Improving closed circuit grinding circuit capacities by revisiting grinding basics - Part 1

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There is always a need to improve milling circuit efficiency to enable extra capacity as an effective means to address the deteriorating feed grades and increasing demand concerns. The roles of high recirculation load and high classification efficiency were discussed individually multiple times for attaining the higher capacities of closed ball milling circuits. However, the classifier efficiency was not well discussed and valued. As a result, grinding circuits commonly operate with 300% to 500% circulating loads and classifier efficiencies in the range of 40% to 60%. A practical methodology that considers classification efficiency and recirculation load for real-world grinding circuit capacity predictions is missing. The advancement in fine screening technology has enabled different operations worldwide to achieve high classification efficiencies, which were unattainable and not practical in the past. This paper develops a model to calculate the relative capacity at different operating conditions, including classification efficiency. We also discuss the operational limitations for achieving high classification efficiency and high circulating loads. It is demonstrated that higher milling productions can be achieved by using the optimised balance of circulating loads and classification efficiency. The classification efficiencies between 85 to 95% and circulating loads between 60 to 150% are typical with fine screening and result in higher mill production rates in the range of 10 – 35% over hydrocyclone circuits. As a result of the metallurgical performance improvement, the extra CAPEX of fine screens is justifiable with a payback period of four to eight months.

Keywords: Grinding circuit capacity, fine screening, closed circuit grinding, first order grinding law, capacity improvement.

INTRODUCTION

The global platinum group metals (PGM) supply is forecasted to reach 22.44 million ounces in 2024, growing at a compound annual growth rate (CAGR) of 6.8% for the period spanning 2020 to 2024 (Research and Markets, 2021). PGM demand declined in recent years due to the impact of Covid-19 and the pandemic on the automotive, industrial, and jewellery sectors, but the market indicates that there will be an increase in demand over the next 10 – 20 years due to the automotive sector's tighter regulations for global greenhouse emission standards (Johnson Matthey Plc, 2021). PGM producers will require better metal recovery and higher throughput processing plants to meet the demand outlet. As indicated in Figure 1, most PGM major producers have head grade ore on the declining trend; one of the main reasons being that most mines are reaching their end of life and/or depleting the high-grade reefs' ore bodies (Sefako *et al.*, 2017). The reduction in the head grades forces the PGM mines to process more ore to produce the same amount of metal, which raises the requirement for the processing capacities of the mills.

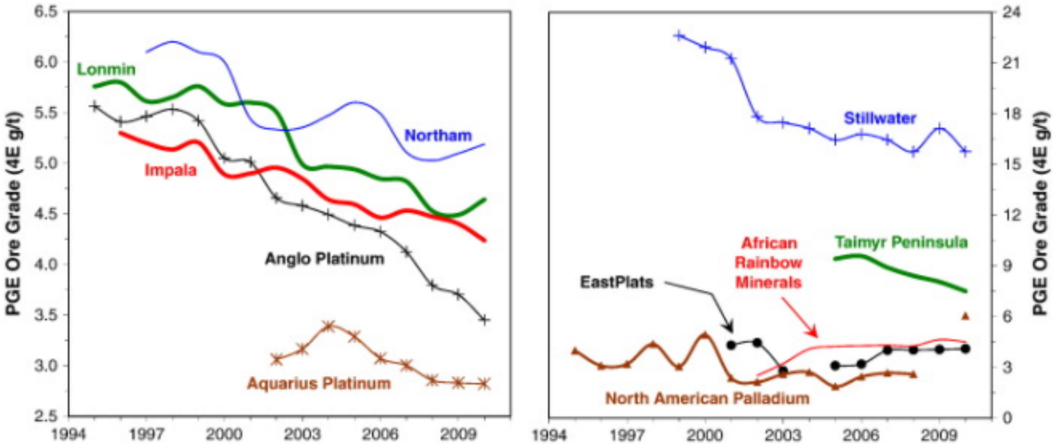

Figure 1. Recent ore grades by company during processing (Mudd, 2012).

Closed ball milling circuits have been well established over the years to achieve the required liberation size for recovering valuable minerals in the downstream processes. While positioned in the middle of the circuit, taking a feed from upstream crushing circuits, and preparing feed to the sensitive flotation circuits, grinding circuits always require more capacity to accommodate changes in ore body or requirements based on downstream technological or market changes. Moreover, increasing ore competence makes ball mill circuits a capacity constraint in the plants. The circulation load and classification efficiencies were discussed numerous times as the factors affecting closed circuit ball mill capacities. Davis (1925) performed experiments on limestone using a 0.9 m diameter mill in a first attempt to compare open circuit and closed circuit grinding. His study concluded some findings helping mill operators also include the relationship between circulation load and ball mill circuit capacity. Davis stated that the circuit's new feed rate keeps increasing with an increase in circulating load, as shown in Figure 2. The critical relationship was then explored and experimented on by noted researchers (Dorr & Anable, 1934; Guest, 1972; Hukki & Allenius, 1968), which subsequently supported the findings of the (Davis, 1925) experimentation at the Minnesota School of Mines Experimentation Station. Figure indicates that the work done increases as larger circulating loads are handled, and the rate of increase in work falls off rapidly above a 50% circulating load. A 500% circulating load produces 2.3 times as many work units as open circuit grinding, but a 100% circulating load has 1.8 times as many units as open circuit grinding. It is therefore apparent that the first 100% of circulating load increases the work units produced by 80%, while the following 400% of circulating load adds only 50% to the work already done.

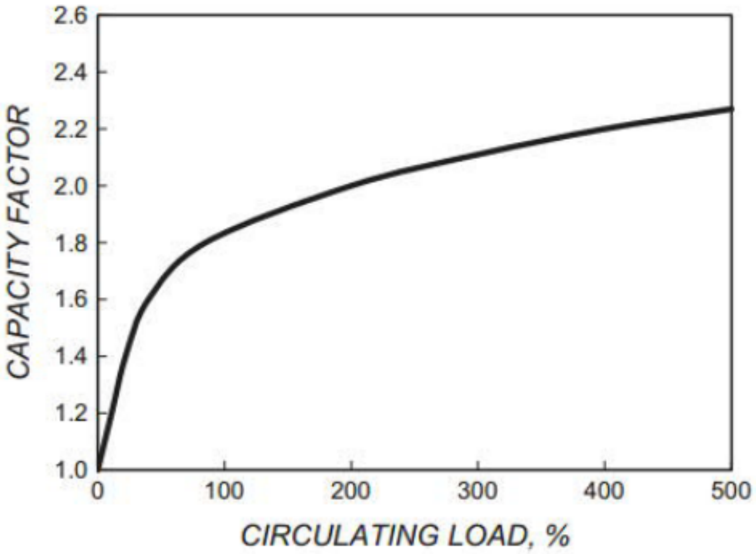

Figure 2. Graph showing the relationship between circulating load and mill circuit capacity (Davis, 1925) (Circulation load is the ratio of the amount of ground material going back to the mill to the material going in the product stream).

Many researchers (Guest, 1972; Hukki, R.T., Heinonen, P., 1973; Hukki & Allenius, 1968) have worked on the relation between classification efficiency and circuit capacity through the experimentations like the one performed by Davis (1925) but with varying classification efficiency/ sharpness. Table I shows part of the results from the experiments of Hukki & Allenius (1968). The mill circuit with higher sharpness of classification (%) produces a higher amount of required product. The higher capacity of the circuit with higher classification sharpness is attributed to the efficient removal of fines, allowing a higher fraction of grinding energy to go to the coarser material, enhancing grinding efficiency.

Table I. New feed rate at three different Sharpness of Classification at the same grinding times. Redrawn after (Hukki & Allenius, 1968)

Sharpness of Classification (%)	New Feed Rate (gm/ min)
100	38.2
75	37.3
50	36.8

The fact that mill capacity increases without a corresponding increase in power is attributed to the more rapid elimination of fines, the reduction of uneconomical over-grinding, and the increased amount of coarse material that may be exposed to the cascading balls at one time. The rapid elimination of fines has two major variables: circulation load and classification efficiency. Morrell (2008) has published a set of experiments to establish the specific energy requirements in a comminution circuit have noticed relationships of reduction in operating bond work index with increasing % recycle and reduction in % bypass as shown in Figure 3. A higher operating index indicates lower grinding efficiency, and a higher % bypass indicates lower classification efficiency.

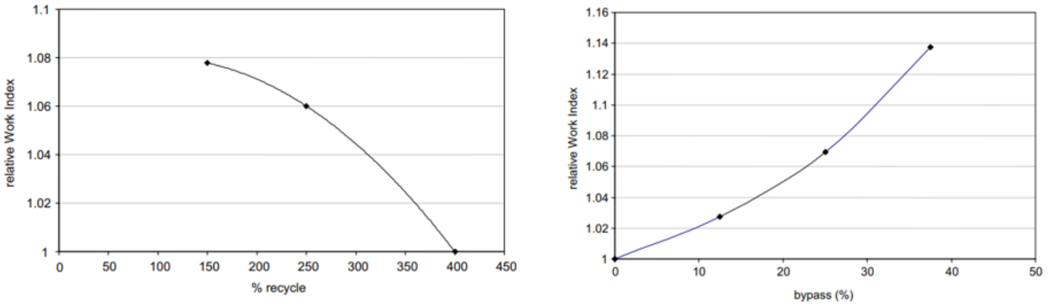

Figure 3. Relationship of operating work index with % recycle load and % bypass (Morrell, 2008a).

Hukki & Eklund (1965) examined the relationship between the sharpness of classification and circulating load in a conventional closed grinding circuit, as shown in Figure 4. It clearly states that with increasing circulating load in the industrial closed grinding circuits, the sharpness of classification reduces. The sharpness of classification or the screening efficiency fraction is the fraction of fine material in feed reporting to the fines fraction of the classifier. First, both circulation load and sharpness of classification affect grinding circuit capacities. Secondly, circulation load and sharpness are dependent on each other. Thus, for effective operations of closed-circuit mills, both the parameters must be understood collectively. Hukki (1979) collectively studied the effect of both circulation load and classification sharpness through a series of experiments, and arrived at a graph shown in Figure 5. It is the extension of the chart developed by Davis (1925), illustrating curves for different classification sharpness suggesting higher circuit capacity for higher classification sharpness and circulating load.

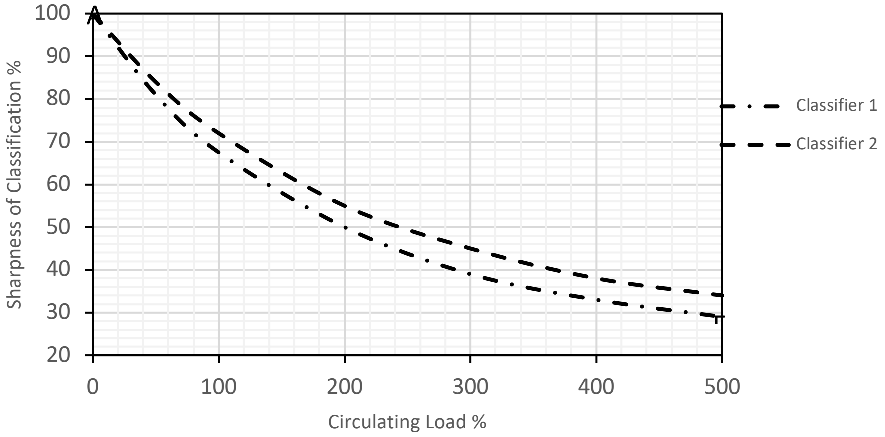

Figure 4. Average industrial data showing the relationship between Sharpness of Classification% and Circulating Load% (Hukki & Eklund, 1965).

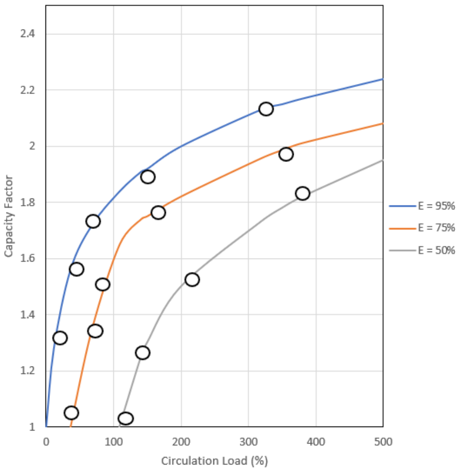

Figure 5. Relationship between Capacity Factor and Circulating Load at different classification efficiencies (Hukki, 1979).

McIvor and team (Bartholomew e*t al.,* 2014, 2014; Laplante *et al.,* 1988; McIvor, 2006) have used the methodology of Classification System Efficiency (CSE) and Functional Performance Characteristics for improving capacity at different grinding circuits. He estimated the effects of three distinctive factors for improving capacity through circuit survey and laboratory data. Three circuit factors are milling dynamics, circulation load, and classification efficiency. CSE is calculated by averaging the percentage of coarse material (referring to the circuit product P80) in the mill feed and discharge. The KPI CSE is reported to be related to overall energy efficiency. Case studies from Barkhuysen *et al.,* (2010); Barrios (2007); Dündar *et al.,* (2014); Mainza (2016) have shown that milling capacity improvement up to 45%, indicating the need for the methodology/ formula for operating the mills at optimum circulation load and classification efficiency. Magdalinovic N (1991) developed and Jankovic & Valery (2013) validated a model for a closed grinding circuit's relative capacity at different circulating loads and classification efficiencies. The equation is shown in equation [1], where K_Q is the relative capacity of the milling circuit (fraction), Q_1, Q_2 the milling circuit capacity under different circulating load and classification efficiency, C the circulating load (fraction), and E is the classification efficiency (fraction).

$$K_Q = \frac{Q_2}{Q_1} = \frac{(1 + C_1)\left(1.5 + C_2 - \frac{1}{E_2}\right)}{(1 + C_2)\left(1.5 + C_1 - \frac{1}{E_1}\right)}$$

[1]

But this model is only for a simplified case where the feed consists of only coarse material and only for traditional closed circuits. (Magdalinovic N, 1991).

The objective of this first part is to develop equations to calculate the relative capacity achieved by conventional circuits subjected to a different feed, circuit product, classification efficiency, and circulation load. The second part of the paper discusses the development of the equations for reverse grinding circuit and its applications around the world.

MODEL DEVELOPMENT

In a continuously operated closed grinding circuit, the classifier is placed after the grinding mill in a conventional way, as shown in Figure 6.

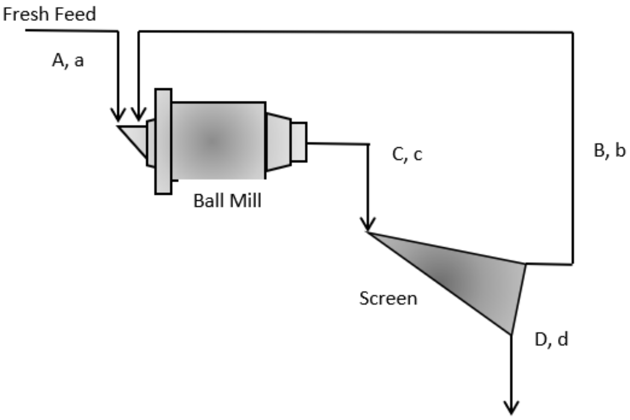

Figure 6. Simplified conventional grinding circuit.

In a continuously operated closed grinding circuit, the tonnage and the fineness of the components may be indicated as follows:

Table II. Indications for tonnage and fineness in the circuit

Description	**Mass (dry TPH)**	**Fineness (fraction of -x microns)**
Fresh feed to mill	A	a
Oversize back to mill	B	b
Mill discharge / Screen feed	C	c
Screen undersize / Circuit product	D	d

From mass balance around the circuit, the amount of fresh feed to the circuit is equal to the amount of the circuit product or screen undersize

$$A = D \qquad [2]$$

The amount of material entering the ball mill is equal to the amount of material leaving the ball mill

$$C = A + B \;\; or \;\; C = D + B \qquad [3]$$

The amount of fine material in the screen feed is equal to the sum of the amount of fine material in screen undersize and screen oversize

$$C * c = D * d + B * b \qquad [4]$$

The circulating load fraction (CL) for a classifier is defined as:

$$CL = \frac{Oversize\ back\ to\ mill}{Fresh\ feed\ to\ mill} \;\; or \;\; CL = \frac{B}{A}$$

$$CL = \frac{Oversize\ back\ to\ mill}{Screen\ Undersize} \;\; or \;\; CL = \frac{B}{D} \qquad [5]$$

The sharpness of classification or the screening efficiency fraction (screen undersize efficiency fraction) at the size x microns can be defined from the recovery formula:

$$E = \frac{Mass\ of\ -x\ Mesh\ material\ in\ the\ screen\ undersize}{Mass\ of\ -x\ Mesh\ material\ in\ the\ screen\ feed} \qquad [6]$$

$$E = \frac{D*d}{C*c} = \frac{D*d}{D*d+B*b} \qquad \text{(Using equation 4)}$$

$$E = \frac{d}{d+b*CL} \qquad \text{(Dividing by D and using equation 5)} \qquad [7]$$

Equation [7] expresses the relationship between the sharpness of classification and circulating load in closed grinding circuits.

If CL = 0, E =1, This is a hypothetical case as a perfect classifier with 100% efficiency is nonexistent. Furthermore, if CL = ∞, E = 0, this is also a hypothetical case as a classifier can not achieve ∞ CL at price of zero efficiencies.

Equation [6] can be expressed to show the amount of fine material (mass of -x microns material) in the mill discharge:

$$C*c = \frac{D*d}{E} \qquad [8]$$

Using equations [3] and [7], the amount of coarse material in the mill discharge can be expressed as:

$$C*(1-c) = C - C*c = D + B - \left(\frac{D*d}{E}\right) \qquad [9]$$

Equation [9], when divided by C = D + B, gives the fraction of the coarse material in the mill discharge (R_d) to the total mill discharge, which is shown below:

$$R_d = 1 - c = \left(\frac{D+B}{D+B}\right) - \left(\frac{D*d}{E*(D+B)}\right) = 1 - \left(\frac{D*d}{E*D*\left(1+\frac{B}{D}\right)}\right)$$

$$R_d = 1 - \left(\frac{d}{E*(1+CL)}\right) = \frac{1+CL-\frac{d}{E}}{1+CL} \qquad [10]$$

The amount of coarse material in the mill feed can be expressed as:

$$A*(1-a) + B*(1-b) = A + B - (A*a) - (B*b) \qquad [11]$$

Equation [11], when divided by A+B, gives the fraction of coarse material in the mill feed (R_f) to the total mill feed as:

$$R_f = \frac{A+B-(A*a)-(B*b)}{A+B} = 1 - \frac{a}{\left(1+\frac{B}{A}\right)} - \frac{b}{\left(1+\frac{A}{B}\right)}$$

$$R_f = 1 - \frac{a}{(1+CL)} - \left(\frac{\frac{d}{E}-d}{(1+CL)}\right) = \frac{\left(1+CL+d-a-\frac{d}{E}\right)}{(1+CL)} \qquad [12]$$

Assuming the fraction of the coarse material in the mill load (R_l) is the arithmetic mean of the fraction in the feed and discharge, the fraction of coarse material inside the mill load (R_l) should be:

$$R_l = \frac{R_f + R_d}{2} = \frac{\left(1 + \frac{d-a}{2} + CL - \frac{d}{E}\right)}{(1 + CL)} \qquad \text{(Adding equations 10 \& 12)} \qquad [13]$$

According to the well-known first-order grinding law, the production rate of fines is equivalent to the rate of disappearance of coarse material and is proportional to the amount of coarse material in the mill (Austin, 1984; Napier-Munn *et al.,* 1996). The following equation describes the first order grinding law:

$$Q = \frac{dM}{dt} = \frac{dR}{dt} \infty R \qquad [14]$$

Where M is the amount of fine product, R is the amount of coarse material, k is the grinding rate constant, and t is the grinding time.

Thus, it is easy to consider the capacity of a ball mill is proportional to the fraction of coarse material inside the mill:

$$Q \infty R_l$$

$$Q = k' * R_l$$

$$Q = k' * \frac{\left(1 + \frac{d-a}{2} + CL - \frac{d}{E}\right)}{(1 + CL)} \qquad [15]$$

The rate of production of fines in the mill can also be shown as:

$$Q = \frac{dM}{dt} = C * c - A * a - B * b = A * (d - a) \qquad \text{(From equation 4)} \qquad [16]$$

$$k' * \frac{\left(1 + \frac{d-a}{2} + CL - \frac{d}{E}\right)}{(1 + CL)} = A * (d - a) \qquad \text{(From equation 15 \& 16)} \qquad [17]$$

Therefore, the mill circuit capacity:

$$A = k' * \frac{\left(1 + \frac{d-a}{2} + CL - \frac{d}{E}\right)}{(1 + CL) * (d - a)} \qquad [18]$$

For different circuits,

Relative capacity K_r can be derived:

$$\boldsymbol{K_r = \frac{A_1}{A_2} = \frac{(d_2 - a_2) * (1 + CL_2)\left(1 + \frac{d_1 - a_1}{2} + CL_1 - \frac{d_1}{E_1}\right)}{(d_1 - a_1) * (1 + CL_1)\left(1 + \frac{d_2 - a_2}{2} + CL_2 - \frac{d_2}{E_2}\right)}} \qquad [19]$$

RESULTS AND DISCUSSIONS

The developed equation [19] provides the ratio of the capacities of a ball mill closed grinding circuit (at different operational conditions) considering the real-life plant scenarios. For the case with no fines (< x microns) in circuit feed and only fines in circuit product i.e., d =1 and a =0 in Figure 6 and Table II, the fraction of fines generated is (d – a), and equation [19] can be reduced to the equation [20] below.

$$K_r = \frac{(1 + CL_2)\left(1.5 + CL_1 - \frac{1}{E_1}\right)}{(1 + CL_1)\left(1.5 + CL_2 - \frac{1}{E_2}\right)} \qquad [20]$$

This equation is the same as developed by Magdalinovic N (1991) and validated by Jankovic & Valery (2013) using ball mill grinding tests conducted by Guest (1972) and Morrell (2008). As the developed equation considers a broader range of parameters actually seen in plant conditions, but for particular feed and product constraints, it is the same as Magdalinovic N, (1991) 's equation. It is safe to conclude that the data used to validate the work of Guest, (1972); A Jankovic & Valery, (2013); and Morrell, (2008b) can also be valided within the developed equation in this paper. Considering that with the increase of the classification efficiency and circulating load, the capacity of the mill increases without additional energy consumption, it follows it reduces the consumption of grinding energy per unit of finished material produced. Thus, the developed formula enables us to calculate the reduction in energy consumed in the production of each ton of PGM, empowering us to produce more environmentally sustainable metals. Theoretically, the grinding circuit capacity can be increased by increasing the circulation load and classification efficiency. But in traditional circuits with cyclones or rake classifiers, the classification efficiency depends on the circulating load. As highlighted by Hukki & Eklund (1965) and shown in Figure 4, the circulating load increases and the classification efficiency decreases . This mutual dependency diminishes the effects of increasing circulation load on the capacity. Moreover, higher pumping and piping capacity requirements to handle high circulation load is also a concern. On the other hand, the classification efficiency was also a limitation with cyclones, rake, and screw classifiers. Though screens have a high classification efficiency, the requirement of a higher plant area to cater high throughput in grinding circuits was a challenge. Although, the recent development of Stack Sizer and Super Stack technology provided high-frequency screen installation with high throughput and classification efficiency. The Derrick high-frequency fine screens provide classification efficiency in the range of 85 to 95% (Albuquerque *et al.,* 2008; Valine & Wennen, 2002). With the advent of Derrick's high-frequency screening technology, grinding circuits can operate at higher capacity with high classification efficiency and normal circulation load (80 – 160%) instead of high circulation load and low classification efficiency. The higher classification efficiency of the high-frequency fine screens can be applied to closed-circuit grinding mills to increase the capacity by 10 – 35% and decrease specific energy requirements in metal production. Screens can easily be retrofitted in existing closed grinding circuits as the recent technological advances require only a limited area for installation.

Case Study

Many data published by Jankovic & Valery, (2013) and Magdalinovic N, (1991) validated the equation they developed, and those data should also validate the new equation developed in this paper. Albuquerque *et al.,* (2008) presented data from the CIA Minera Condestable mine in Peru comparing cyclone and fine screening performance. In this case, the application of fine screening increased the classification efficiency from 62% to 85%, as shown in Table III. As per the developed formula, the expected capacity increment for the circuit is 18 % which is similar to the actual plant capacity increment of 17 – 26 %.

Table III. Key circuit parameters at CIA Minera Condestable Mine for hydrocyclone and screen circuit

Parameter	**Cyclone**	**Screen**
a	0.092	0.092
d	0.794	0.801
E	**0.63**	**0.85**
CL	2.04	0.96

Equivalent results have been obtained with fine screens installed in PGM operations in Africa. Details are available upon request.

CONCLUSIONS

Improvements in classification efficiency are a better option for increasing capacity for ball mills in a closed circuit owing to limited improvements by increasing circulation load. The developed mathematical model predicts the relative capacity of a closed grinding circuit as a function of circulating load and classification efficiency. The closed circuits with screens can achieve a higher capacity through increased classification efficiency than a circuit using hydrocyclones. Practically, there is a potential for increasing the capacity by 10 to 35% and decreasing energy consumption per unit of metal production through existing fine screening technology.

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