

**REPLACEMENT OF WET BALL MILLING WITH HIGH-PRESSURE GRINDING  
AHEAD OF MINERAL SEPARATION**

C. Gagnon<sup>1</sup>, A. Rosa<sup>1</sup>, S. Makni<sup>1</sup>, and \*R. McIvor<sup>1</sup>

B. Klein<sup>2</sup>, A. Kumar<sup>2</sup>, F. Wang<sup>2</sup>, D. Gong<sup>2</sup>, and C. Saud<sup>2</sup>

<sup>1</sup>COREM

1180 rue de la Minéralogie

Quebec City, Quebec, Canada G1N 1X7

(\*Corresponding author: rob@metcomtech.com)

<sup>2</sup>University of British Columbia

Vancouver, B.C., Canada V6T 1Z4

**ABSTRACT**

In response to the Natural Resources Canada “Crush It Challenge”, Corem partnered with the University of British Columbia and led a project to develop and demonstrate the use of high-pressure grinding to replace the workhorse of the industry, wet ball milling, with high-pressure grinding. Two plant case studies, a small tonnage gold recovery operation, and a large tonnage copper recovery operation, were carried out. Plant circuit performances were compared to pilot plants operated on the same circuit feed set up to represent the novel equipment and flowsheet that was developed to produce separation circuit feed. Numerous obstacles to industrial implementation of high-pressure grinding in this role which were recognized at the outset of the work were successfully addressed. In both cases, comminution equipment energy savings alone, and final stage total circuit energy savings, exceeded 60% and 50%, respectively. Downstream mineral separation performance was the same or better.

**KEYWORDS**

**High-pressure fine grinding, mineral separation feed preparation**

## OBJECTIVE, CHALLENGES, OPPORTUNITY AND THE PROJECT TEAM

The objective of this work was to replace wet ball milling ahead of mineral separation with high-pressure grinding (HPGr).

A flow sheet envisioned at the start of the work is shown in Figure 1.

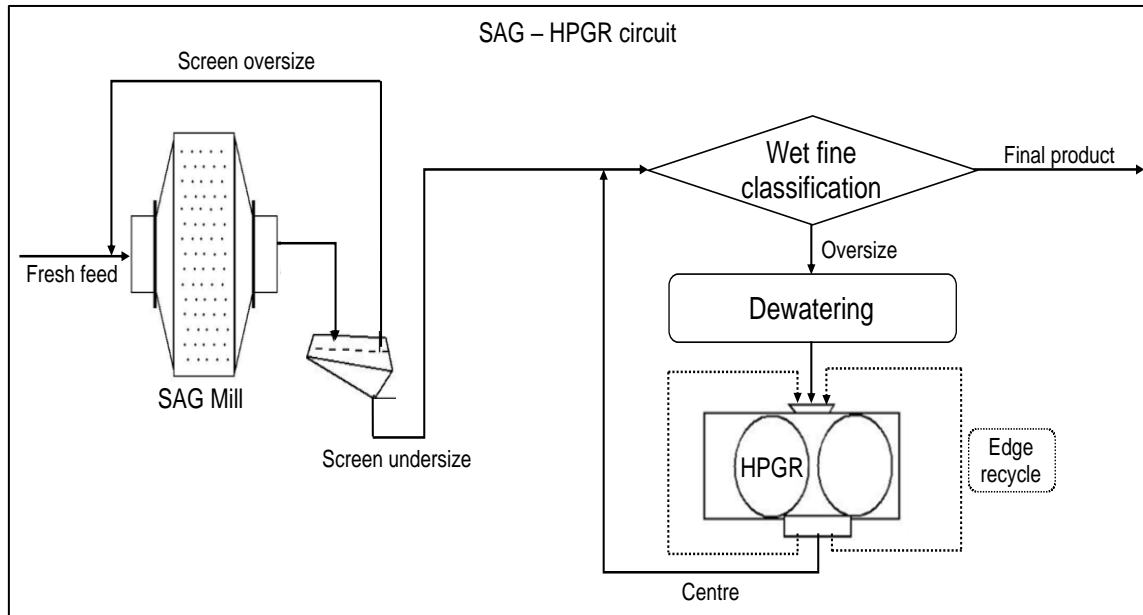


Figure 1 - Conceptual Flow Sheet Replacing Wet Ball Milling with HPGr

Although high-pressure grinding (HPGr) has made inroads into the minerals industry, collectively the numerous challenges faced to replace fine, wet, closed-circuit ball milling have meant that it has not been seriously considered for this role. Unaddressed issues included: How would very moist, fine material behave in the rolls? How much size reduction will take place on such feed? What degree of dewatering would be needed to feed the rolls, and what is the best way to achieve it? What energy savings over ball milling, if any, would be achieved? Would extreme rolls surface wear occur? Would an over-abundance of extreme fines be produced? How will downstream processes react? What classification method should be applied? What steps and arrangement would the flow sheet consist of? Is it possible to estimate HPGr energy needs from small-scale tests? And could the economics of such a circuit possibly be favorable?

The Natural Resources Canada “Crush It Challenge” provided the opportunity to assess this possibility. The COREM comminution team partnered with the University of British Columbia (UBC), which had long been researching and developing high-pressure grinding technology, to submit a proposal to investigate replacement of wet ball milling with HPGr. Several Canadian mineral processing plant operators were approached as potential case studies, including the two ultimate project participants, Porcupine Gold Mine (PGM) and Copper Mountain Mine (CMM). The proposal was accepted as one of six “Crush It Challenge” semi-finalists, each granted \$800K (Canadian) to pursue a target of 20% overall energy reduction in minerals industry comminution. This paper provides a summary of the results of that investigation.

The initial step was to expand the team and bring together as much expertise as possible to help plan and execute the project. Equipment manufacturers recruited were Weir Minerals and Koppers Equipment (whose pilot HPGr equipment were in place at COREM pilot facilities in Quebec City and UBC pilot facilities in Vancouver, respectively), Thyssenkrupp (the Germany based manufacturer of HPGr equipment), Derrick Manufacturing (the USA based manufacturer of fine screening equipment), and Weir

Minerals, once again, for their classification and dewatering equipment expertise. Later, FLSmidth and Andritz AG were also approached for their assistance and advice, as were Persio Rosario and Edward Wipf.

## GENERAL METHODOLOGY

Each of the two plant comminution circuits was to be audited for performance evaluation, in particular ball milling circuit comminution energy usage, and for collection of samples for preliminary test work (to guide design of the pilot circuit) and the eventual comparative pilot circuit testing itself. Work Index Efficiency (Global Mining Guidelines Group, 2016) and Functional Performance Analysis (McIvor, 2006) were to be applied to compare plant ball mill circuit and pilot plant HPGr circuit energy use performances. In addition to mineralogical analyses, gold gravity and leaching tests would be performed on Porcupine circuit products, and flotation tests would be performed on Copper Mountain circuit products.

## TEST WORK

Project test work was carried out in six areas.

- A. The two plant circuit audits and collection of samples for the test work.
- B. Piston press testing for preliminary operating parameter evaluations and for scale-up.
- C. Preliminary classification, dewatering, and high-pressure grinding rolls testing.
- D. Rolls surface wear testing.
- E. The pilot plant circuit test runs.
- F. Downstream mineral separation testing.

Only key aspects of the work, on which thousands of hours were spent over more than two years, are summarized here. Many more details may be found in the full report (Gagnon et al, 2021).

The plant case studies offered two typical, yet significantly different, examples of industry ball milling. They are described in Table 1 and the flowsheets are shown in Figures 2 and 3.

Table 1 - Comparison of Porcupine and Copper Mountain Grinding Circuits

Description	Porcupine Gold Mine	Copper Mountain Mine
Ore type	Gold	Copper porphyry
Grinding circuit	‘A’ rod + ball mill	SAG + ball mills
Grinding circuit feed rate (t/h)	143	1760
Grinding installed power (MW)	2.1	41.5
Ore competency	Medium	Very high
Beneficiation circuit	Gravity – Leaching	Flotation

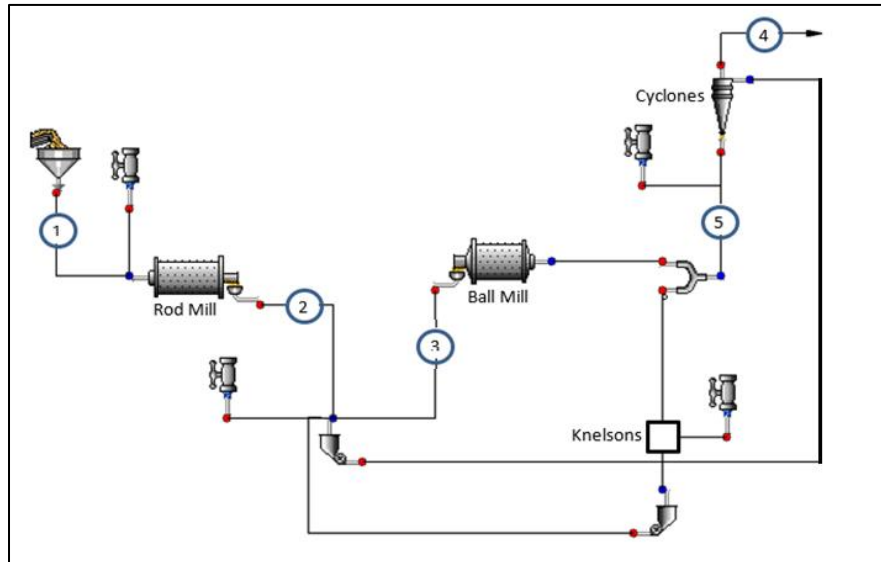


Figure 2 - The Porcupine Gold Mine 'A' Grinding Circuit Flow Sheet

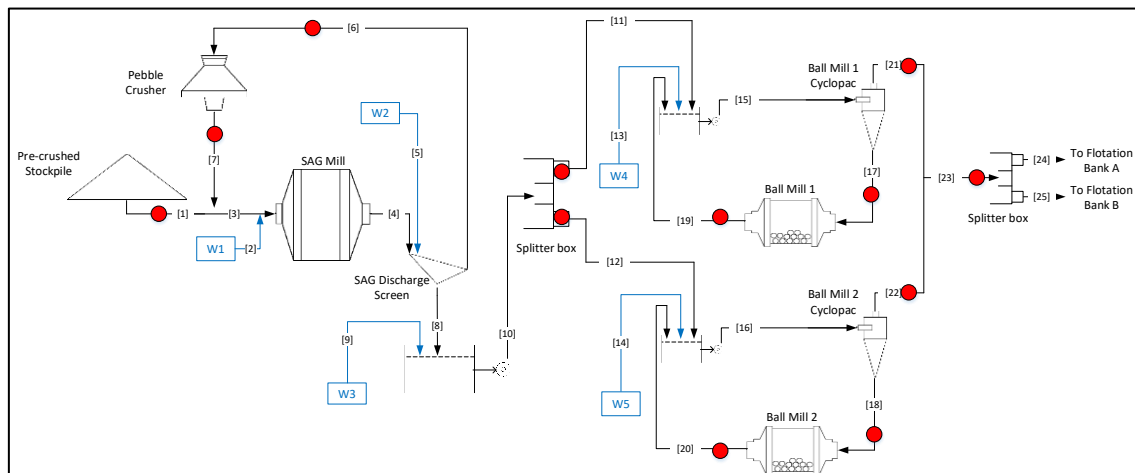


Figure 3 - The Copper Mountain Mine Grinding Circuit Flow Sheet

The measured circuit performances will be presented later with comparative results from the pilot plant runs with HPGr. Immediately before or after circuit sampling for the performance audits, large samples of ball mill circuit feed (rod mill discharge at PGM, and SAG screen undersize at CMM) were collected for the pilot plant runs. As well, large samples of both ball mill feed materials (cyclone underflows) were collected for preliminary piston press and pilot equipment testing, as this material would be similar in nature (i.e., classifier oversize) to the HPGr rolls feed in the pilot plant.

Piston press testing was conducted on the plant ball mill feed (cyclone underflow) materials for preliminary assessment of best design and operating conditions for the pilot rolls. As expected, specific energy increased linearly with pressure. Feed moisture in the range of 3-9% had no effect on the specific energy vs. energy input relationships, nor did it affect grinding performance. Also included were “as is” vs. fines removed (minus 150 microns for PGM, minus 250 microns for CMM) single pass tests. Analysis of

the data (test material F80's and P80's) by UBC showed increased reduction ratio and reduced Operating Work Index (in the range of approximately 10-15%) with the fines removed.

However, Functional Performance Analysis was also applied to the data, quantifying the separate effects that fines removal had on classification and on grinding. The Functional Performance Equation for ball milling circuits, but equally applicable to any fine grinding circuit, is derived as follows.

A reference particle size, such as the grind target  $P_{80}$ , is chosen to differentiate between 'fine' (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 machine such as the piston press, or HPGr rolls) power being applied to it.

$$\text{Production rate of fines} = \text{Power applied to coarse} \times \text{Machine grinding rate of coarse} \quad (1)$$

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.). It is termed the circuit "Classification System Efficiency", or "CSE".

$$\text{Production rate of fines} = \text{Total machine power} \times \text{CSE} \times \text{Machine grinding rate of coarse} \quad (2)$$

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:

$$\text{Machine grinding efficiency} = \text{Machine grinding rate of coarse} / \text{Material grindability} \quad (3)$$

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.

$$\text{Production rate of fines} = \text{Total machine power} \times \text{CSE} \times \text{Machine grinding efficiency} \times \text{Material grindability} \quad (4)$$

When comparing tests on the same material, grindability remains fixed, so Machine grinding rates of the coarse material can be compared directly. 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. While variability between tests was high, from 1.0 to 1.6 times higher grinding rates, depending on the other test conditions (pressure and moisture), both sets of 12 tests on each material averaged the same 1.27 times higher grinding rate with the fines removed over "as is". See Figure 4 summarizing subsequent confirmation piston tests, all conducted at 9% moisture, on CMM ball mill feed.

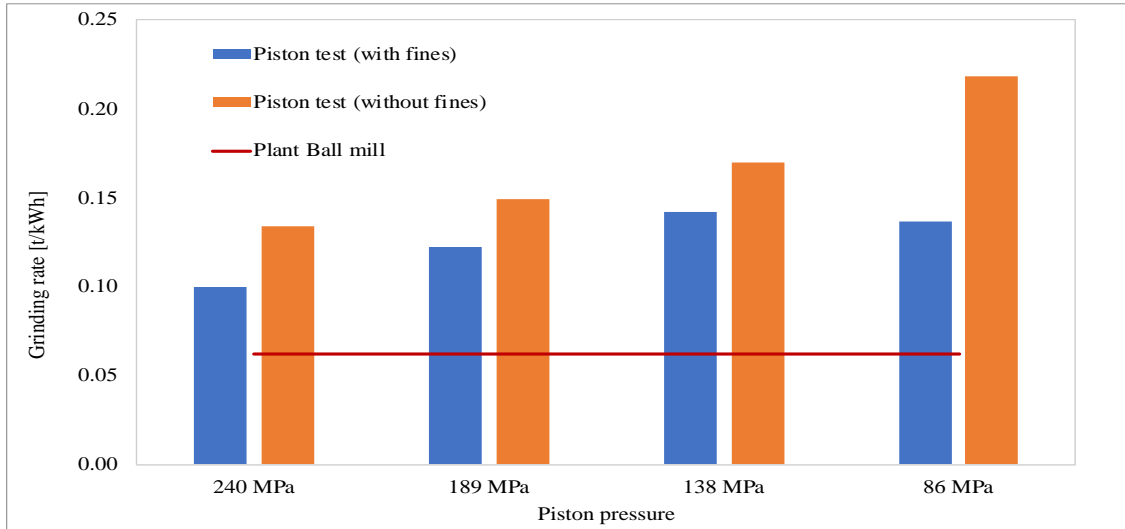


Figure 4 - CMM Ball Mill Feed Machine Grinding Rates With and Without Fines (9% Moisture)

Thus, Functional Performance Analysis of the high-pressure, open-circuit piston press testing provided the major discovery, and also quantified, that grinding efficiency on the coarse material (plus 150 and 250 microns, respectively) increased between 25 and 30% in the absence of the “fines”. Apparently, breakage of “coarse” particles in the high-pressure, packed bed takes place far more effectively without the interference caused by the presence of fine particles between them.

This discovery boded well for the project objective of maximizing energy savings. It also stresses the importance of good fines removal by the circuit classifier to achieve high machine grinding efficiency. This is in addition to the desired classifier duty of not sending finished size material to the machine, which itself wastes its space and energy, and results in overgrinding. It may be noted separately that CSE increased from an average of 65% to 80% (with fines removed) during the initial PGM piston tests, and from 72% to 85% (with fines removed) during the initial CMM piston tests.

Locked-cycle piston press testing was conducted on the circuit feeds to assess the capability of such small-scale test equipment to predict full (or pilot) scale HPGr equipment energy use. The test developed by UBC for this purpose is akin to a Bond locked-cycle test. Details of the development of this test will be reported elsewhere, and the results of the tests on PGM and CMM circuit feeds are compared to pilot plant data later in this paper.

An extensive review of all available size classification and dewatering equipment was carried out by UBC. This review also will be reported elsewhere.

Samples of both PGM and CMM cyclone underflows were sent to Derrick Manufacturing for pilot equipment testing for both sizing and dewatering. The desired outcome was to thoroughly wet screen for fines removal, and then to dewater the sizing screen oversize on a dewatering screen to feed the rolls. Screen undersize would proceed to downstream processing, with any needed additional dewatering/thickening step needed due to high water usage on the sizing screen. Pilot rolls experiments at different water/solids mixtures showed that 10% moisture by weight (or lower) was required for either screen oversize material (solids SG = 2.7) to be fed continuously and pass smoothly through the rolls without the water and solids separating and becoming unmanageable. The Derrick dewatering screen achieved 12-13% moisture. Therefore, remaining options for dewatering ahead of the rolls were large capacity, low vacuum (belt or table) filters, and centrifuges. Tests of both these equipment at Corem and UBC showed that 9% moistures were readily achievable from either. The filter option was assumed for this study, although the centrifuge, or other options,

remain open. Test feeds for the pilot circuit rolls test, conducted in locked-cycle batches, were to be achieved by mixing to the desired (9%) moisture, knowing that this was readily achievable.

Preliminary pilot rolls tests were also carried out on cyclone underflow samples to determine the best operating conditions for the pilot circuit tests, besides feed moisture. This included testing of pressing force, rolls speed, and zero gap setting.

Samples of both PGM and CMM cyclone underflows were also sent to Thyssenkrupp in Germany for “ATWAL” rolls surface wear testing at the higher than usual moistures to be encountered in this situation. While testing above 3% moisture was unsuccessful because of the small machine’s inability to draw in the feed, tests at 1% and 3% moisture showed little indication of excessive wear being caused by high moisture levels. While a matter for further investigation, this suggested that wear life of the roll liners could be predicted reasonably well from the 1-3% feed moisture tests. PGM material was classified as “moderate / highly abrasive”, yielding roughly 12 months predicted operating life of studded roll liners, while CMM material was classified as “low abrasive”, yielding roughly double that life.

The 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 rolls. An available Sweco screen with an opening of 223 microns was chosen to provide final product sizing similar to the plant, which had a P80 of 108 microns. 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 4). The pilot circuit P80 was 124 microns. The pilot circuit specific energy consumption was 3.3 kWh/t, versus the plant ball mill circuit value of 10.2 kWh/t.

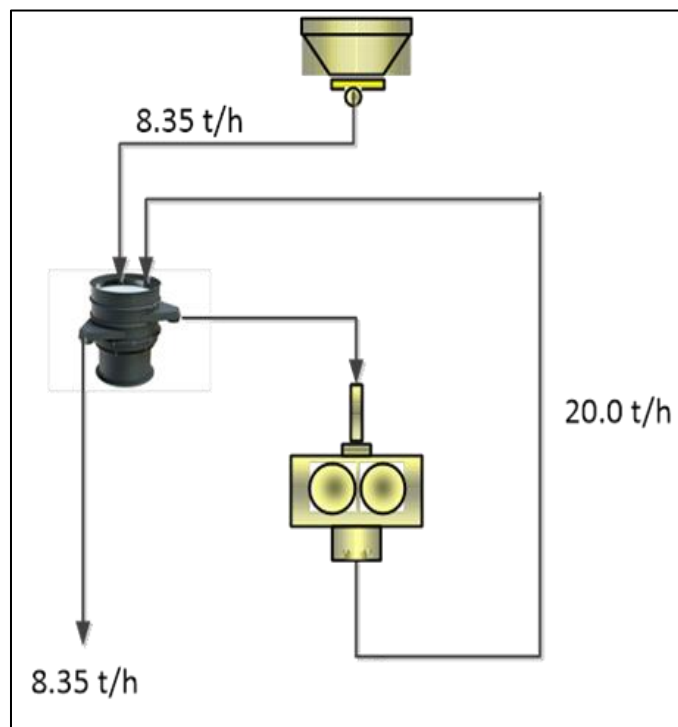


Figure 4 - The PGM Pilot Plant at Corem Steady State Conditions

The CMM ball mill circuit feed material was locked-cycle, batch pilot tested at UBC using the Koppers 750 mm diameter by 220 mm wide Hexadur surface HPGr rolls. An available Sweco screen with

openings of 300 microns was chosen to provide final product sizing similar to the plant, which had a P80 of 205 microns. Other test conditions included 9% rolls feed moisture, 3.5 N/sq. mm 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 5). The pilot circuit P80 was 192 microns. Specific energy consumption was 5.7 kWh/t, versus the plant ball mill circuit value of 13.1 kWh/t.

Metallurgical testing was carried out on the pilot HPGr circuit products, for comparison with samples of the same feed materials ground with laboratory grinding mills. The plant cyclone overflows could not be used for such purposes because of gravity gold recovery in the grinding circuit at PGM, and because of CMM flotation feed (cyclone overflow) sample aging.

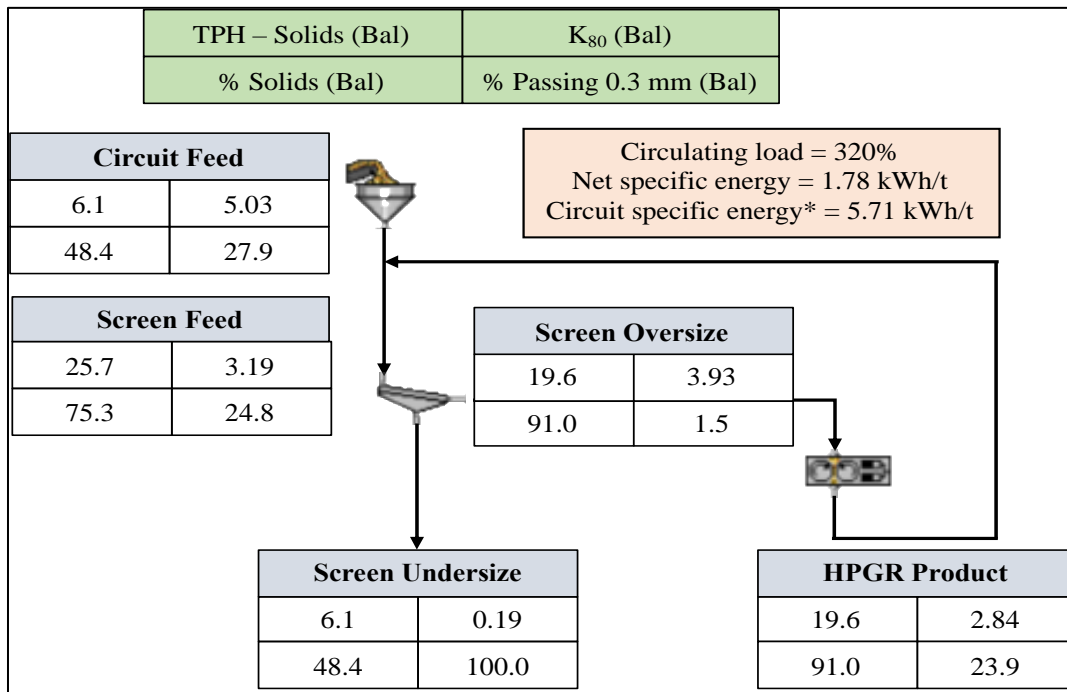


Figure 5 - The CMM HPGr Pilot Plant at UBC Steady State Conditions

## RESULTS

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 Tables 2 through 5.



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

Description	Plant ball mill circuit	HPGr pilot circuit
F <sub>80</sub> (µm)	1,607	1,285
P <sub>80</sub> (µm)	108	124
W (kWh/t)	10.2	3.31
W <sub>io</sub> (kWh/t)	14.3	5.35
Test W <sub>i</sub> (kWh/t)	15	14.9
W <sub>i</sub> Eff (Test/Operating)	105%	279%
Eff increase (Pilot/ Industrial)	--	2.66
Comminution energy reduction	--	62%

Table 3 - Plant and Pilot Plant Functional Performances for Porcupine Gold

Description	Plant Ball mill circuit	Pilot HPGR circuit
Fresh feed rate (t/h)Plant and Pilot Plant	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 (t/h)	=143 x (89.7-28.1) = 88.1	=8.35 x (86.9-29.8) = 4.8
Classification efficiency (CSE)	= (75.2 + 60.5)/2 = 67.9	= (100+76.3)/2 = 88.2
Bond test grindability (g/rev)	1.71	1.8
Mill grinding efficiency	0.0522	0.1087
CSE ratio (pilot/ industrial)	--	1.3
Machine grinding eff (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 factor to higher CSE, and a factor of just over 2 from machine comminution efficiency. These translate to 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 <sub>80</sub> (µm)	4,100	5,030
P <sub>80</sub> (µm)	205	192
W (kWh/t)	13.1	5.39
W <sub>io</sub> , kWh/t	24.2	9.28
Test W <sub>i</sub> , kWh/t	20.8	21.1
W <sub>i</sub> efficiency, %	86	227
Efficiency improvement	-	2.64
Energy savings, %	-	62

Table 5 - Plant and Pilot Plant Functional Performances for Copper Mountain

Description	Plant Ball mill circuit	Pilot HPGR circuit
Fresh feed rate (t/h)	1760	6.1
Mill power excluded losses (kW)	23,088	32.9
%Passing 212 $\mu\text{m}$ in fresh feed	26.2	24.0
%Passing 212 $\mu\text{m}$ in circuit final product	81.2	83.8
%retained 212 $\mu\text{m}$ in mill feed	82.4	100
%retained 212 $\mu\text{m}$ in mill discharge	69.4	81.4
Circuit fines production rate (t/h)	$1760 \times (81.2 - 26.2) = 967$	$6.1 \times (83.8 - 24.0) = 3.65$
Classification efficiency (CSE)	$(82.4 + 69.4)/2 = 76.0$	$(100 + 81.4)/2 = 90.7$
Lab grindability $W_i$ (g/rev)	1.08	1.01
Mill grinding efficiency	0.051	0.121
CSE pilot/ industrial	-	1.20
Machine grinding efficiency (pilot/industrial)	-	2.37
Total circuit eff 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 an overall factor of 2.8, attributing close to 1.2 of this factor 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.

Preliminary full-scale circuit designs were completed in order to compare total ball milling circuit versus HPGR circuit energy usages. Figures 6 and 7 show the HPGR replacement flow sheets for PGM and CMM.

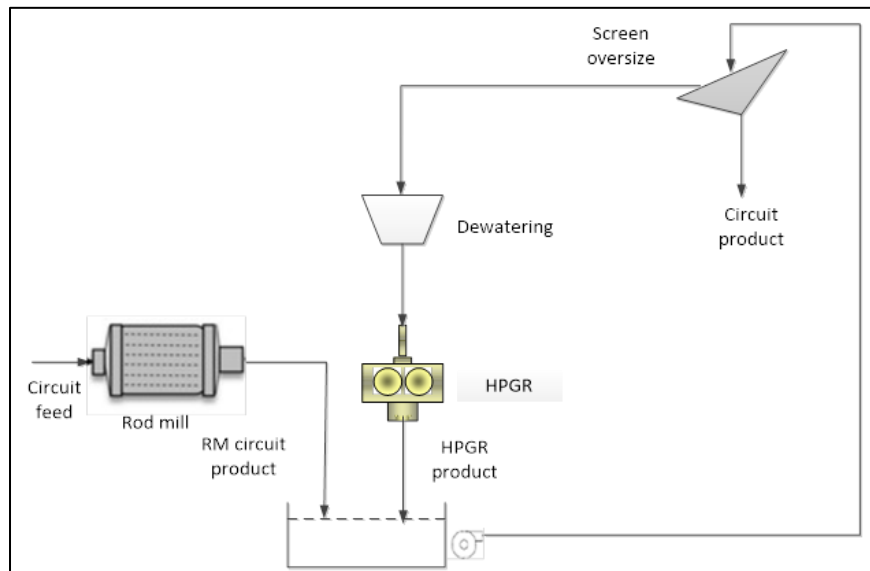


Figure 6 - Porcupine Gold HPGR Flowsheet Replacing Ball Milling

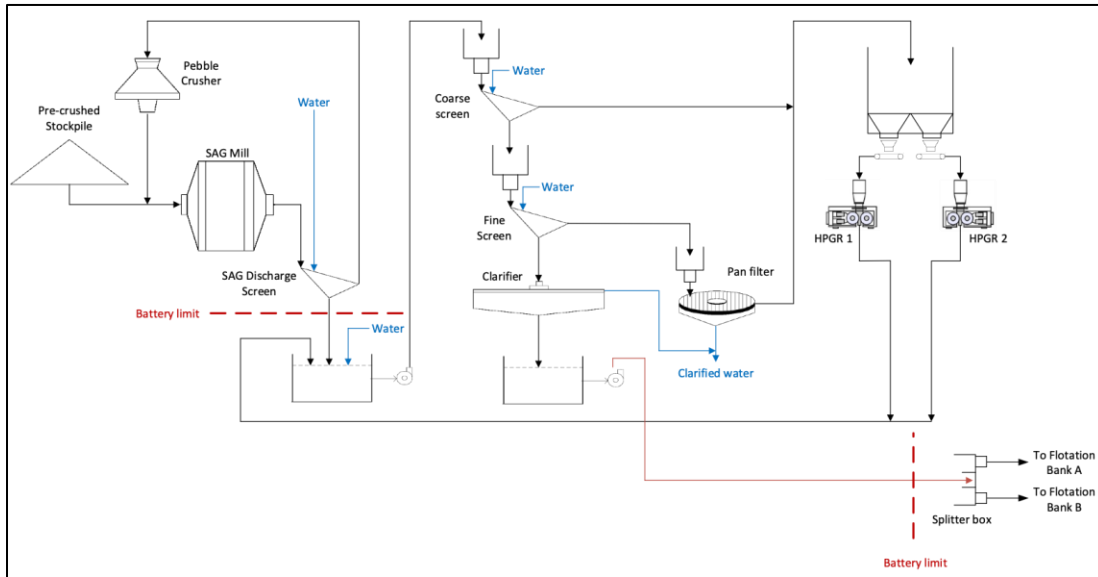


Figure 7 - Copper Mountain HPGr Flowsheet Replacing Ball Milling

Screening and (large capacity, low vacuum) filtering, along with classifier feed pumping and an added clarifying or thickening step after the grinding circuit were considered, as were grinding media “embedded” energies (Ballantyne, 2019) for their manufacture and delivery. These savings were subsequently also factored across total (run-of-mine ore to cyclone overflow) comminution circuit energy usages to arrive at the energy savings values summarized in Table 6.

Table 6 - Summary of Energy Savings with HPGr Replacing Ball Milling

	Porcupine Gold Mine (Circuit ‘A’)	Copper Mountain Mine
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.

\*\*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 pilot plant final products showed no extreme fines production compared to plant cyclone overflows. Metallurgical testing showed very similar total (gravity plus leaching) gold recovery on HPGr pilot circuit product and a conventionally ground PGM pilot circuit feed sample. For CMM, flotation rougher concentrate grade was measurably higher. Mineralogical analyses confirmed no increased gold liberation for PGM, and slightly improved copper mineral liberation for CMM ore ground by HPGr. Micro-cracking analysis technology is not yet fully developed for such fine particles.

Very preliminary economic analysis of the new HPGr flowsheet showed that the roughly double cost of the equipment for HPGr over ball milling can be justified only where there is a very high cost for energy. However, HPGr circuit optimization beyond replacement of an existing ball mill will impact this. For example, a multi-stage HPGr circuit could reduce the final step workload, circulating load, and associated

classification and dewatering equipment needs. As well, carbon emissions are now assigned real dollar costs during project alternative evaluations.

The UBC locked-cycle piston test was carried out on samples of the pilot circuit feeds. Tables 7 and 8 summarize the locked-cycle piston press and pilot plant results for PGM and CMM. While still undergoing development of the small-scale press versus larger equipment energy usage, they show it is possible to make a reasonable prediction of larger equipment specific energy needed from these small-scale tests.

Table 7 - Locked Cycle Piston-Press and Pilot HPGR Test Results on PGM Sample

Description	Piston press results	HPGR results
Specific pressing force, N/mm <sup>2</sup>	-	3.25
Piston pressure, MPa	189	-
Specific energy per pass, kWh/t	1.28	1.38
Circulating load, %	252	240
Circuit specific energy, kWh/t	3.23	3.31
P <sub>80</sub> , mm	0.126	0.124
Func. Perf. grinding rate @ 212 µm, t/kWh	0.275	0.230

Table 8 - Locked Cycle Piston-Press and Pilot HPGR Test Results on CMM sample

Description	Piston press results	HPGR results
Specific pressing force, N/mm <sup>2</sup>	-	3.5
Piston pressure, MPa	189	-
Specific energy per pass, kWh/t	1.49	1.67
Circulating load, %	303	321
Circuit specific energy, kWh/t	4.51	5.38
P <sub>80</sub> , mm	0.212	0.192
Func. Perf. grinding rate @ 300 µm, t/kWh	0.200	0.153

## CONCLUSIONS

As a result of this study many questions regarding the possible application of high-pressure grinding in the current role of wet ball milling have been addressed. The “Crush It Challenge” objective of 20% total plant comminution circuit energy savings has been well exceeded. Further work to optimize the flowsheet will increase its energy effectiveness. As further follow-up, a demonstration circuit to incorporate continuous material handling is being pursued. As a novel combination of existing technologies, use of the new flowsheet may now be considered. With the discovery of the synergy between fines removal and high-pressure grinding efficiency, even the most optimistic expectations of the investigating team were exceeded.

## ACKNOWLEDGEMENTS

This work was made possible by the Natural Resources Canada “Crush It Challenge”.

Members of the combined Corem and UBC research team owe thanks to the following organizations which made essential contributions to this project.

- Porcupine Gold Mine (Newmont Mining Company) and Copper Mountain Mining Company: For contributing plant access and support during the plant surveys, needed samples, and operating data.
- Derrick Corporation: For contributing dewatering and screening tests at their pilot facilities in Buffalo, N.Y.; for flowsheet equipment sizing and cost information; and for technical advice given throughout the project.
- Thyssenkrupp Industrial Solutions (USA), Inc.: For rolls wear testing at their facilities in Neubeckum, Germany; and for technical advice given throughout the project.
- Weir Minerals: For guidance with the Corem pilot high-pressure grinding rolls test work, and technical advice given throughout the project; and for assistance with flowsheet design, equipment selection and cost information.
- Koppern Equipment: For guidance with the UBC pilot high-pressure grinding rolls test work, technical advice given throughout the project, and for equipment selection and cost information.
- FLSmidth A/S and Andritz AG, for assistance with dewatering equipment assessment, selection and cost information.

Thanks are also owed to Persio Rosario and Edward Wipf for their valued discussion.

University of British Columbia students and their directors contributed extensive research and review work to the project.

## REFERENCES

Ballantyne, G., 2019, “Quantifying the Additional Energy Consumed by Ancillary Equipment and Embodied in Grinding Media in Comminution Circuits”, Symposium on Semi-Autogenous and High Pressure Grinding Technology, Vancouver.

Gagnon, C., Rosa, A., Makni, S., McIvor, R., Klein, B., Kumar, A., Wang, F., Gong, D., and C. Saud., 2021, “Development and Demonstration of HPGR Grinding and Novel Classification to Mineral Separation Circuit Feed Sizing in Replacement of Ball Milling”, Final Report, the Natural Resources Canada “Crush It Challenge”.

Global Mining Guidelines Group, 2016, “Determining the Bond Efficiency of Industrial Grinding Circuits”, <http://www.gmggroup.org>

McIvor, R. E., 2006, “Industrial Validation of the Functional Performance Equation for Ball Milling and Pebble Milling Circuits”, Mining Engineering, November, pp. 47–51.