrading” or “Ore Sorting” aim to reject material from the process that is sub-economic at a point in the process where material historically could not be upgraded. As this step is prior to an energy, water and cost intensive processing step, comminution, there are significant opportunities for this technology to reduce the input intensity of mineral processing.

In order to incorporate cut-off grade analysis on these opportunities, the following aspects of the process need to be well understood.

- Segmented processing costs – An understanding of unit costs associated with mineral process before, during and after ore sorting.
- Sorting Separation and Recovery – Each deposit, and in some cases domains within a deposit, will have different ore sorting opportunities depending on the mineral structure of the deposit. This is characterized by a relationship between the amount of mass that can be sorted and the amount of contained valuable mineral that can be accepted for further processing. This relationship needs to be well defined and understood.
- Operating Strategy – Depending on where the overall operational bottleneck is, and where it would preferably be, different strategies will be used to optimize the ore sorting process. Understanding if the mining or processing facility is the bottleneck, plus the potential use of a low-grade stockpiling strategy, is key to understanding the economic impact of ore sorting opportunities.

A case study was generated based on a hypothetical operating zinc mine contemplating the use of sensor based ore sorting to reject waste material and increase the grade of material for further processing illustrate the differences between a variable cut-off grade strategy and the traditional method of evaluating mineral processing opportunities. Table 0.1 illustrates key assumptions and outcomes of the different evaluation methods.

Table 0.1 Key Economic Evaluation Assumptions and Metrics

	<b>Base Case</b>	<b>Traditional Evaluation</b>	<b>Variable Cut-Off Grade Evaluation</b>
<b>LOM (years)</b>	10	8	7.5
<b>LOM Material Mined (Mt)</b>	125		
<b>LOM Strip Ratio</b>	2.5		
<b>LOM Revenue (\$M)</b>	5,981	5,897	5,898
<b>LOM Operating Costs (\$M)</b>	2,000	1,870	1,840
<b>Operating Profit (\$M)</b>	3,981	4,027	4,059
<b>Ore Sorting Capital (\$M)</b>		100	
<b>Ore Sorting Zinc Recovery</b>	-	99%	93%
<b>Ore Sorting – Mass Accepted for downstream processing</b>	-	80%	63%
<b>NPV8 of Ore Sorting Opportunity (\$M)</b>	-	\$131	\$201
<b>IRR (%) of Opportunity</b>	-	9.5%	10.5%

The use of a cut-off grade strategy defines the value of finding an operating point at which material that does not contain enough value to justify downstream costs (and is therefore not economic to process further) is removed. The amount of mass that should actually be rejected in the sorting step is much higher in the cut-off grade evaluation, despite the loss of additional valuable metal, indicating that in the traditional evaluation case material that does not have enough value to warrant further processing is being processed through the site bottleneck. The use of this method ensures that more uneconomic waste material is rejected, ultimately resulting in lower operating costs. The other key difference is that in a situation where the process is bottlenecked downstream of the sorting step (in this example, in the comminution step), the value of maximizing the mining rate and accelerating cash flow is evident in the NPV calculation.

Use of the developed variable cut-off grade methodology should provide projects and operations that are considering the use of coarse ore upgrading technologies a more fulsome indication of the value of the technology.

## **Dedication**

This project is dedicated to my loving wife, Wendy Rairdan. The pursuit of my MBA degree has spanned over 10 years, during which the travel and course work commitments have been substantial. The last decade has seen our family grow with the addition of two children (Amber and Asa), relocate to multiple international destinations, and face multiple other family challenges – throughout which Wendy’s support of my completing this program has never wavered.

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# **1: Introduction**

## **1.1 Coarse Ore Upgrading – Concept and Methodologies**

Mineral processing of base and precious metals sulphide ores containing metals such as copper, zinc, lead, nickel, gold, and silver, is an industry with input costs that exceed US\$100 billion per year worldwide annually. The facilities used to conduct mineral processing, generally referred to as mills or concentrators, can have operating budgets in excess of US\$300 million annually for a single plant.

Operating a concentrator is highly energy intensive as the majority of these processes involve crushing and grinding ore into very fine particle stream such that valuable mineral particles can be separated from the non-valuable minerals (gangue). Recent estimates suggest that as much as 3%<sup>1</sup> of the world's electricity is consumed in ore comminution processes, and the cost of this power can represent as much as 60% of a site's overall concentrator operating costs. For these reasons, there is currently a push towards a group of new technologies generally referred to as "Coarse Ore Upgrading" in order to reduce operating costs and input (water and power) intensity.

In a typical sulphide mining operation, there are only two points in the process where the quality of the site product can be upgraded (ie. gangue mineral is rejected). The first point is during the mining process, when ore material that naturally contains higher or lower grades is physically separated by mining equipment and sent to different locations. For example, material that has been broken using explosives will be sent either to a waste dump or to the concentrator based on the value of the material. This decision is typically made based on a Cut-Off Grade (COG), such that material with contained payable metal value higher than the COG reports to the concentrator.

In the majority of operations, all of the material sent to the concentrator is crushed and ground to a predetermined product size before froth flotation. Flotation represents the second traditional point in the process where upgrading occurs, ultimately resulting in a saleable product. Technologies focused on coarse ore upgrading focus on the steps between the selective mining

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<sup>1</sup> (CEEC - Center for Eco-Efficient Comminution n.d.)

and flotation processes. There are three main categories of technologies in various stages of development that collectively represent coarse ore upgrading. In addition to the following descriptions, Appendix A includes basic examples of how three of these technologies would be applied in a sulphide mining operation.

- Size Based Sorting – In this case, either the natural breakage characteristics of an ore or selective breakage during the blasting process result in varying grades at different size fractions of an ore stream. This variability is exploited through screening or other size classification method, resulting in two or more streams with varying grade that can be dealt with separately.

- Bulk Sensor Based Sorting – These technologies attempt to measure the quality of large quantities (1 – 1000 tonnes) of ore at a time using sensing technology, such as X-ray transmission, optical, or induction sensors. Once sensed, the “lot” of material is distributed to one of multiple locations for further handling or processing.

- Particle Scale Sensor Sorting – Technologies in this class attempt to measure the quality of individual particles of material, generally between 5mm and 200mm in diameter. Based on the measurement of similar sensors to the bulk sorting units, individual particles are physically separated into differing streams, most often through the use of pneumatic ejection.

- Dense Medium Separation – These technologies utilize a mixture of fine solids and water that act as a liquid with high specific gravity. A series of mechanical devices are used to separate material based on the specific gravity of an individual particle. The concept of separation by specific gravity is not in itself novel, but new application of existing technologies has resulted in inclusion of this list.

In all four of the above cases, similar logic can be used to evaluate the opportunity. In each case, money is spent to remove part of the mass flow resulting in higher grade material advancing to the next step of processing, and a waste stream being generated that contains some amount of valuable material that requires disposal. For the bulk of this paper, discussion will focus on particle scale sensor sorting (referred to as simply “sorting” technologies). However, the outcome of the study should be equally applicable to the other three forms of coarse ore upgrading.

## 1.2 Traditional Evaluation of Processing Projects

Historically, mining and concentrator operations have been thought of as silos. One classic example stems from Teck Resource's Highland Valley Copper operation in which both the mine and the mill generally agreed that "The mine's job was to fill the piles, the mill's was to empty them<sup>2</sup>". The piles referenced in the aphorism are the coarse ore stockpiles where mined material is stored prior to processing. The practical outcome of this way of thinking is that the mill simply processes what the mine provides. Analysing an ore sorting opportunity in this paradigm would result in the answering of the question:

### **How will this improve the processing operations value?**

In order to evaluate the opportunity, processing impacts and costs are directly quantified. In a recent paper, Lessard, de Bakker and McHugh (2014) (Lessard, de Bakker and McHugh 2014) present and detail a method for evaluating ore sorting opportunities from a traditional mineral processing methodology. These authors focus on the development of three different levels of ore sorting operation, denoted as relaxed, moderate, and aggressive. In the relaxed case, almost every particle that contained valuable metal was accepted to the main process, where in the aggressive case some particles that contained some level of valuable metal were rejected. The economic analysis was completed by utilizing the following steps:

1. Establishment of Base Case: Define the throughput and head grade of a given process, and calculate the operating costs associated with the given throughput and head grade.
2. Quantify the impact of sorting on the process: This would include allowance for the sorting costs, rehandling of rejected material, and the impact on the operational costs of the material noted.

Based on the above, the impact of operating costs can be quantified before and after the sorting case. Alternatively, the throughput can be increased to maximize a particular area of the process, but with the addition of some processing capacity. In either case, ore sorting will generally have a positive impact on the processing economics as the unit costs (per metal product unit) will generally decrease. The methodology can determine the impact on the economics of the process, but does not quantify the impact on the overall site. For example, the assumption that the throughput of the plant can be increased to increase the metal throughput of the plant is dependent on the ability of the mine to deliver material at a cost effective mining rate to satisfy the process requirements.

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<sup>2</sup> Author's experience

Although an acceptable way of analysing value from within a segmented section of the overall business, as this opportunity affects the broader operation there is a need for a more fulsome definition of the opportunity value., there appears to be more to the value proposition than is captured in this manner.

### **1.3 Cut-off grade Based Deposit Evaluation**

Mining engineers use a very different way to evaluate value than mineral processors have traditionally used. During the mining engineering process, material to be mined is classified as ore or waste, resulting in three different categories of material. The first is material that is of low enough grade (valuable metal content) that it is not valuable enough to mine and it is located in an area where there is no need to move the material to access higher grade, economic ore. This material will not be mined. The second class of material is called waste rock. This material does not have enough grade to be processed economically, but it does need to be mined in order to access higher grade, more valuable material. The third type of material is ore, which contains enough value to not only offset the mining and processing of itself, but also to offset the cost of mining any waste rock that needs to be removed in order to access the ore material. However, there also needs to be enough value in the ore to make an acceptable economic return of capital employed, in addition to simply covering the operating costs.

Stemming from these three types of material are a series of cut-off grades. A cut-off grade is an amount of valuable material in a quantity of material at the tipping point between these types of material. The Mine Cut-Off Grade (COGmine) is the grade at which any material below is not mined due to its own value. Once material has been mined, and the choice is to be made between sending the material to a waste stockpile (as waste rock) or to the mill (as ore), a Mill Cut-Off Grade (COGmill) is often applied. This COGmill is also known as an internal cut-off grade, particularly if there is a substantial difference in the mining costs for ore or waste material. The difference between these COG's revolves around sunk costs. For the COGmill, a large proportion of the mining costs (drilling, blasting, mining G&A, and truck loading) are sunk. In addition, the cost of hauling the material to a waste dump partially offsets the cost of hauling the material to the processing facilities and processing the material. Explained mathematically, both COG's are shown below.

### COGmine Calculation<sup>3</sup>

$$Xc = \frac{[Mo + Po + Oo]}{Rf (V - R)}$$

### COGmill Calculation<sup>4</sup>

$$Xc = \frac{[Po + Oo]}{Rf (V - R)}$$

Where:

Xc = Mine or Mill Cut-Off Grade

Mo = Mining costs on a metric tonne basis

Po = Processing costs on a metric tonne basis

Oo = Overhead costs on a metric tonne basis

Rf = Flotation Recovery (proportion of valuable product recovered)

V = Value of one unit of valuable product

R = Refining, transportation, and other costs incurred per unit of valuable product.

Since mining costs are a substantive part of the mining process, it can be seen that the mine cut-off grade is always higher than the mill cut-off grade.

Variations of these cut-off grade analyses are available for situations where the site is mining rate limited, milling rate limited, has a choice of processing options, etc.<sup>5</sup> For this analysis, the base COGmill will be used, which assumes that neither the mine nor the mill are materially constrained and that all costs are 100% variable, resulting in a mining decision that is solely based on the grade of material in question. A schematic depicting the use of a cut-off grade strategy to operate a mine is included in Appendix B for further reference.

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<sup>3</sup> (Rendu 2008)

<sup>4</sup> (Rendu 2008)

<sup>5</sup> (Rendu 2008)

## 2: Economic Evaluation Analysis Development

### 2.1 Conceptual Framework

The concept of a COGmill requires that once material has been deemed ore, then all of that material can be sent to the process to recover the valuable material. Introduction of a sorting step changes this concept. The COGmill can be modified, as there is an opportunity to remove some lower value material further down the process (after additional costs are sunk) to reject material that would be viewed as uneconomic. Modifying this cut-off grade has an impact on the operating margin of the mining process. In order to further understand this process, the processing costs (Po) will need to be further broken down into the main components of mineral processing. Note that these steps can vary, but for the sake of clarity, a straightforward base metal sulphide milling process is illustrated in figure 2.1. Figure 2.2 illustrates a similar process, but with the addition of an ore sorting step.

Figure 2.1 Traditional Process

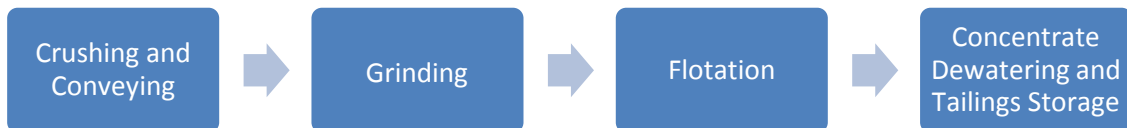
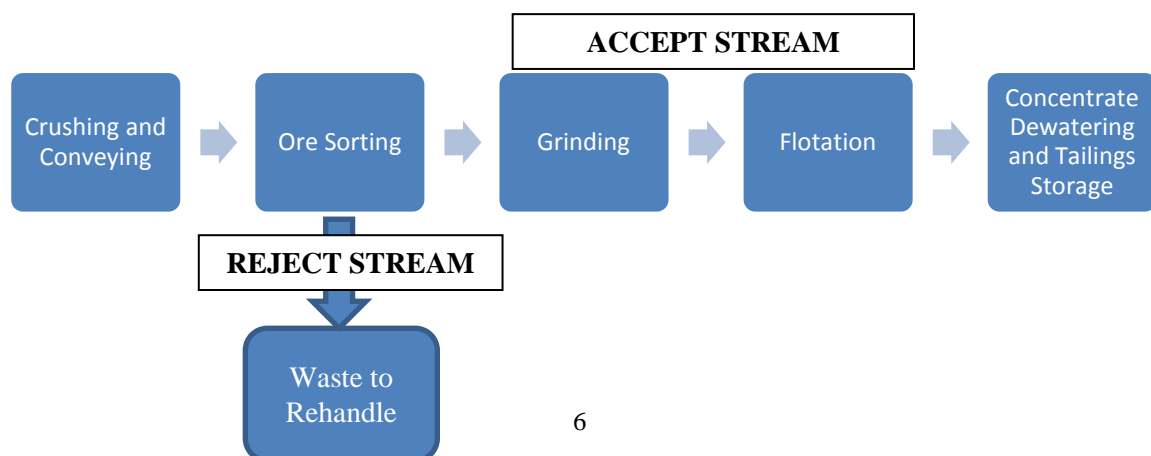


Figure 2.2 Process Including Ore Sorting





The following two charts (in figures 2.3 and 2.4 below) indicate the difference in margin between a traditional process and a process with a sorting step. As material is moved through the process, costs are sunk into processing, reducing the opportunity value remaining in the material. If sunk costs were to exceed the value during the process, the material would effectively be cash negative to process. In both of the illustrated cases, the same material is mined, but it can be seen how the margin is improved at the point in the process where material is rejected and the opportunity value does not drop in parallel with the operating costs, increasing the margin.

Figure 2.3 Margin Curve - Linear Mining Process

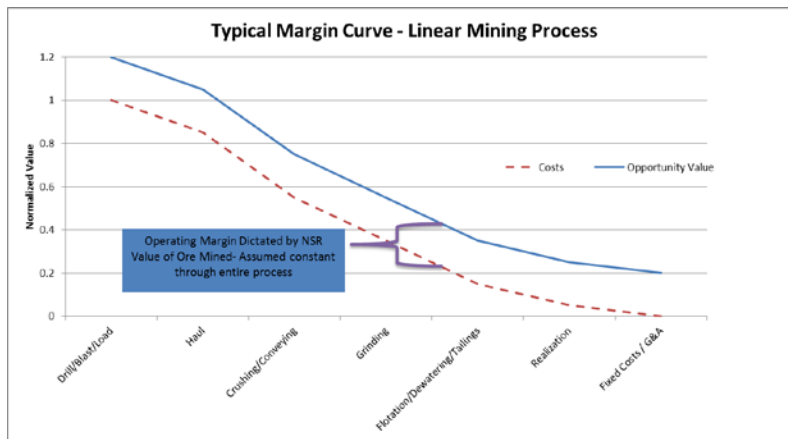
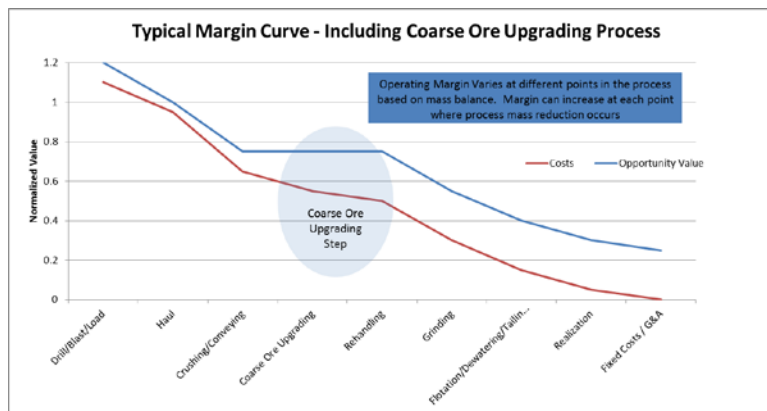


Figure 2.4 Margin Curve – Inclusion of Coarse Ore Upgrading Process



## 2.2 Sorting Cut-Off Grade Equation Development

Whereas the traditional process can treat processing costs as a single unit cost (variable on a time basis, but constant on a metric tonne basis), the second case requires a more complex analysis as the basis will change depending on the proportion of material sorted. For the evaluation including ore sorting, it is suggested that the processing costs be broken down into four categories for each sorting step. All costs are on a per metric tonne basis of material subjected to the process in question.

Pps	=	Processing costs incurred prior to the sorting process
Ps	=	Processing costs incurred during the sorting process
Pas	=	Processing costs incurred after the sorting process (main stream)
Psw	=	Processing and transportation costs incurred by the sorting waste stream

Three other key factors are the amount of material, of the original mine ore flow, that reports to the accepted stream and the recovery of valuable material to both the accepted stream and the flotation concentrate stream (ie. flotation recovery).

S	=	Fraction of mine ore reporting to the accepted stream
Rs	=	Fraction of valuable material reporting to the accepted stream
Rf	=	Fraction of valuable material reporting to the flotation concentrate
Uaccept	=	Value of Accept Stream

At the point of sorting, the value of the accepted material should be greater than the downstream processing costs, which include the processing of the waste reject, sorting process costs, and downstream costs of the accept stream in order to have positive value. Therefore:

$$U_{accept} > Ps + S(Pas) + (1 - S)Psw$$

Integrating the previously stated methods of calculating the value of a mined unit of ore, the following equation is proposed:

$$RsRf(V - R)X = Ps + S(Pas) + (1 - S)Psw$$

Where  $X$  is the grade of the mined material.

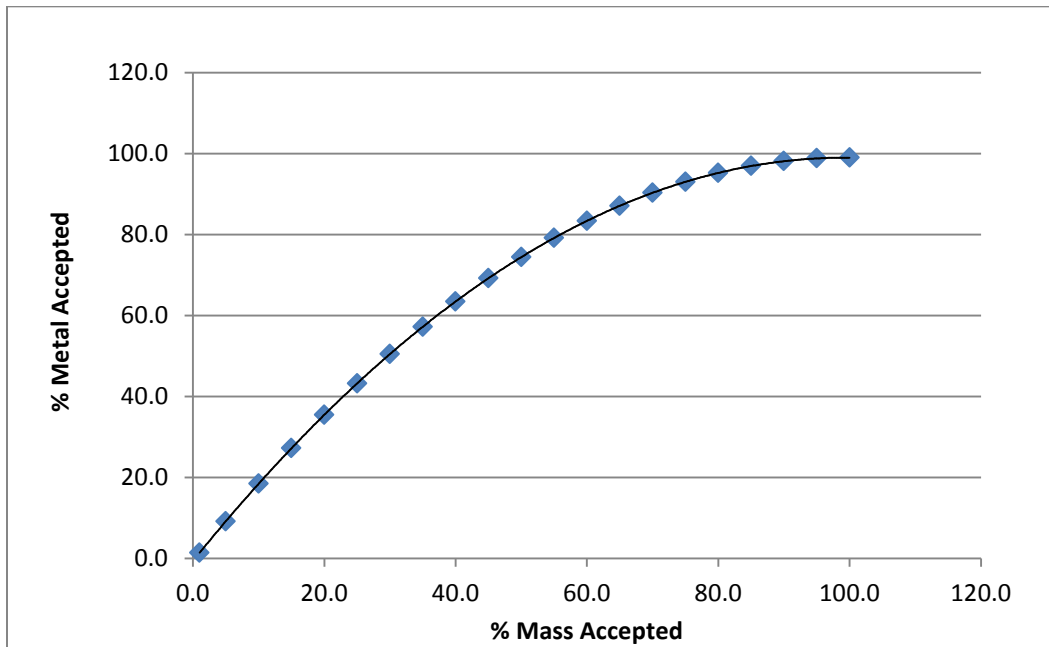
Therefore, by setting the value of the sorted material at a minimum while still exceeding both the sorting costs and the downstream costs of the accept and reject material, the cut-off grade from a sorting perspective can be denoted as:

$$Xcogs = \frac{Ps + S(Pas) + (1 - S)Psw}{RsRf(V - R)}$$

### **2.3 Sorting Recovery / Mass Accept Relationship**

A parameter that needs to be well understood in order to utilize these equations is the fraction of the processed material that will report to the accepted stream from the sorting process ( $S$ ). This proportion will vary depending on the cut-off grade and the material characteristics of the deposit. This relationship can be described in a chart linking the percent of mass accepted to the percent of metal accepted. If this relationship is linear, there would be no benefit from ore sorting as no upgrading will occur through the rejection of mass. Deposits that are amenable to ore sorting will have a curved relationship, an example of which is shown in Figure 2.5.

Figure 2.5 Accept Stream Mass / Metal Relationship



It can then be assumed that in general, there is a relationship between sorting metal recovery ( $R_s$ ) and fraction of material reporting to the accept stream ( $S$ ). Therefore, either of these two variables can be described using the other, such that:

$$S = f(R_s) \quad \text{or} \quad R_s = f(S)$$

Since the overall costs and revenue will change with  $S$  and  $R_s$ , the sorting cut-off grade will change depending on where on the above curve the sorting operation is operated at. In order to determine what cut-off grade is reasonable, the equations above need to be applied through the range of  $S$  values (0 -100) to determine the lowest cut-off grade possible. It is at this point that the sorting system revenue and costs are balanced on a sunk cost basis. This lowest cut-off grade, coupled with the associated  $S$  and  $R_s$ , should be used as the sorting cut-off grade.

## 2.4 Equation Application

The sorting waste stream is comprised of many individual particles, each of which has been subjected to a sensor-based analysis to determine the metal content of the material. The sensor reading at which a particle is sorted between the reject and upgraded streams is known as the cut-point. As this process is not perfect, some particles with grade above the cut point will

report to the waste stream and others with grades below the cut-point will report to the upgraded streams. Therefore, once a COGsort is calculated, it can be applied in three ways.

1. Particle Basis: In this case, every particle that is sensed to have a grade below the COGsort (ie. COGsort is equal to the cut-point) is rejected. This is a potential option as every particle is being measured and is being evaluated as to whether it can carry the downstream costs and add value to the operation. However, the end result is that the stream will have an overall grade substantially lower than the COGsort as the waste stream will include a blend of particles ranging from no valuable material to particles just slightly lower grade than the COGsort.
2. Stream Basis: In this case, the particles are sensed in a manner in which some individual particles above the COGsort are purposely directed to the reject stream in order to target an entire stream grade equal to the COGsort. This will result in more mass reporting to the waste stream, and a higher grade accept stream reporting to the remainder of the process.
3. Stockpile Generation Basis: In this case, an operating particle cut-off grade well in excess of the COGsort can be used to generate a reject stream that is in excess of the COGsort. This material will still, by definition, be ore as it will have positive opportunity value. However, the capacity of the downstream circuit will be better utilized with higher grade accepted material. Effectively, this results in the rejected material being classified as low-grade material for stockpile, and should be stored in a manner in which it can be processed at a future date.

The decision as to which of these methods to use to determine the operating point of the sorting system lies in where the overall site bottleneck resides. The first case may be applied if the site bottleneck rests with the capacity of the mining fleet and/or constraints to the mining rate. Since the mining rate is restricted, the mine would endeavour to produce as high a grade material as possible, and the milling process would focus on maximizing the amount of metal production during a given time period. The second case is used if stockpiling space and/or complexity is the constraint. This method will increase the utility of the process at a higher mining rate, but does indicate that stockpiling the reject stream would not be a good business decision as the opportunity value of the material would be negative. In this case, the reject would be stored along with the rest of the mining waste material without any concern for loss of opportunity value. In scenario three, there is adequate mining ability and stockpiling constraints are not an issue, which would put the site production bottleneck on the process downstream of the sorting

step. In this case, the goal will be to maximize the utility of the downstream process, and allow the rest of the site to operate at whichever rate can support the bottleneck rate.

### 3: Case Study – Hypothetical Zinc Mine Opportunity

#### 3.1 Case Study Assumptions

In order to illustrate the concepts presented, a hypothetical, simplified case of a mid-scale high grade zinc mine operating in remote conditions (such that electricity is diesel-power generated) was developed. It is assumed that this mine is mid-life, and there is sufficient ore at current cut-off grades to operate for 15 years. Key assumptions for the base case (without ore sorting) and ore sorting scenarios include:

##### **Pre-Ore Sorting Assumptions:**

Current Life of Mine:	10 years
Annual Processing Rate:	5.0M dmt/a
Mining Strip Ratio:	1.5
Annual Mining Rate:	12.5M dmt/a
Mine Operating Costs:	\$10.0 / tonne mined
Processing Operating Costs:	\$22.0 / tonne processed
Admin OPEX	\$8 / tonne processed
Annual Head Grade	10.6% Zinc
Mine Cut-off Grade	6.4% Zinc
Flotation Recovery	85%
Zinc Concentrate Grade	55%
Net Smelter Return (including shipping)	\$600/mt concentrate or: \$1091/mt zinc in concentrate

##### **Ore Sorting Assumptions:**

Ore Sorting Capital Cost	\$100M
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Processing Operating Costs (prior to sorting):	\$4 / tonne processed
Processing Operating Cost (post sorting)	\$18 / tonne accepted
Sorting Operating Cost	\$1.0 / tonne processed
Sorting Recovery	99% Zinc to Accept Stream
Sorted Mass Report to Accept Stream	85%
Reject Mass Rehandling Costs	\$2.0 / tonne rejected
Grade/Tonnage Curve of Deposit (insert)	

In addition, it is assumed that the site is bottlenecked around the comminution (ie. grinding) circuit of the processing plant. As the grinding circuit is a very cost intensive process, especially considered the assumption of diesel-generated electricity, the bottleneck is in the appropriate location for the hypothesized operation.

Another key assumption in any analysis of this type is the grade-tonnage curve of the deposit. This graph, shown in section 3.3, denotes how much of the material is mineralized and to what extent.

### **3.2 Traditional Economic Evaluation of an Ore Sorting Opportunity**

In this case, the capital cost is applied as a negative cash flow in the year prior to sorting operations starting, and the same mine plan (same tonnage and grade) is executed through a modified plant at a higher throughput. A summary sheet of the production plan and cash flow is included in Appendix C for all scenarios, including the traditional evaluation method.

The bottleneck is assumed to be the process downstream of the sorting step, such that the mining rate is increased to allow this bottleneck to be fully utilized. In the base case, the mine operates at 12.5 million tonnes per year versus 15.625 million tonnes per year in the ore sorting case. Costs are applied on a unit basis to the different streams (mined, sorted, reject and accept). As the cost of this process are heavily weighted towards the reject stream, which is expected due to the high cost of grinding energy that this material would be subjected to, the project economics are favourable towards ore sorting. The split of material between the reject and accept streams was based on the concept that very little metal would want to be lost to the reject stream, and based on the defined separation curve, it was assumed that 99% of the contained zinc could be recovered through sorting with 80% of the mass reporting to the accept stream.



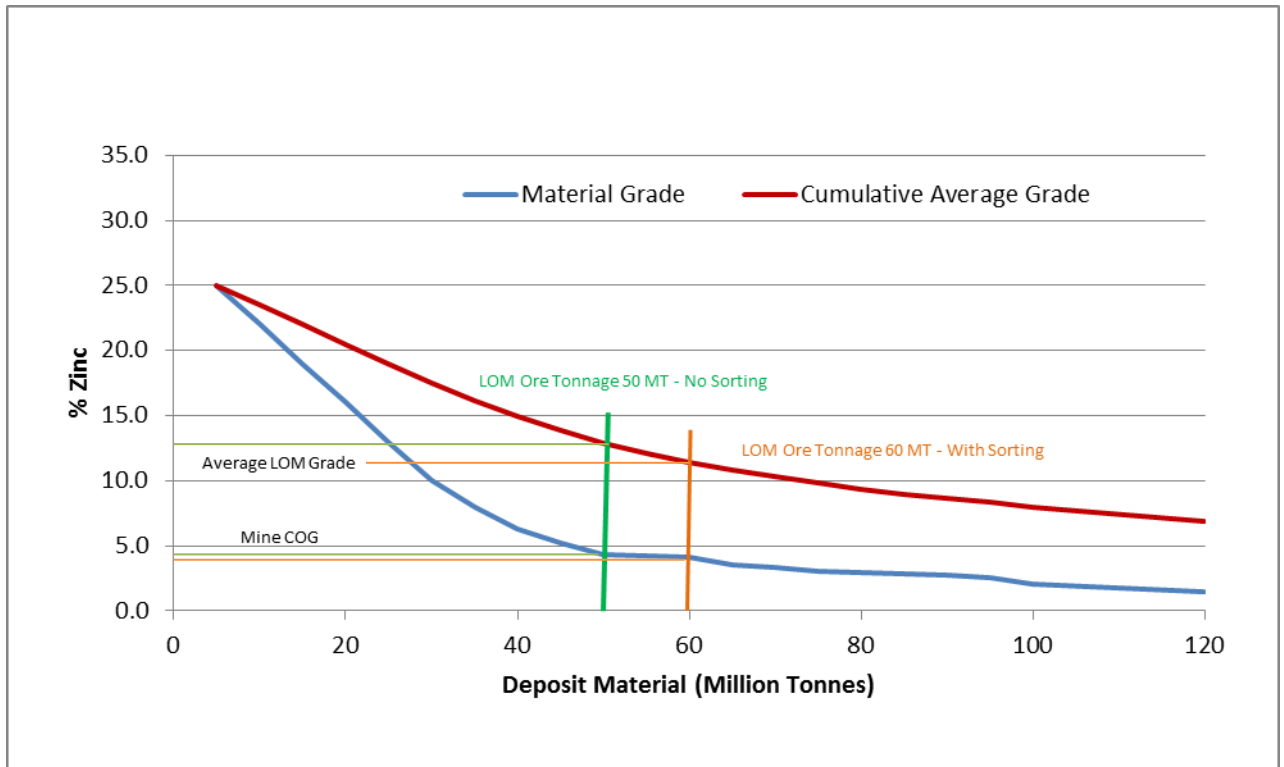
The total operating costs for the mine are reduced by approximately \$130 million, with no increase in revenue (similar metal production rates). Due to the reduction in operating costs and the acceleration of metal production and therefore revenue, this \$100 million investment would have a net present value (NPV) at an 8% discount rate of \$131 million.

### **3.3 Application of Cut-off Grade-based Economic Evaluation**

In order to incorporate cut-off grade analysis into the process, two steps are required. The first step is the calculation of the sorting cut-off grade. As per the above equations, the sorting cut-off grade is the point at which particles below a certain grade do not contain enough metal to cover the additional downstream processing required to convert the material into revenue generating product. For this calculation, both the cut-off grade equation and the defined sorting separation curve were used to find the minimum cut-off grade point. It was found that an optimal operating point was 63% mass accept point and a sorting metal recovery of 93.1%. Although in this situation about 6.9% of the metal fed from the mine to the process is lost, this material is not deemed as economic as the material does not contain enough material to cover the downstream processing costs. Taking this optimal point and including it in the sorting cut-off grade calculation produces a cut-off grade of 1.7% zinc and an associated mine cut-off grade of 4.0%.

This mine cut-off grade is substantially lower than the base case cut-off grade of 4.3% zinc. Using the reduced cut-off grade, the amount of material in the deposit that is classified as ore, with zinc grades about the cut-off grade, increases from 50 million tonnes to 60 million tonnes. The LOM head grade is reduced from 12.9% from 11.4%. This is shown graphically in Figure 3.1 the grade-tonnage curve of the deposit.

Figure 3.1 Grade-Tonnage Curve of the Deposit



Taking into account this increase in tonnes processed and the lower grade, the economics of the opportunity are evaluated in a similar manner to the traditional method. Due to a further reduction in material being fed to the accept stream (only 63% of a mine plan with 120% of mined material, the absolute value of the operating costs are reduced a further \$30 million from the traditional evaluation method. The revenue is at very similar levels to both the base case and traditional evaluation methodology.

Due to the acceleration of the zinc production (and revenue) due to the higher processing rate and the reduced operating costs, the NPV of the sorting project at 8% discount rate is increased from \$131 million to \$201 million, an increase of 53%. Although this does only translate to an increase in IRR of 1.0% between the two evaluation methodologies, this is material considering this increase is strictly due to the evaluation (and proposed operational) strategy.

## **4: Conclusion**

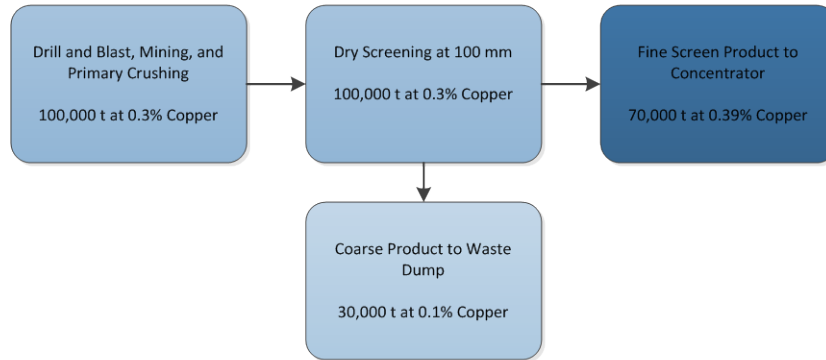
It can be concluded that the inclusion of a cut-off grade strategy can provide a more fulsome view of the impact of an ore sorting application on a sulphide mining operation, including the impact on the overall mine plan. As the sorting application will fundamentally shift the cost structure of a site by providing an additional point of upgrading to the process, it stands to reason that the impact on the material to be mined should be quantified and understood

Utilizing the equations developed in this report, whether evaluating an opportunity to implement a coarse ore upgrading step or determining the operating strategy of an operating system, should help tie the value created in the mining and processing activities into a single value-based enterprise. This should increase the utility of the both the operating and resource assets being applied in the venture.

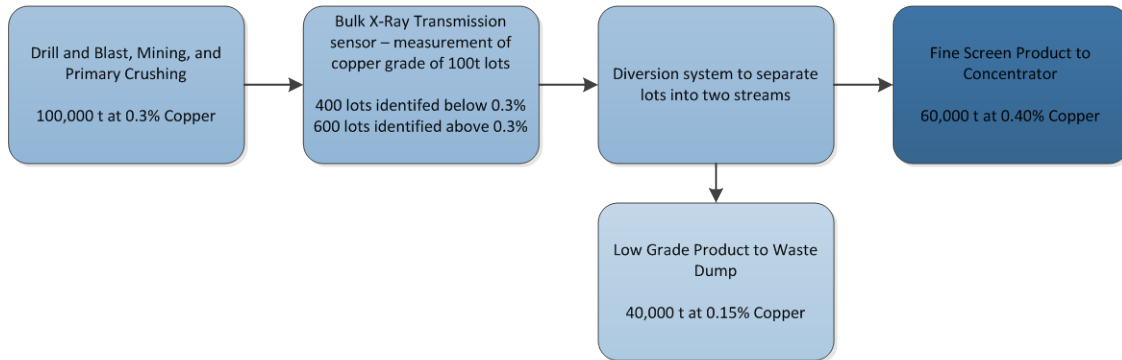
## **Appendices**

# Appendix A – Coarse Ore Upgrading Examples

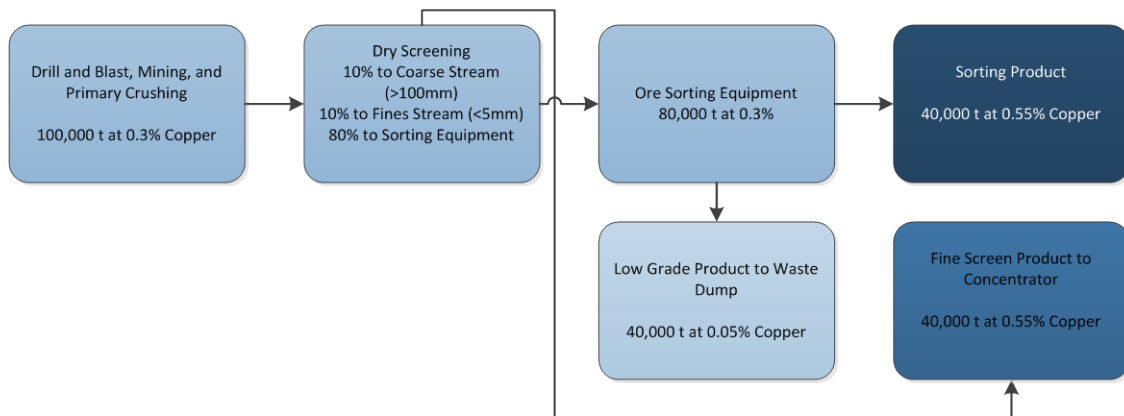
Size Based Sorting Example – Screening of Primary Crusher Product



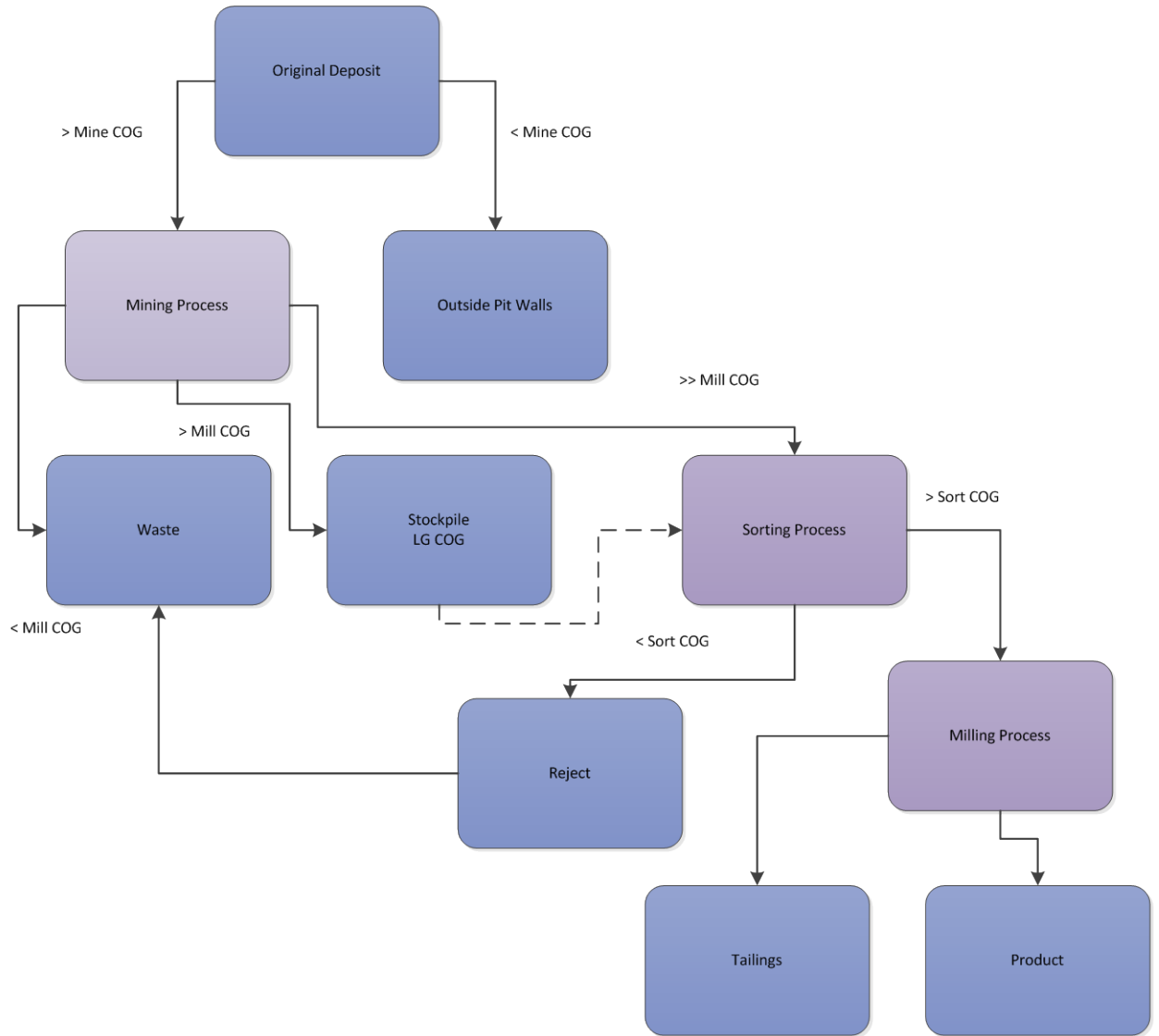
Bulk Sensor Sorting Example – Sorting material in 100 t lots



Particle Sensor Sorting Example



## Appendix B – Conceptual Framework of Cut-Off Grade based Operating Strategy



**Appendix C – Business Case Production, Cash Flow, and Present Value  
Tables for Base, Traditional Ore Sorting, and COG based ore sorting  
evaluations**

Current LOM Plan - BASE CASE, No Ore Sorting		8 % Discount Rate									
Year	1	2	3	4	5	6	7	8	9	10	
Mined Tonnage	12,500,000	12,500,000	12,500,000	12,500,000	12,500,000	12,500,000	12,500,000	12,500,000	12,500,000	12,500,000	
Processed Tonnage	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000	
Zinc Concentrate Produced	996,818	996,818	996,818	996,818	996,818	996,818	996,818	996,818	996,818	996,818	
Mine Operating Costs	\$ 50,000,000	\$ 50,000,000	\$ 50,000,000	\$ 50,000,000	\$ 50,000,000	\$ 50,000,000	\$ 50,000,000	\$ 50,000,000	\$ 50,000,000	\$ 50,000,000	
Processing Operating Costs	\$ 110,000,000	\$ 110,000,000	\$ 110,000,000	\$ 110,000,000	\$ 110,000,000	\$ 110,000,000	\$ 110,000,000	\$ 110,000,000	\$ 110,000,000	\$ 110,000,000	
Admin OPEX	\$ 40,000,000	\$ 40,000,000	\$ 40,000,000	\$ 40,000,000	\$ 40,000,000	\$ 40,000,000	\$ 40,000,000	\$ 40,000,000	\$ 40,000,000	\$ 40,000,000	
Revenue	598,140,750	598,140,750	598,140,750	598,140,750	598,140,750	598,140,750	598,140,750	598,140,750	598,140,750	598,140,750	
Total Operating Costs	\$ 200,000,000	\$ 200,000,000	\$ 200,000,000	\$ 200,000,000	\$ 200,000,000	\$ 200,000,000	\$ 200,000,000	\$ 200,000,000	\$ 200,000,000	\$ 200,000,000	
Annual Operating Profit	398,140,750	398,140,750	398,140,750	398,140,750	398,140,750	398,140,750	398,140,750	398,140,750	398,140,750	398,140,750	
Present Value of Operating Profit	\$ 398,140,750	\$ 368,648,843	\$ 341,341,521	\$ 316,056,964	\$ 292,645,337	\$ 270,967,905	\$ 250,896,208	\$ 232,311,304	\$ 215,103,059	\$ 199,169,499	
Total Present Value	\$ 2,885,281,388										

Mine OPEX	4.0	\$/t mined
Mine OPEX	10	\$/t processed
Processing OPEX	22	\$/t processed
Admin OPEX	8	\$/t processed
V-r	1091	\$/t contained zinc
R	0.85	
Mine COG	4.3%	Zinc
Mill COG	3.2%	Zinc



**Current LOM Plan - Traditional Ore Sorting Analysis**

	Ore Sorting Capital							
	1	2	3	4	5	6	7	8
Mined Tonnage	15,625,000	15,625,000	15,625,000	15,625,000	15,625,000	15,625,000	15,625,000	15,625,000
Processed Tonnage	6,250,000	6,250,000	6,250,000	6,250,000	6,250,000	6,250,000	6,250,000	6,250,000
Accepted Tonnage	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000
Rejected Tonnage	1,250,000	1,250,000	1,250,000	1,250,000	1,250,000	1,250,000	1,250,000	1,250,000
Zinc Concentrate Produced	1,228,578	1,228,578	1,228,578	1,228,578	1,228,578	1,228,578	1,228,578	1,228,578
Mine Operating Costs	\$ 62,500,000	\$ 62,500,000	\$ 62,500,000	\$ 62,500,000	\$ 62,500,000	\$ 62,500,000	\$ 62,500,000	\$ 62,500,000
Processing/sorting Operating Costs	\$ 18,750,000	\$ 18,750,000	\$ 18,750,000	\$ 18,750,000	\$ 18,750,000	\$ 18,750,000	\$ 18,750,000	\$ 18,750,000
Reject Stream Rehandle Costs	\$ 2,500,000	\$ 2,500,000	\$ 2,500,000	\$ 2,500,000	\$ 2,500,000	\$ 2,500,000	\$ 2,500,000	\$ 2,500,000
Accept Stream Costs	\$ 100,000,000	\$ 100,000,000	\$ 100,000,000	\$ 100,000,000	\$ 100,000,000	\$ 100,000,000	\$ 100,000,000	\$ 100,000,000
Admin OPEX	\$ 50,000,000	\$ 50,000,000	\$ 50,000,000	\$ 50,000,000	\$ 50,000,000	\$ 50,000,000	\$ 50,000,000	\$ 50,000,000
Revenue	737,147,045	737,147,045	737,147,045	737,147,045	737,147,045	737,147,045	737,147,045	737,147,045
Total Operating Costs	\$ 233,750,000	\$ 233,750,000	\$ 233,750,000	\$ 233,750,000	\$ 233,750,000	\$ 233,750,000	\$ 233,750,000	\$ 233,750,000
Annual Operating Profit	503,397,045	503,397,045	503,397,045	503,397,045	503,397,045	503,397,045	503,397,045	503,397,045
Present Value of Operating Profit	\$ 503,397,045	\$ 466,108,375	\$ 431,581,829	\$ 399,612,805	\$ 370,011,856	\$ 342,603,571	\$ 317,225,528	\$ 293,727,341
Total Present Value	\$ 3,124,268,351							
Capital Required	\$ 100,000,000							
Capital NPV (at Year 1)	\$ 108,000,000							
Post-Project NPV	\$ 3,016,268,351							
Difference vs. Base Case	\$ 130,986,963							
IRR	9.5 %							

	10	2	1	20	2	8
Mine OPEX	\$/t processed	\$/t processed	\$/t processed	\$/t processed through	\$/t processed through	\$/t processed
Processing OPEX						
Sorting Cost						
Accept Stream OPEX						
Reject Rehandle						
Admin OPEX						

Current LOM Plan - COG Based Ore  
Sorting Analysis

8 % Discount Rate

Year	0	1	2	3	4	5	6	7	8
Mined Tonnage		16,515,200	16,515,200	16,515,200	16,515,200	16,515,200	16,515,200	16,515,200	9,193,600
Processed Tonnage		7,940,000	7,940,000	7,940,000	7,940,000	7,940,000	7,940,000	7,940,000	4,420,000
Zinc Concentrate Produced		1,300,962	1,300,962	1,300,962	1,300,962	1,300,962	1,300,962	1,300,962	724,213
Mine Operating Costs		\$ 66,060,800	\$ 66,060,800	\$ 66,060,800	\$ 66,060,800	\$ 66,060,800	\$ 66,060,800	\$ 66,060,800	\$ 36,774,400
Processing Operating Costs		\$ 113,859,600	\$ 113,859,600	\$ 113,859,600	\$ 113,859,600	\$ 113,859,600	\$ 113,859,600	\$ 113,859,600	\$ 63,382,800
Admin OPEX		\$ 63,520,000	\$ 63,520,000	\$ 63,520,000	\$ 63,520,000	\$ 63,520,000	\$ 63,520,000	\$ 63,520,000	\$ 35,360,000
Revenue		780,577,069	780,577,069	780,577,069	780,577,069	780,577,069	780,577,069	780,577,069	434,527,789
Total Operating Costs		\$ 243,440,400	\$ 243,440,400	\$ 243,440,400	\$ 243,440,400	\$ 243,440,400	\$ 243,440,400	\$ 243,440,400	\$ 135,517,200
Annual Operating Profit		537,136,669	537,136,669	537,136,669	537,136,669	537,136,669	537,136,669	537,136,669	299,010,589
Present Value of Operating Profit		\$ 537,136,669	\$ 497,348,768	\$ 460,508,118	\$ 426,396,406	\$ 394,811,487	\$ 365,566,191	\$ 338,487,214	\$ 174,469,807

Capital Required	\$ 100,000,000.00	\$ 108,000,000.00
Total Present Value	\$ 3,086,724,660	
Improvement Over Base Case	\$ 201,443,272	
	1.865215484	
IRR	10.5	

Mine OPEX	4 \$/t mined
Mine OPEX	10
Processing OPEX	14.3
Admin OPEX	8
V-r	1091
R	0.85
RS	0.93
Mine COG	3.7%

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