# Development of Fine High-Pressure Grinding for Mineral Processing Plants

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## Abstract

Foretelling the obsolescence of wet ball milling, Corem and the University of British Columbia collaborated with two processing plants and multiple equipment manufacturers to develop, and pilot-plant test, its replacement with high-pressure grinding. They succeeded in demonstrating industrial readiness with circuit equipment that is all widely used today. The Functional Performance Equation revealed enormous synergy between classification and compression zone grinding performances, contributing to the reduction of total circuit energy usage and projected operating costs by over half. This paper presents the work leading to the discovery of the exceptional efficiency of high-pressure grinding in this role.

## Keywords

Fine high-pressure grinding, wet secondary grinding, mineral separation circuit feed grinding/preparation

## Introduction

Wet grinding ball mills are the workhorses for size reduction in the minerals industry, typically responsible for approximately half of the plant energy used for comminution. Although high-pressure grinding rolls (HPGR) have been found to be effective replacements for other comminution equipment, their potential use for replacing wet ball milling has not been explored. The Natural Resources Canada "Crush It Challenge" provided the opportunity to explore the replacement of wet ball mills with HPGR. Corem partnered with the University of British Columbia (UBC), Porcupine Gold Mine (PGM), Copper Mountain Mine (CMM), and equipment providers including Weir Minerals, Derrick Manufacturing, Koppern Equipment, Thyssenkrupp, Andritz, and FL Smidth. As one of six "Crush It Challenge" semi-finalists, a C$800K grant was received to pursue a target of at least a 20% reduction in mineral processing plant comminution energy use. This was hopefully to be achieved by a large decrease in milling circuit energy with the use of HPGR instead of ball mills. An added driving force is the related potential reduction in green house gas (GHG) emissions, which could be significant industry wide.

## Method

### TESTWORK SUMMARY AND THE PLANT CASE STUDIES

The two plant comminution circuits were audited for performance evaluation, specifically the ball milling circuit comminution energy consumption. As well, large samples were collected for (a) preliminary testwork (to guide the design of the pilot circuit) and for (b) the eventual comparative pilot HPGR circuit testing. Work Index Efficiency (Global Mining Guidelines Group, 2016) and Functional Performance Analysis (McIvor, 2006) were to be applied to compare plant ball mill circuit to pilot plant HPGR circuit energy use. In addition to mineralogical analyses, gold gravity and leaching tests were to be performed on Porcupine plant and pilot plant circuit products, and flotation tests similarly were to be performed on the two Copper Mountain circuit products.

Project testwork was carried out in six steps.

A. The two, plant ball mill circuit audits, with accompanying sample collections for testwork.
B. Preliminary classification, dewatering, and high-pressure grinding rolls testing.
C. Piston-press testing for preliminary operating parameter evaluations and for scale-up.
D. Rolls surface wear testing.
E. The pilot plant circuit tests.
F. Comparative circuit product characteristics and downstream mineral separation testing.

Some key aspects of the work are presented here. A summary has been presented at the annual Canadian Mineral Processors Conference by Gagnon et al. (2022), and many more details may be found in the full report (Gagnon et al., 2021).

The plant case studies offered two distinct examples of industry ball milling circuits. They are described in Table 1 and the flowsheets are given in Figure 1 and Figure 2.

Table 1—Porcupine and Copper Mountain Grinding Circuit Descriptions

| Description | Porcupine Gold Mine | Copper Mountain Mine |
|---|---|---|
| Ore Type | Gold | Copper porphyry |
| Grinding Circuit | ‘A’ rod + ball mill | SAG/peb.cr. + ball mills |
| Grinding Circuit Feed Rate (mt/h) | 143 | 1760 |
| Typical Target $P_{80}$ (μm) | 106 | 212 |
| Ore Specific Gravity | 2.7 | 2.8 |
| Grinding Installed Power (MW) | 2.1 | 41.5 |
| Ore Bond Ball Mill WI (kWh/mt) | 15 | 21 |
| Beneficiation circuit | Gravity—Leaching | Flotation |

Ed. Note: the authors have elected to use ‘mt’ for metric tonnes.

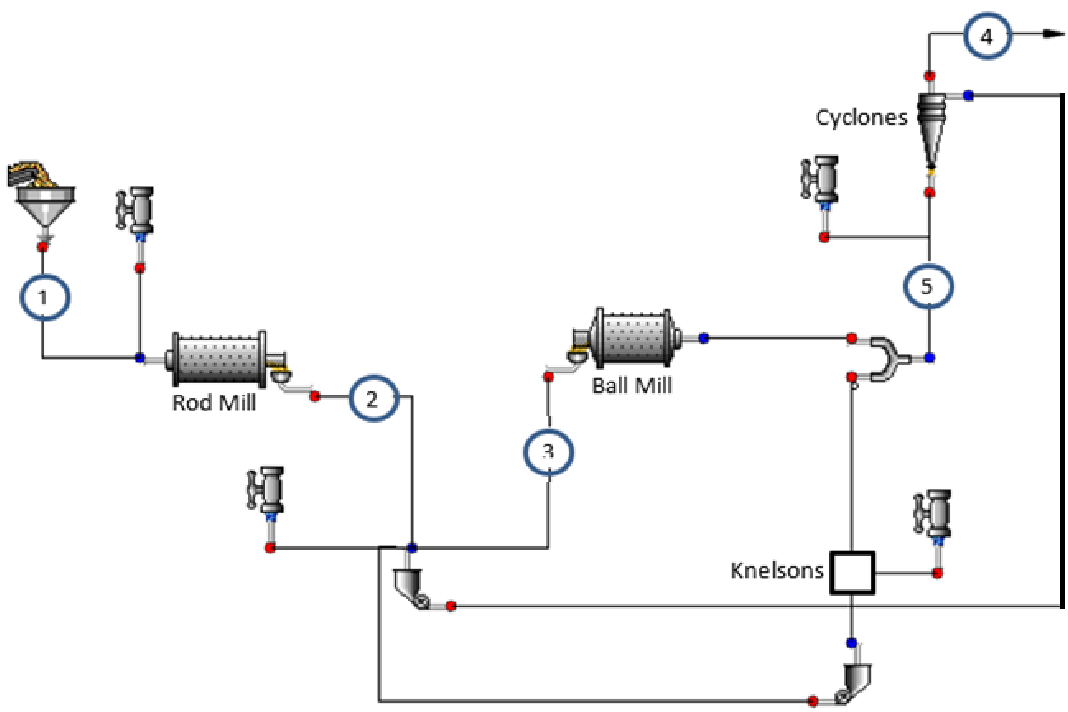


Figure 1—The Porcupine Gold Mine ‘A’ Grinding Circuit

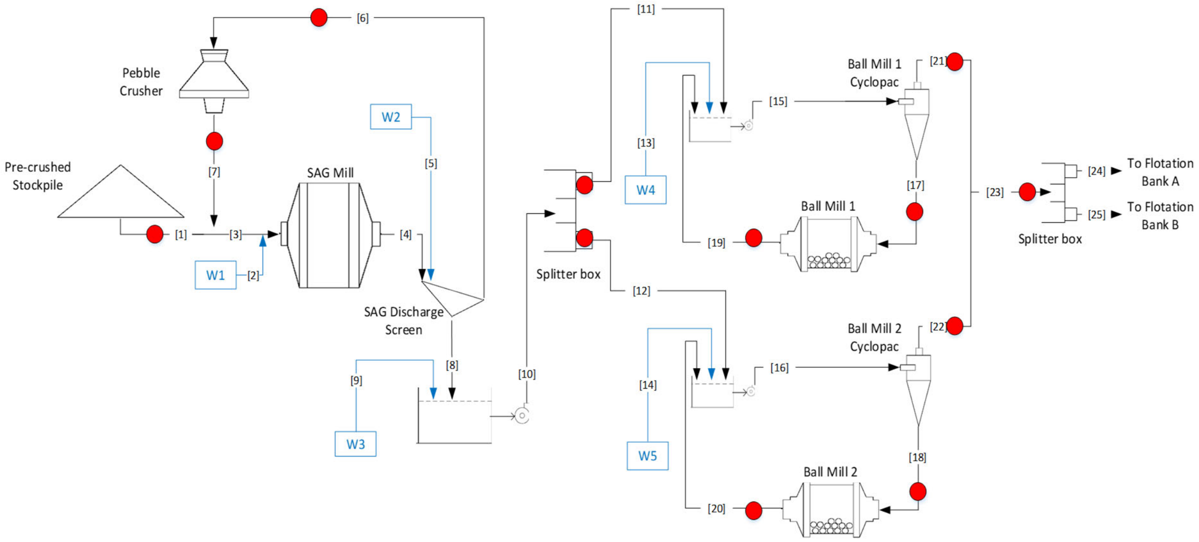


Figure 2—The Copper Mountain Mine Grinding Circuit

## PRELIMINARY TESTWORK

### Preliminary Classification, Dewatering, and High-Pressure Grinding Rolls Testing

Copper Mountain and Porcupine cyclone underflow samples were used as proxies of expected classifier oversize streams in the HPGR circuit for preliminary testing. Slump tests on these samples at different moistures indicated the need to achieve moisture levels in the range of 10%–12% to reduce fluidity to the point where their behavior was more like a paste than a liquid. Tests feeding the pilot rolls at different moistures showed the need to achieve 11% moisture for PGM and 9% moisture for CMM for them to behave suitably in the rolls. Exploration and testing of many different classification and dewatering equipment performances also rapidly led to the conclusion that the new flowsheet should employ fine screening followed by filtering of screen oversize to feed the rolls. As well, this equipment arrangement could be reproduced in the pilot plant batch locked-cycle tests. As 9% moisture by weight (21% by volume for PGM with ore SG=2.7, and 22% by volume for CMM with ore SG =2.8) was readily achievable by low vacuum, high capacity (belt or table) filtering, this value was specified as the moisture in the solids to feed the rolls in the pilot plant circuit tests. The resulting details of the pilot plant flowsheets are described in the section on the pilot testing that follows.

Rolls surface wear testing was conducted at the Thyssenkrupp laboratories in Germany on plant cyclone underflow samples. While the small diameter of the wear test rolls limited the moisture at which they successfully draw in the material, increasing sample moisture from 1% to 3% indicated no detrimental effect of increasing moisture on rolls surface wear. Based on comparisons with similar materials, wear life expectancy of roll liners was indicated to be approximately one year for the highly siliceous PGM ore, and about double that for CMM.

### Piston Press Testing

Purposes of piston press testing were twofold. First, suitable design pressure and other operating conditions were explored with batch tests conducted on plant cyclone underflow samples. Secondly, locked-cycle tests were conducted on plant ball mill circuit feed samples to compare how piston press test results, in terms of specific energy consumption, would compare to the larger scale pilot plant tests (which are assumed also to represent full-scale equipment). This relationship might then provide a means of estimating preliminary energy requirements of HPGR equipment in this role during early mine project studies when test samples are very limited.

The piston press equipment used at UBC is shown in Figure 3, along with a typical force-displacement curve used to calculate energy input during compression of the test sample. The die container holds 240 millilitres of test feed material which has been crushed and screened to all pass 12.5 mm.

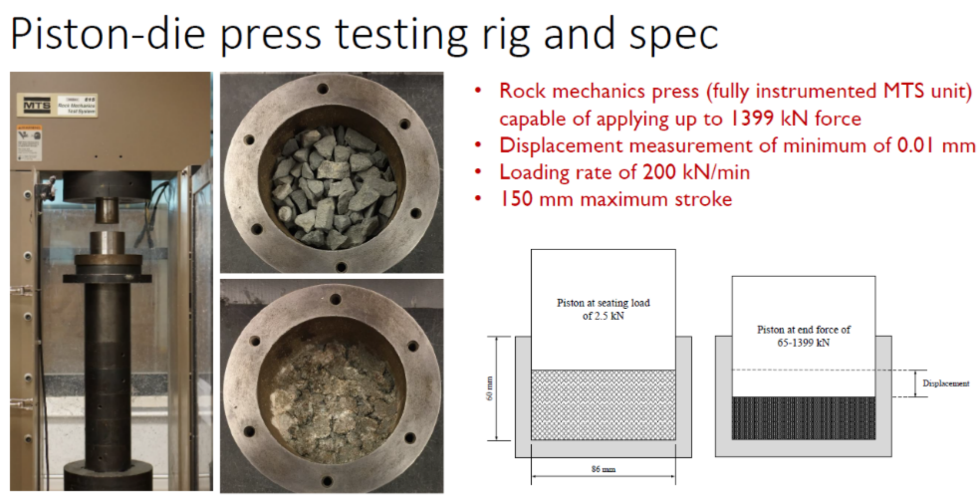


Figure 3a—UBC Piston Press Equipment

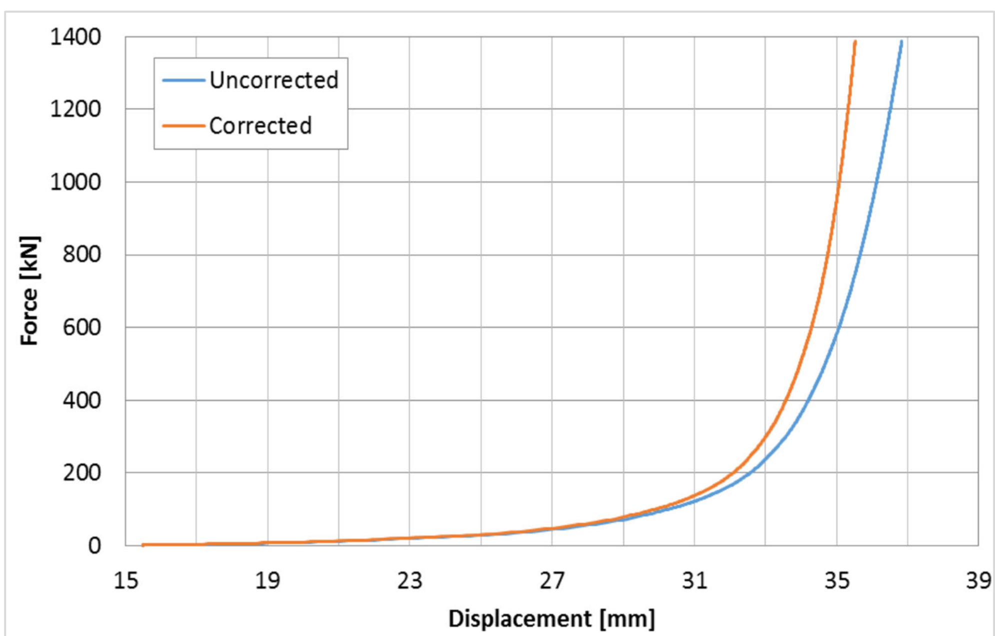


Figure 3b—Example Force-Displacement Curve with Correction for Piston Die Assembly Strain

Piston press batch testing was carried out on PGM and CMM plant circuit cyclone underflow material at UBC in order to explore the effects of varying machine pressure, moisture content, and fines content on the size reduction performance of the piston-press machine. Moistures from 3%–9% were shown to have little or no effect. But it was from this testing that the extraordinary effect of removing fines from the test feed sample had on grinding efficiency was discovered using the Functional Performance Equation. Work Index analysis alone indicated a 10%–15% increase in efficiency with fines removal, but grossly underestimated the grinding efficiency improvement because of the relatively small shifts in the $P_{80}$, versus the larger increases in product-size material generated during the piston press testing.

The Functional Performance Equation has been applied broadly to characterize the performance of (1) ball milling circuits (McIvor, 2006). The same equation can be applied to any fine comminution circuit, including (2) the batch (open circuit) piston press tests carried out on the cyclone underflow (ball mill feed) samples, (3) locked-cycle piston press tests, and (4) the HPGR pilot plant circuits. To conduct Functional Performance analysis, a reference particle size, such as the grind target $P_{80}$, is chosen to differentiate between 'fine' (larger than product size) material, and its 'coarse' (plus product size) counterpart. From a circuit sampling survey, or, in this case, from a single pass (batch, or open circuit) test, the production rate of new fine product size material is calculated from the circuit tonnage rate (or mass tested) and the percentage of 'fines' in the circuit feed and product streams (or mass tested). This new product size production rate is generated from grinding 'coarse' material via the mill (or any machine, such as the piston press, or HPGR) power being applied to it.

*Production Rate of Fines = Power Applied to Coarse x Machine Grinding Rate of Coarse* (1)

The *Power Applied to Coarse* is equal to the *Total Machine Power* times the percentage of coarse material inside the machine. This percentage is estimated by taking the average of coarse material in the machine feed and discharge. This value represents the useful application of machine power and is dependent on factors related to the setup of the classification equipment, grinding residence time, etc., and is termed the circuit "Classification System Efficiency", or "CSE."

*Production Rate of Fines = Total Machine Power x CSE x Machine Grinding Rate of Coarse* (2)

We can measure the material grindability, as done in a Bond test, providing a standard, laboratory grindability, in grams per revolution. By taking the ratio of the *Machine Grinding Rate* over the standard laboratory test grindability, we have a relative measure of the machine's grinding efficiency. That is:

*Machine Grinding Efficiency = Machine Grinding Rate of Coarse / Material Grindability* (3)

Divide the *Machine Grinding Rate of Coarse* in Equation 2 by *Material Grindability* to obtain *Machine Grinding Efficiency*, and multiply by *Material Grindability* to balance the equation. The result is the Functional Performance Equation.

*Production Rate of Fines =* (4)

*Total Machine Power x CSE x Machine Grinding Efficiency x Material Grindability*

When comparing tests on the same material, grindability remains fixed, so *Machine Grinding Rates of Coarse* can be compared directly.

*Production Rate of Fines = Total Machine Power x CSE x Machine Grinding Rate of Coarse* (2)

During the PGM ball mill circuit survey, at 150 µm, the *Production Rate of Fines* (minus 150 µm) is calculated from the circuit feed and product size distributions and circuit tonnage.

*Production Rate of Fines = (% fines in circuit product - % fines in circuit feed) x tonnage rate*

*= (89.7%–28.1%) x 143 t/h = 88.1 t/h*

The CSE is equal to the average of the % coarse in the ball mill feed and discharge:

*CSE = (% in feed + % in discharge)/2 = (75.2 + 60.5) / 2 = 67.9%*

Then

*Ball mill Grinding Rate of Coarse = (Production Rate of Fines) / (Total Machine Power x CSE) =*

*= 88.1 t/h / (1454 kW x 67.9%) = 0.089 t/kWh.*

The ball mill is producing 0.089 mt of new minus 150 µm product size material for each kWh of energy applied to the plus 150 µm material within it.

Batch piston tests at four different pressure levels, each at 3%, 6%, and 9% moisture, were performed as is, and with fines removed, on samples of both cyclone underflows. CSE for each PGM test was calculated as the average percentage of the plus 150 µm in the piston press feed and product size distributions. As these are also the circuit feed and product for these tests, the new material generated by the (open) circuit, this facilitates calculation of the piston press grinding rate of plus 150 µm size material. The same was done for CMM using minus 250 µm, in this case as, the definition of "fines."

As an example, in one batch test the die was loaded with 382 g (0.000382 t) of PGM test feed (cyclone underflow) which was 83.5% plus 150 µm. The force-displacement curve provided a total energy (work) input of 0.512 Watt-hours, equivalent to specific energy input on the whole sample of 1.34 kWh/t. The test product was 64.2% plus 150 µm. Therefore:

CSE = (83.5% + 64.2%) / 2 = 73.9%. The amount of coarse material being ground during the test averaged (73.9% of 382 g =) 282 g.

Specific energy applied to coarse = 73.9% of 1.34 kWh/t = 0.99 kWh/t

The amount of new minus 150 µm material produced was (83.5%–64.2%) x 382 g = 66.0 g (0.000066 t)

66 grams was produced from 0.99 kWh/t applied to 282 g (0.000282 t) of plus 150 µm material.

The energy input (in kWh) was 0.99 kWh/t x 0.000282 t = 0.000279 kWh

Therefore, the grinding rate of the plus 150 µm material during this test was 0.000066 t / 0.000279 kWh = 0.24 t/kWh.

Variability of relative grinding rates between piston press tests without and with fines removed was high, from 1.0 to 1.6 times higher grinding rates with fines removed, with other test conditions held constant. However, both sets of 12 pairs of tests averaged 1.27 times higher grinding rate with the fines removed. See Figure 4 summarizing piston test results on the PGM cyclone underflow (ball mill feed) sample collected for preliminary testing. Although similar (but not identical) to the survey ball mill feed, one may note comparative grinding rates of the piston press are all much higher than the grinding rate in the PGM ball mill of 0.089 t/kWh.

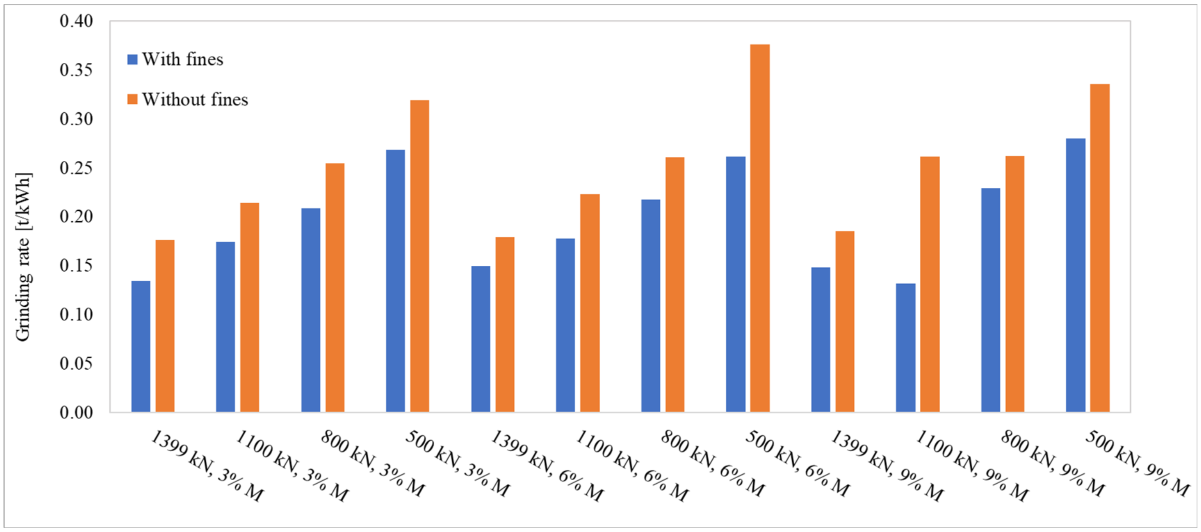


Figure 4a—PGN Ball Mill Feed Sample Piston Press Grinding Rates

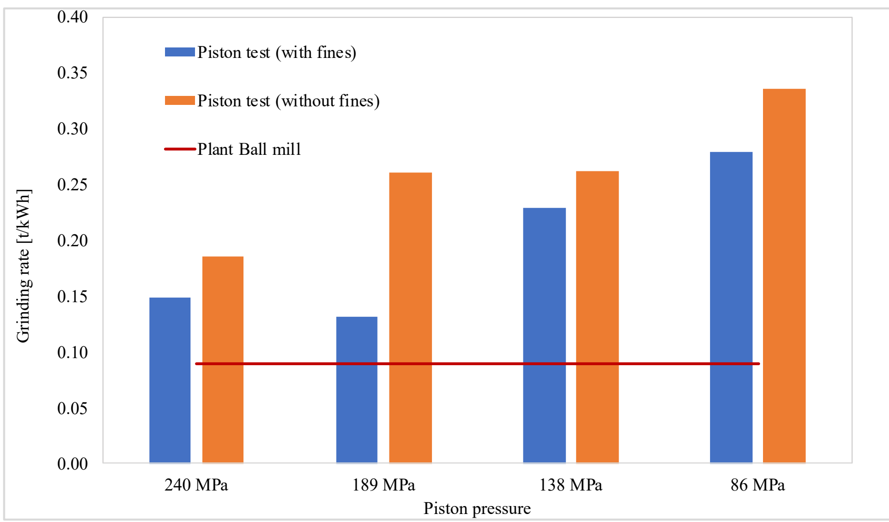


Figure 4b—PGN Mill Feed Sample Piston Press Grinding Rates at 9% Moisture

Thus, Functional Performance Analysis of the high-pressure, open-circuit piston press testing was instrumental in revealing, also quantifying, the major discovery that grinding efficiency on the coarse material increased 25% to 30% in the absence of the "fines". Apparently, breakage of "coarse" particles in the high-pressure compression zone takes place far more effectively without the presence of fine particles among them.

This discovery boded well for the project objective of maximizing energy savings. It also stressed the importance of good fines removal by the circuit classifier to achieve high HPGR grinding efficiency, in addition to the duty of not sending finished size material back to the machine. Subsequent piston press testing has shown that the energy efficiency benefit of fines removal is progressive with the portion of fines removed from the HPGR machine feed. This suggests that an economic trade-off can be found between fines removal and the cost of highly effective (in terms of fines removal performance) classifiers.

Locked-cycle piston press tests were carried out on both ball mill circuit feed samples. Material moisture was maintained at 9%. The test was designed similarly to a Bond ball mill grindability test, using a closing screen to achieve a $P_{80}$ similar to that of the plant (and subsequently the pilot plant). Similar to a Bond ball mill Work Index test, fresh (circuit) feed is used to make up for material removed during each screening cycle, and the test is continued until equilibrium is reached. Circulating load cannot be fixed, but rather is a function of the amount of size reduction per piston press grinding cycle. A comparison of the results between these tests and the pilot plant tests is given later. Once again, the results can be expressed and compared most meaningfully in terms of the CSE and machine grinding rate.

## THE PILOT PLANT TESTING

PGM ball mill circuit feed material was locked-cycle, batch pilot tested at Corem using the Weir RP 2.0, 800 mm diameter by 250 mm wide, studded surface HPGR. A Sweco screen with an opening of 223 µm was chosen to provide final product sizing. Other test conditions included 9% rolls feed moisture, 3 N/sq. mm specific pressing force, rolls speed of 0.5 m/s, and zero gap of 5 mm. Seven cycles were completed. The steady-state solids mass flows are shown below (Figure 5). The pilot circuit $P_{80}$ was 124 µm, versus 108 µm in the plant. The pilot circuit specific energy consumption was 3.3 kWh/t, versus the plant ball mill circuit value of 10.2 kWh/t.

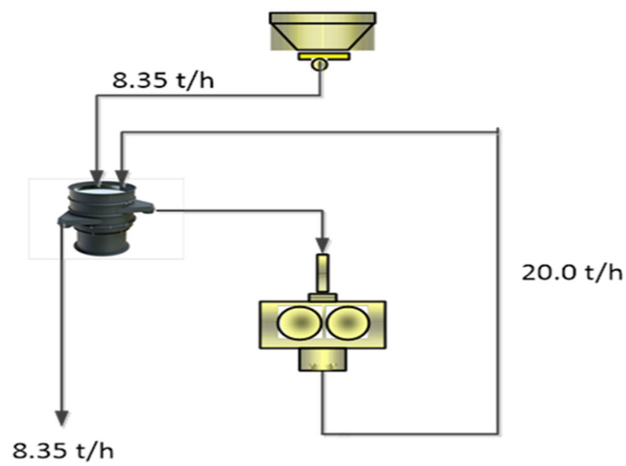


Figure 5—The PGM HPGR Pilot Plant Steady State Conditions

CMM ball mill circuit feed material was locked-cycle, batch pilot tested at UBC using the Koppern 750 mm diameter by 220 mm wide, Hexadur surfaced HPGR. An available Sweco screen with openings of 300 µm was chosen to provide final product sizing similar to the plant, which had a $P_{80}$ of 205 µm. Other test conditions included 9% rolls feed moisture, 3.5 N/mm$^2$ specific pressing force, rolls speed of 0.55 m/s, and a zero gap of 9 mm. Six cycles were completed. The steady state conditions are shown below (Figure 6). The pilot circuit $P_{80}$ was 192 µm. Specific energy consumption was 5.7 kWh/t, versus the plant circuit (two ball mills) value of 13.1 kWh/t.

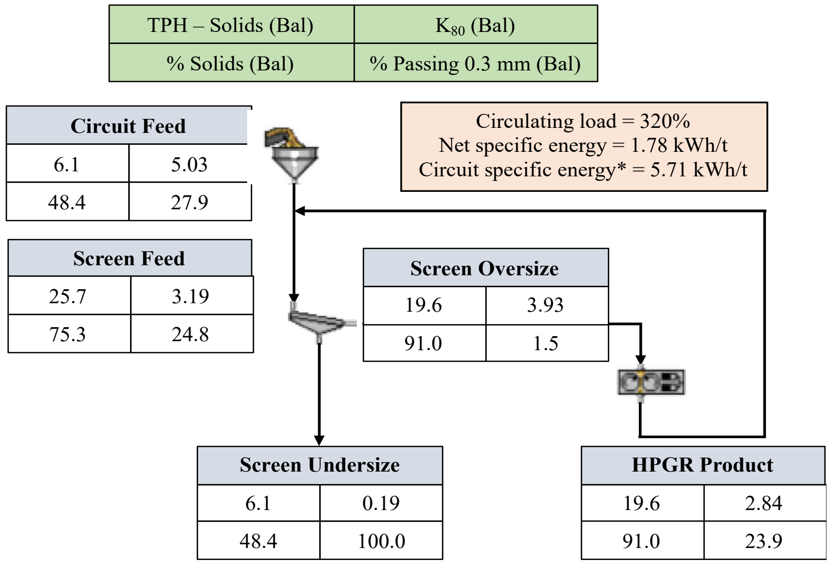


Figure 6—The CMM HPGR Pilot Plant Steady State Conditions

## Discussion

### COMPARATIVE PLANT AND PILOT PLANT PERFORMANCES

The plant (ball mill) versus pilot plant (HPGR) comminution machine energy usages were compared using Work Index Efficiency and Functional Performance analyses. These accounted for differences between plant audit circuit feeds and the pilot plant test samples that were collected just before (PGM) or after (CMM) the plant audits, as well as the differences in circuit product size distributions. Results are summarized in Table 2 through Table 5.

Table 2—Plant and Pilot Plant Work Index Performances for Porcupine Gold

| Description | Plant Ball Mill Circuit | HPGR Pilot Circuit |
|---|---|---|
| $F_{80}$ (µm) | 1,607 | 1,285 |
| $P_{80}$ (µm) | 108 | 124 |
| W (kWh/mt) | 10.2 | 3.31 |
| Wio (kWh/mt) | 14.3 | 5.35 |
| Test Wi (kWh/mt) | 15 | 14.9 |
| Wi Eff (Test Wi/Wio) | 105% | 279% |
| Eff Increase (Pilot/ Industrial) | - | 2.66 |
| Comminution Energy Reduction | - | 62% |

Table 3—Plant and Pilot Plant 150 µm Functional Performances for Porcupine Gold

| Description | Plant Ball Mill Circuit | Pilot HPGR Circuit |
|---|---|---|
| Fresh Feed Rate (mt/h) | 143 | 8.35 |
| Mill Power (kW) | 1454 | 27.6 |
| %Passing 150 µm in Fresh Feed | 28.1 | 29.8 |
| %Passing 150 µm in Circuit Product | 89.7 | 86.9 |
| %Retained 150 µm in Mill Feed | 75.2 | 100 |
| %Retained 150 µm in Mill Discharge | 60.5 | 76.3 |
| Circuit Fines Production Rate (mt/h) | =143 x (89.7-28.1) = 88.1 | =8.35 x (86.9-29.8) = 4.8 |
| Classification System Efficiency (CSE) | = (75.2 + 60.5)/2 = 67.9 | = (100+76.3)/2 = 88.2 |
| Bond Test Grindability (g/rev) | 1.71 | 1.8 |
| Machine Grinding Efficiency | 0.0522 | 0.1087 |
| CSE Ratio (pilot/ industrial) | -- | 1.3 |
| Machine Grinding Eff Ratio (pilot/ industrial) | -- | 2.08 |
| **Total Circuit Efficiency Increase** | | **2.71** |

PGM Work Index Efficiency showed a factor of 2.7 times increased energy efficiency for pilot plant HPGR versus plant ball milling. Functional Performance Analysis attributed close to 1.3 of this to higher CSE, and a factor of just over 2 from machine comminution efficiency. These combine to provide a 62% comminution machine energy saving with HPGR over ball milling.

Table 4—Plant and Pilot Plant Work Index Performances for Copper Mountain

| Description | Plant Ball Mill | Pilot HPGR |
|---|---|---|
| $F_{80}$ (µm) | 4,100 | 5,030 |
| $P_{80}$ (µm) | 205 | 192 |
| W (kWh/mt) | 13.1 | 5.39 |
| Wio (kWh/mt) | 24.2 | 9.28 |
| Test Wi (kWh/mt) | 20.8 | 21.1 |
| Wi Efficiency (Test Wi/Wio) | 86% | 227% |
| Efficiency Improvement | - | 2.64 |
| Energy Savings, % | - | 62 |

Table 5—Plant and Pilot Plant 212 µm Functional Performances for Copper Mountain

| Description | Plant Ball Mill Circuit | Pilot HPGR Circuit |
|---|---|---|
| Fresh Feed Rate (mt/h) | 1760 | 6.1 |
| Mill Power (kW) | 23,088 | 32.9 |
| %Passing 212 µm in Fresh Feed | 26.2 | 24.0 |
| %Passing 212 µm in Circuit Product | 81.2 | 83.8 |
| %retained 212 µm in Mill Feed | 82.4 | 100 |
| %retained 212 µm in Mill Discharge | 69.4 | 81.4 |
| Circuit Fines Production Rate (mt/h) | 1,760 x (81.2 – 26.2) = 967 | 6.1 x (83.8 – 24.0) = 3.65 |
| Classification System Efficiency (CSE) % | (82.4 + 69.4)/2 = 76.0 | (100 + 81.4)/2 = 90.7 |
| Lab Grindability (g/rev) | 1.08 | 1.01 |
| Machine Grinding Rate (mt/kWh) | 0.055 | 0.122 |
| Machine Grinding Efficiency | 0.051 | 0.121 |
| CSE Ratio Pilot/Industrial | - | 1.20 |
| Machine Grinding Efficiency Ratio (pilot/industrial) | - | 2.37 |
| **Total Circuit Efficiency Increase** | | **2.84** |

CMM Work Index Efficiency showed a factor of 2.6 times increased efficiency for pilot plant HPGR versus plant ball milling. Functional Performance Analysis calculated a similar overall increased circuit efficiency factor of 2.8, attributing close to 1.2 of this value to higher CSE, and a factor of almost 2.4 from machine grinding efficiency. Once again, a 62% overall comminution machine energy savings was experienced with HPGR over ball milling.

That the calculated efficiency improvement for the two circuits came out as equal is coincidental. That the two ores responded similarly to HPGR treatment is not. Micro-cracking was substantially higher on both these ores than when conventionally comminuted, particularly in the gangue minerals (Makni et al., 2023). This means similar results are to be expected on other ores.

## COMPARATIVE PILOT PLANT AND PISTON PRESS TESTING RESULTS

The UBC locked-cycle piston test was carried out on samples of the pilot circuit feeds. Tables 6 and 7 summarize the locked-cycle piston press and pilot plant results for PGM and CMM. While still undergoing development, this shows that it is possible to make a reasonable prediction of larger equipment specific energy needs from these small-scale tests.

Table 6—Locked Cycle Piston-Press and Pilot HPGR Test Results on PGM Sample

| Description | Piston Press Results | HPGR Results |
|---|---|---|
| Specific Pressing Force ($N/mm^{2}$) | - | 3.25 |
| Piston Pressure (MPa) | 189 | - |
| Specific Energy per Pass (kWh/mt) | 1.28 | 1.38 |
| Circulating Load (%) | 252 | 240 |
| Circuit Specific Energy (kWh/mt) | 3.23 | 3.31 |
| $P_{80}$, mm | 0.126 | 0.124 |
| Machine Grinding Rate @ 212 µm (mt/kWh) | 0.275 | 0.230 |

Table 7—Locked Cycle Piston-Press and Pilot HPGR Test Results on CMM sample

| Description | Piston Press Results | HPGR Results |
|---|---|---|
| Specific Pressing Force ($N/mm^{2}$) | - | 3.5 |
| Piston Pressure (MPa) | 189 | - |
| Specific Energy per Pass (kWh/mt) | 1.49 | 1.67 |
| Circulating Load (%) | 303 | 321 |
| Circuit Specific Energy (kWh/mt) | 4.51 | 5.38 |
| $P_{80}$, mm | 0.212 | 0.192 |
| Machine Grinding Rate @ 300 µm (t/kWh) | 0.200 | 0.153 |

While being further developed, these test results show that preliminary HPGR machine energy requirements can be determined from such small-scale tests. This opens the door to consideration of HPGR in this role for new applications at an early stage of study.

## CIRCUIT PRODUCT CHARACTERISTICS AND DOWNSTREAM MINERAL SEPARATION PERFORMANCES

This project is fully reported in another paper being presented here at SAG 23 (Makni et al., 2023). Briefly, HPGR circuit product size distribution was very similar to that from closed-circuit ball milling, producing no added extreme fines; micro-factures were significantly more abundant in high-pressure ground materials, especially in gangue minerals; total gold recovery from Porcupine ore by gravity and leaching was similarly very high for both types of circuits; and flotation performance of Copper Mountain ore was improved for the HPGR circuit product, reflecting the improved liberation shown by microscopic mineral liberation analyses.

## REPLACEMENT HPGR CIRCUIT DESIGNS AND OVERALL CIRCUIT ENERGY SAVINGS

Circuits employing HPGR at both locations would replace the ball milling circuits' pumps and cyclones with fine screening fed by pumping, dewatering of screen oversize to 9% moisture to feed the rolls, and collection of generously used water in screening by a product thickener (at Porcupine) or clarifier (at Copper Mountain). The initial designs of these circuits were necessary in order to provide the overall secondary grinding circuit energy savings shown below, not just that for the comminution machine itself. Energy savings are shown in Table 8. Details of the replacement circuit designs are provided elsewhere (Gagnon et al., 2021 and 2022).

Table 8—Summary of Energy Savings with HPGR Replacing Ball Milling

| | Porcupine Gold Mine (Circuit 'A') | Copper Mountain Mine Ball Mills |
|---|---|---|
| Ball Mill vs. HPGR Only | 62% | 62% |
| Ball Mill Circuit vs. HPGR Circuit* | 52% | 54% |
| Plant Comminution Circuit** | 28% | 30% |

*From grinding circuit feed to mineral separation circuit feed, including energy usage of grinding equipment and all auxiliary equipment, and ball mill grinding media embodied energy (Ballantyne et al., 2019).
**From "run-of-mine" concentrator feed to mineral separation circuit feed, including energy usage of all stages of crushing and grinding equipment, and total estimated values for energy usage of all auxiliary equipment and steel wear embodied energy.

The equivalent GHG emission reduction estimates (US Department of Environmental Protection, 2023) are:

- For PGM: 6,000 mt/y $CO_2$ equivalent
- For CMM: 93,000 mt/y $CO_2$ equivalent.

Corem recently compiled a list of wet secondary ball mills and their motors used in the Canadian metal minerals processing. Extrapolating the above values, total GHG emission reductions through industry wide implementation of this technology would total a reduction of approximately 1.8 million mt/y $CO_2$ equivalent.

## Conclusions and Future Work

Besides proving the concept and demonstrating the technical feasibility of replacing wet ball milling with high-pressure grinding, the most important outcome of this work is the comminution device energy savings measured of over 60%. The Functional Performance Equation empowered the discovery of greatly increased grinding efficiency in the compression zone of high-pressure grinding in the absence of fines, and facilitates comparison of the separate classification and grinding performances between the plant ball mill circuit, the piston-press in batch or locked-cycle mode, and the HPGR pilot plant. A greenfield flowsheet would offer the opportunity to optimize HPGR in this role beyond the constraints placed in this study to replace an existing ball milling circuit. Classification and dewatering equipment options continue to be further explored. A continuous demonstration circuit installation site is being sought, considered by the writers to be the best way to facilitate rapid industrial deployment of this technology.

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