CREATIVE AND SIMPLER HPGR CIRCUITS MAY INCREASE THEIR APPLICATION EVEN IN THE CURRENT RESTRICTIVE FINANCIAL ENVIRONMENT

*P.P. Rosario and J.A. Drozdiak

HATCH
Comminution Group, Global
400 – 1066 West Hastings Street
Vancouver, Canada, V6E 3X2
*(*Corresponding author: prosario@hatch.ca)*

CREATIVE AND SIMPLER HPGR CIRCUITS MAY INCREASE THEIR APPLICATION EVEN IN THE CURRENT RESTRICTIVE FINANCIAL ENVIRONMENT

ABSTRACT

The inherent conservatism of the mining industry is well understood, but the current hurdles encountered with financing new projects have complicated instances when new technologies such as high pressure grinding rolls (HPGR) are considered, especially if it translates into higher capital costs for the project. In this study, we do not suggest revolutionary changes, but instead incremental adjustments which can reduce circuit complexity and the corresponding capital costs, while maintaining the benefits of HPGR technology. Two non-conventional HPGR / ball mill circuits for high and low tonnage scenarios are presented and the capital costs, layout considerations and ancillary equipment requirements evaluated.

KEYWORDS

Comminution, crushing, milling, HPGR, hard ore, circuit design, SAG

INTRODUCTION

The application of HPGR technology in comminution circuits is well established for the processing of cement, diamonds and iron ore (Broeckmann & Gardula, 2005), and over the past 10 to 15 years, this technology has slowly been applied to hard ores in high-tonnage precious and base metal operations. Unfortunately, under the current economic climate, the ability to finance large capital projects has become very difficult and companies tend to have an easier time securing funding if the capital expenditures are low with a proven process method. The traditional semi-autogenous grinding (SAG) mill / ball mill circuits easily fit into this mould, having been installed in countless plants around the world over the past 30 years with relatively low capital requirements. In contrast, it has been well-documented that HPGR-based circuits are capital intensive with complex material handling systems (Seidel, Logan, LeVier, & Veillette, 2006). Although these circuits benefit from reduced operating costs with the increase in energy efficiency and the elimination of steel grinding media (Rosario, Boyd, & Grundy, 2009), if the company is unable to secure financing to build the plant, these advantages remain out of reach. With the current trend to retrofit existing SAG circuits with a secondary crushing circuit to achieve design throughput, the opportunity to circumvent this gross inefficiency by making HPGR-based circuits more capital friendly would greatly benefit the industry.

In this paper, we present two examples of HPGR-based circuits which are designed for high and low tonnage operations of 50,000 t/d and 15,000 t/d, respectively. In each case, the design of the circuit focuses on reducing capital requirements by adopting the latest generation of process equipment and providing slight circuit modifications to reduce the need for ancillary equipment.

The “Standard” HPGR Circuit

Of the many possible flowsheets that have been proposed for HPGRs, those using HPGRs as tertiary crushers, in closed-circuit with wet fine screens, are expected to provide maximum energy efficiency (Jankovic, Valery, Sonmez, & Oliveira, 2014). The fine screens classify out coarse material for circulation back to the HPGR while also ensuring an acceptable top-size for downstream processes such as ball milling. A safety coarse-screen, in closed circuit with secondary crushing, precedes the HPGR and prevents oversized material from damaging the rolls (Morley, 2006). This flowsheet configuration was selected for a number of high tonnage projects in the Southern Hemisphere, including Boddington (Figure 1) Cerro Verde (Figure 2), and most recently Sierra Gorda (Figure 3).

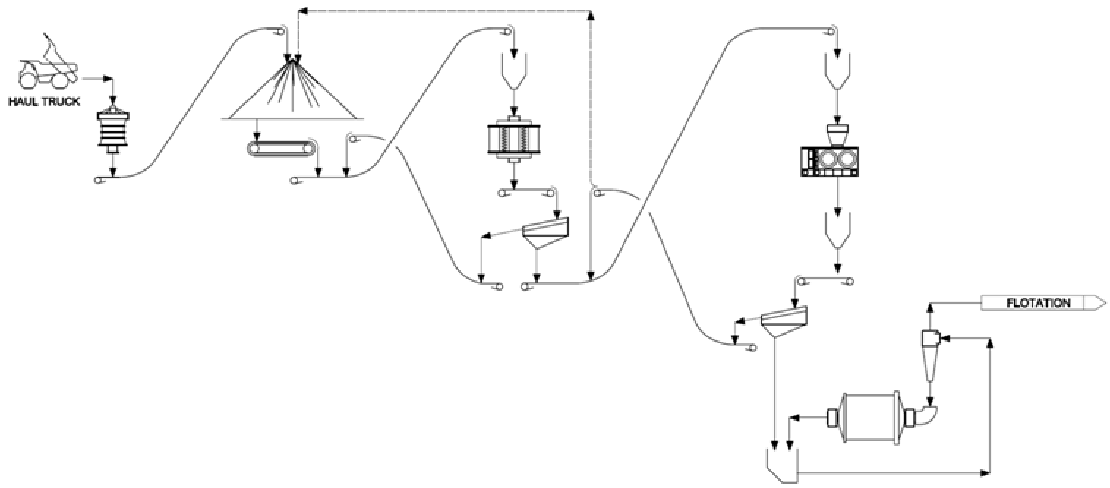

Figure 1 – Boddington comminution circuit (Dunne, Hart, Parker, & Veillette, 2007)

Boddington has a design capacity of 35 Mtpa (approximately 96,000 t/d) and processes two very hard gold ores with average Bond ball mill work indices (BWi) of 15.1 and 16.6 kWh/t, Bond rod mill work indices (RWi) of 22.8 and 24.2 kWh/t, and JK Axb values of 27.9 and 25.5. The circuit is comprised of five 746 kW cone crushers, four 2.4 m diameter (D) x 1.65 m length (L) 5.5 MW HPGRs, and four 7.9 m D x 11.9 m L (26 x 39 ft) 15.6 MW ball mills (Dunne et al 2007). The projected roll surface wear life was estimated to be 4,250 hours. A 2006 trade-off study showed that a preliminary semi-autogenous ball crushing (SABC) circuit would have 7% lower capital costs than the HPGR circuit, and that the HPGR circuit provided 12% savings in comminution operational costs. The study concluded that the lower operational costs of the HPGR circuit offset its higher capital costs (Seidel et al, 2006). Furthermore, after commissioning, the HPGR roller wear life was found to average 5,000 hours with expectations to achieve 6,000 hours with improved profile design (Hart, Parker, Rees, Manesh, & Mcgaffin, 2011).

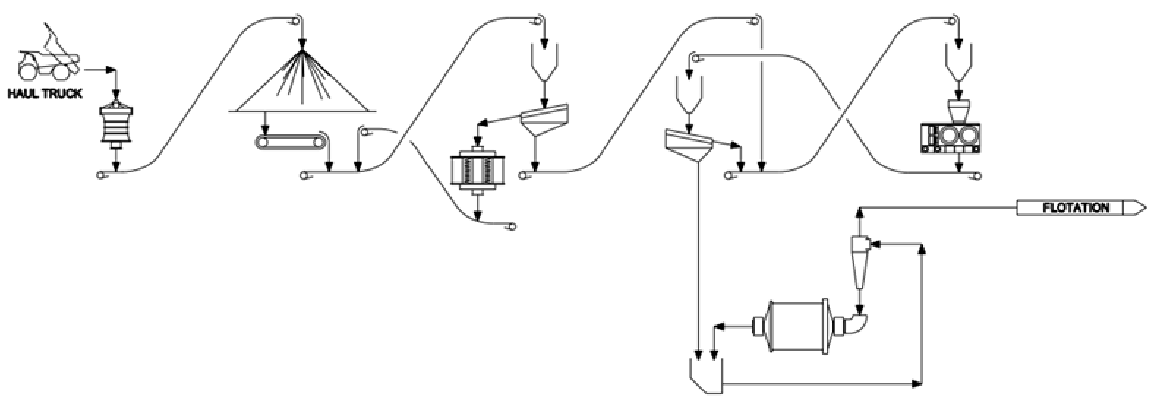

Figure 2 – Cerro Verde comminution circuit (Vanderbeek, 2006)

Cerro Verde has a design capacity of 108,000 t/d of hard copper-molybdenum ore (average BWi of 15.3 kWh/t). The circuit is comprised of four 746 kW cone crushers, four 2.4 m D x 1.65 m L 5.0 MW

HPGRs, and four 7.3 m D x 10.7 m L (24 x 35 ft) 12 MW ball mills. The projected roll surface wear life is 6,000 hours. Just prior to startup, Vanderbeek (2006) reported that although estimated capital costs were higher for the HPGR circuit than an equivalent SAG circuit, the estimated total comminution operational costs were 1.33 US$/t and 1.70 US$/t for the HPGR and SAG circuits respectively. The main contributors for this difference being the costs of power and grinding media. The estimated total comminution circuit specific energy for the SAG circuit was determined to be 20.1 kWh/t, as compared to 15.9 kWh/t for the HPGR circuit. In addition to operating cost savings, risk analysis conclusions and internal rate of return factors resulted in the decision to install an HPGR circuit instead of a SAG circuit.

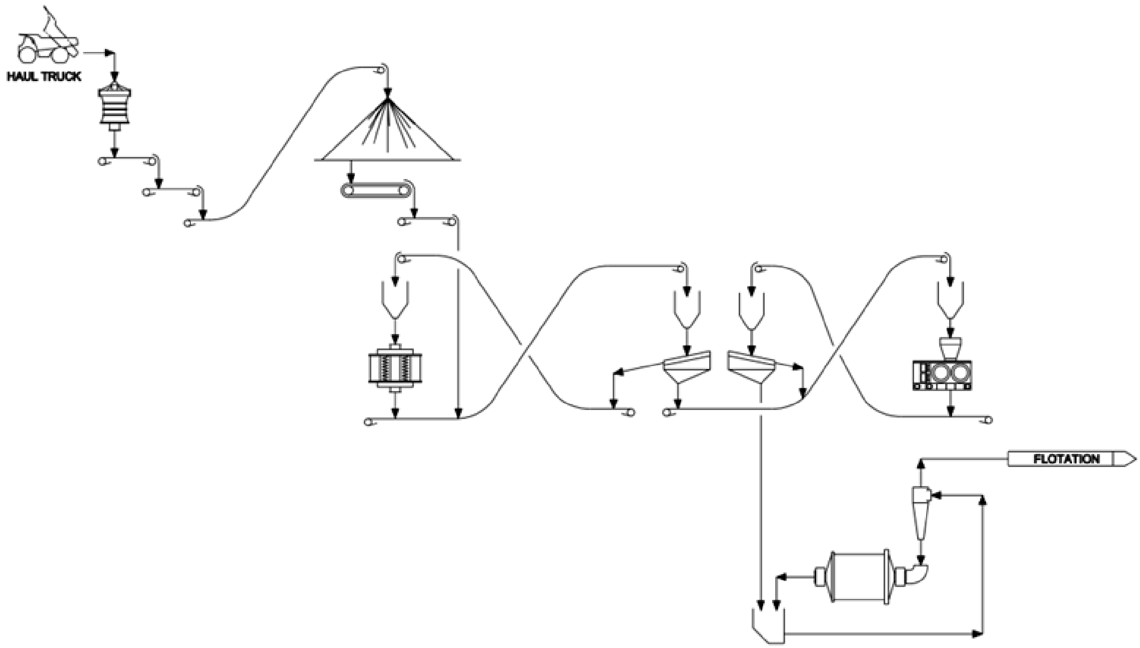

Figure 3 – Sierra Gorda comminution circuit (Pincock, Allen & Colt, 2011)

Sierra Gorda has a design capacity of 110,000 t/d of hard copper-molybdenum ore (average BWi of 17.5 kWh/t). The circuit is comprised of four 933 kW cone crushers, four 2.4 m D x 1.65 m L 5.6 MW HPGRs, and three 7.9 m D x 13.4 m L (26 x 44 ft) 17 MW ball mills (Pincock et al, 2011). The design of the circuit is similar to the Cerro Verde flowsheet and incorporates large surge bins and the operation of the secondary crushing circuit in reverse closed circuit.

In each of the above examples, a number of similarities can be observed:

- The primary crushing circuit remains a separate entity, with the coarse ore stockpile acting as a buffer between the gyratory crusher and the secondary crusher and HPGR.
- The secondary crushing circuit operates in closed circuit with screens to ensure a maximum top size of approximately 50 mm to each 2.4 m D HPGR.
- Plenty of surge capacity is provided between the ball mill and the HPGR to sustain constant feed to the ball mills while maintaining the secondary crushing and HPGR circuits. In the case of Boddington, four fine ore bins with a total live capacity of 20,000 tonnes are used, while at Cerro Verde and Sierra Gorda, 20,000 tonne and 24,000 tonne fine ore bins are installed respectively.

OBJECTIVES

The main objective of this work is to suggest alternative HPGR-based circuits with reduced capital expenditures (CAPEX) to improve the chances of keeping these circuits viable in projects facing the current project financing hurdles. We believe that important benefits provided by the HPGR, such as energy savings and reduction in greenhouse gas emissions, should be applied to a greater number of projects and in different regions around the world, including regions were indoor process plants are required. To assist in achieving this objective, the total capital cost of the comminution circuit must be lowered to a range similar to SAG mill or crusher-based circuits, especially when treating hard or extremely hard ore types.

We have developed two alternative HPGR-based circuits for 50,000 t/d and 15,000 t/d and will present the benefits and shortcomings of these non-conventional circuits when compared to the traditional HPGR and 3-stage crushing circuits. The main areas of focus will include the elimination of ancillary equipment and the corresponding reduction in CAPEX, as well as a comparison of layouts and a reduction in footprint. Since it has already been demonstrated that savings in operating expenditures (OPEX) are more prominent in hard ores when comparing crusher or HPGR-based circuits to SAG-based circuits, we will focus solely on CAPEX and assume no major changes in OPEX result from the proposed circuit modifications.

METHODOLOGY

Design Criteria

Two hypothetical mining projects were used for this study. These hypothetical projects are assumed to be located in very remote areas, subjected to harsh winters, with plant heating requirements, and reliance on self-generated electricity.

The physical and grindability parameters of the ore are also hypothetical, but similar to real ore characteristics documented in published papers and/or official reports. These benchmarked operations, whose names will not be disclosed, were built quite recently, and are examples of SAG circuits that have encountered challenges in achieving design capacity and have planned or implemented circuit modifications to alleviate the issue.

Some unknown parameters, such as HPGR modeling parameters, were assumed based on typical or average values for ores with similar hardness and allow for some conservatism. It has also been assumed that these two ore bodies contain a low percentage of clays and are formed of non-stick rocks, i.e. ores that are amenable to crushing and high pressure grinding, and produce moderately competent HPGR product cakes that can be de-agglomerated by the application of wet screening.

The assumed daily production values, final grind sizes, physical and grindability parameters of the ore, and the HPGR modeling parameters were grouped to generate the core process design criteria for the two hypothetical projects, as shown in Table 1.

Table 1 – Summarized design criteria

	Units	Project #1	Project #2
Feed Rate	t/d	50,000	15,000
Solids SG	-	2.75	2.90
ROM Top Size	mm	1,200	950
ROM F80	mm	650	550
Crusher (Impact) Work Index	kWh/t	15.4	16.9
JK Parameter A x b	-	28.5	24.3
Ball Mill Work Index	kWh/t	19.0	15.5
Ball Mill Work Index Reduction	%	8.0%	8.0%
HPGR Net Spec. Energy Required	kWh/t	2.0	2.0
HPGR Specific Throughput Rate	ts/hm^3	210.0	210.0
Final Product P80	µm	200	125

Flowsheets

We believe that these mining projects would be great candidates for circuits based on crushers and HPGRs, especially due to the expected high costs for energy (diesel power) and steel grinding media (remote location). In addition, similar to many projects today, they may be very sensitive to CAPEX.

Project #1

The traditional HPGR circuit proposed for Project #1 includes two 2.4 m D HPGRs and two 746 kW cone crushers in closed circuit with two screens. The circuit configuration is similar to the one installed at Cerro Verde but with approximately half the tonnage. The flowsheet and corresponding equipment list are presented in Figure 4 and Table 2, respectively. This circuit utilizes a number of large surge bins and operates the secondary crushing circuit in reverse closed circuit to ensure an acceptable top size to the HPGR. These two aspects of the circuit contribute to the higher capital cost of the circuit and the elimination of the large surge bins and secondary crusher recycle conveyors would simplify the circuit and decrease the overall footprint. Both modifications would reduce the overall cost of the circuit.

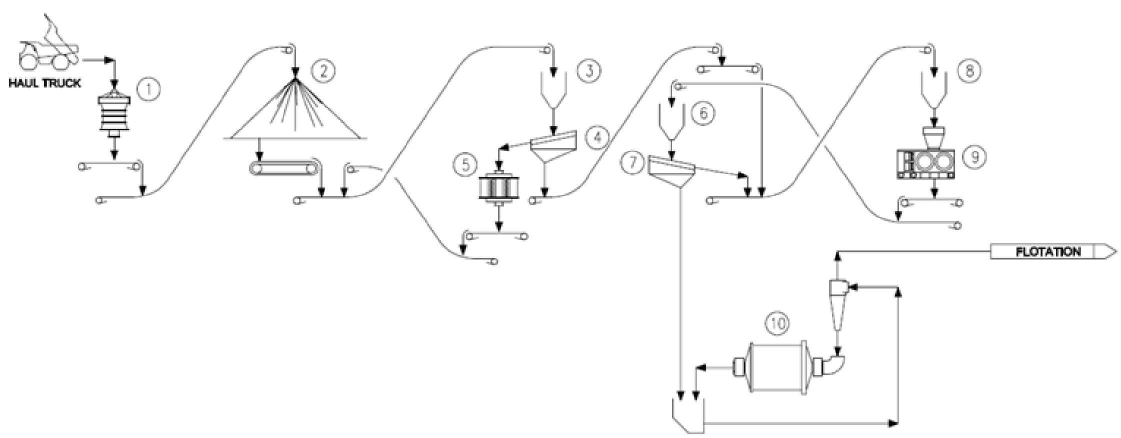

Figure 4 – Project #1 Base Case comminution circuit

Table 2 – Project #1 Base Case equipment list

Ref. #	Equipment Type	Quantity	Size	Power*
1	Primary Gyratory Crusher	1	60” x 89”	600 kW
2	Coarse Ore Stockpile	1	25,000 t	-
3	Secondary Crusher Feed Surge Bin	1	1,500	-
4	Secondary Crusher Vibrating Screens	2	4.2 m x 8.5 m	90 kW
5	Secondary Cone Crushers	2	-	746 Kw
6	Ball Mill Feed Surge Bin	1	10,000 t	-
7	Ball Mill Feed Screens	4	3.6 m x 8.5 m	90 kW
8	HPGR Feed Surge Bin	1	2,200 t	-
9	High Pressure Grinding Rolls	2	2.4 m x 1.7 m	5,000 kW
10	Ball Mills	2	7.6 m x 12.2 m	13,000 kW
	Feeders	12	Various	89 kW
	Conveyors	11	Various	4,045 kW

* Unit power value for main equipment and total power for feeders and conveyors

The Alternative circuit proposed for Project #1 includes a larger cone crusher with 1,865 kW and a single screen to scalp the crusher feed, similar to standard secondary crushing circuits. The implementation of a larger secondary cone crusher allows higher capacity and the ability to tighten up the closed side setting to a range of 28 – 34 mm, resulting in a top size of 55 – 65 mm. The increased crusher capacity also allows for the opportunity to size the crusher for an availability of 68%, operating it in tandem with the primary crusher. An apron feeder is installed below the primary crusher dump pocket to control the feed rate to the circuit. To eliminate the requirement of a 10,000 t ball mill feed bin, the coarse ore stockpile has been shifted to after secondary crushing. A single 3.0 m D HPGR operated in closed circuit with wet screening is installed in the tertiary crushing circuit and the larger model provides the opportunity to feed the HPGR at a maximum top size of 70 – 75 mm. The flowsheet and corresponding equipment list are shown in Figure 5 and Table 3, respectively.

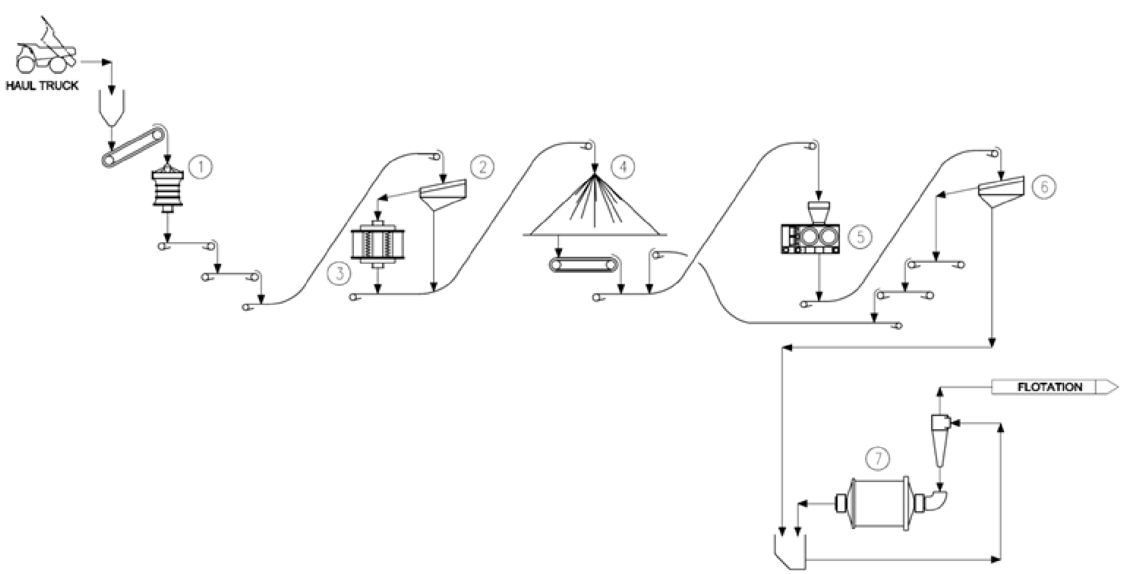

Figure 5 – Project #1 Alternative comminution circuit

Table 3 – Project #1 Alternative equipment list

Ref. #	Equipment Type	Quantity	Size	Power*
1	Primary Gyratory Crusher	1	60” x 89”	600 kW
2	Secondary Crusher Screen	1	3.6 m x 8.5 m	90 kW
3	Secondary Cone Crusher	1	-	1,865 kW
4	Coarse Ore Stockpile	1	25,000 t	-
5	High Pressure Grinding Roll	1	3.0 m x 2.0 m	9,000 kW
6	Ball Mill Feed Screens	2	3.6 m x 8.5 m	90 kW
7	Ball Mills	2	7.9 m x 12.5 m	15,000 kW
	Feeders	4	Various	30 kW
	Conveyors	10	Various	2,748 kW

* Unit power value for main equipment and total power for feeders and conveyors

The following are the positives and drawbacks of the Alternative circuit proposed for Project #1.

Positives:

- **Reduced ancillary equipment** – operating secondary crushing in open circuit eliminates the extra conveyors associated with transferring crusher product back to the feed screen while also reducing the capacity requirements for the screen. Situating the coarse ore stockpile after secondary crushing eliminates the need for a large surge bin prior to the grinding circuit. Installing a larger HPGR simplifies the circuit and reduces the amount of material handling equipment. Overall, including the elimination of tall surge bins, the Alternative circuit has a fewer number conveyors with shorter belt lengths and lower power requirements.
- **Smaller footprint** – the reduction in ancillary equipment reduces the overall footprint of the plant. Since our case studies focus on remote locations and cold winters, the reduction in footprint will result in substantial cost savings in building size and heating requirements.
- **Less transfer points in material handling system** – a reduced number of transfer points (e.g number of feeders and transfer chutes) could lower the number of unpredicted maintenance events (not assumed, but a good possibility for better overall availability), and lower dust generation and the corresponding collection requirements.

Drawbacks:

- **Lower availability factors** – the Base Case used a primary crushing availability of 70%, a secondary crusher / HPGR availability of 85% and a grinding availability of 93%. With the circuit modification, the Alternative was sized with an availability of 68% for primary and secondary crushing and 90% for the HPGR and ball mills.
- **Slightly larger ball mill** – in addition to the increased size and power resulting from a lower ball mill availability, the selection of a single HPGR and 2 screens will create a slightly larger transfer size to the ball mill. Both factors contribute to a higher power demand for grinding.
- **Top size control** – although secondary crushing is expected to produce a particle top size smaller than the operating gap of the HPGR, the possibility of larger particles slipping through the open side of the crusher during non choke-fed conditions, or feed run-up and run-down phases of normal start-stop operations, has been noted (Morley, & Daniel, 2009). With tighter control and instrumentation, proven advances with online gap adjustment and the addition of variable frequency drives (VFD) for cone crushers (Jacobson & Lamminmaki, 2013), this concern can be mitigated.
- **Less surge capacity** – the reduction in surge bins requires that improved control measures be implemented to maintain constant feed conditions throughout the circuit. The operation of the HPGR and the ball mills without large four-hour surge bins results in additional equipment requirements such

as the necessity to install variable speed drives on the ball mills to vary power draw. In addition, careful maintenance and proper operating philosophies must be in place

- **Alternative mechanical systems –** the Alternative circuit utilizes a splitter for the HPGR product and two high-angle conveyors to feed the ball mill screens. This setup may be considered as a disadvantage or a challenge to maintain, however, we trust current engineering solutions, with examples of such systems working successfully in the literature (Gruendken, Matthies, & van der Meer, 2008; Rotzinger, & Major, 2011).

Project #2

The conventional 3-stage crushing circuit proposed for Project #2 includes three 597 kW cone crushers, one in secondary crushing and two in tertiary crushing, and a large fine ore bin prior to grinding to ensure a constant feed to the ball mill. The flowsheet and associated equipment list are presented in Figure 6 and Table 4, respectively.

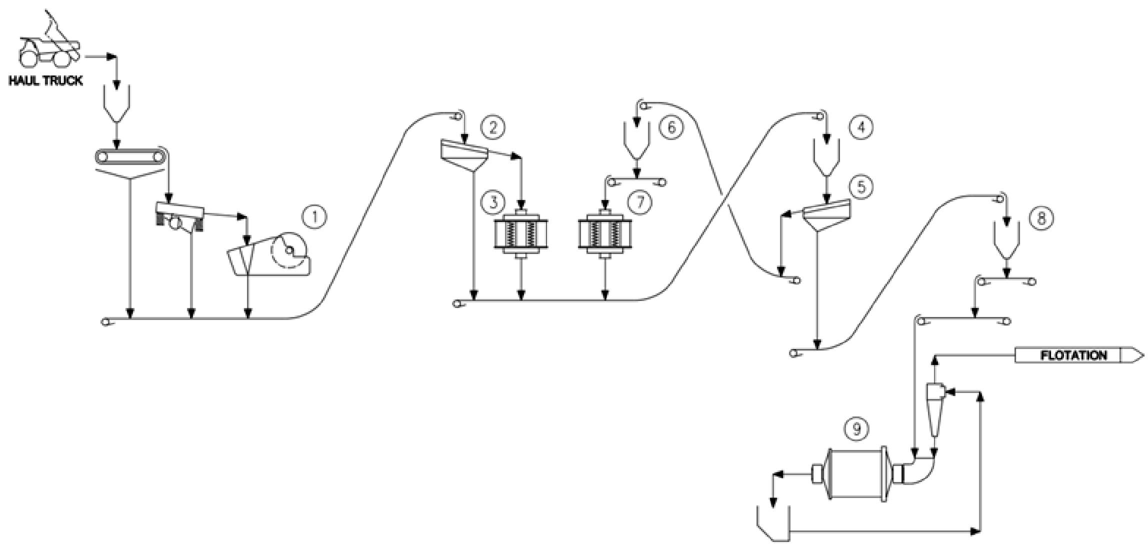

Figure 6 – Project #2 Base Case comminution circuit

Table 4 – Project #2 Base Case equipment list

Ref. #	Equipment Type	Quantity	Size	Power*
1	Primary Jaw Crusher	1	1,600 mm x 1,200 mm	250 kW
2	Secondary Crusher Vibrating Screen	1	3.0 m x 7.3 m	55 kW
3	Secondary Cone Crusher	1	-	597 kW
4	Tertiary Crusher Screen Feed Bin	1	290 t	-
5	Tertiary Crusher Vibrating Screens	2	3.0 m x 8.5 m	55 kW
6	Tertiary Crusher Surge Bin	1	725 t	-
7	Tertiary Cone Crushers	2	-	597 kW
8	Fine Ore Bin	1	7,500 t	-
9	Ball Mill	1	7.3 m x 11.3 m	11,500 kW
	Feeders	3	Various	22 kW
	Conveyors	11	Various	1,171 kW

* Unit power value for main equipment and total power for feeders and conveyors

The alternative circuit proposed for Project #2 includes a larger 933 kW secondary cone crusher and a 2.0 m D HPGR operated with edge recycle. In this option, a "coarse" ore stockpile is included after secondary crushing and the HPGR and ball mill are operated without surge capacity. Higher size reduction in secondary crushing and the application of edge recycle in the HPGR circuit both help ensure an adequate top size of 20 mm to the ball mill. The elimination of wet screening with the adoption of edge recycle will also improve the capacity of the HPGR and eliminate the various problems associated with processing a high moisture feed.

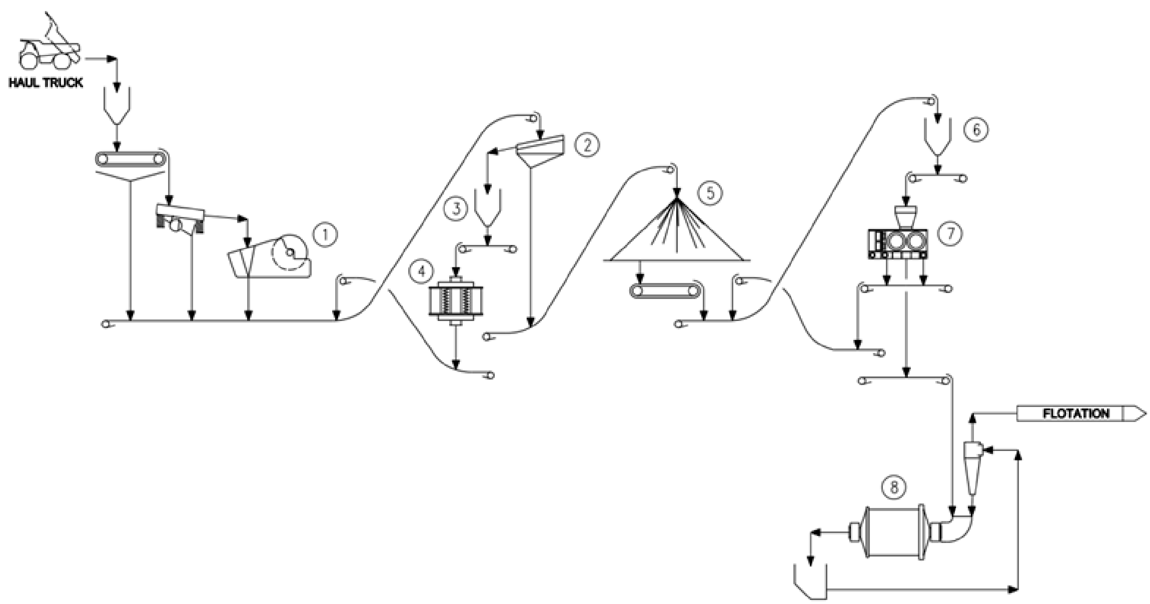

Figure 7 – Project #2 Alternative comminution circuit

Table 5 – Project #2 Alternative equipment list

Ref. #	Equipment Type	Quantity	Size	Power
1	Primary Jaw Crusher	1	1,600 mm x 1,200 mm	250 kW
2	Secondary Crusher Vibrating Screen	1	4.2 m x 8.5 m	90 kW
3	Secondary Crusher Surge Bin	1	87 t	-
4	Secondary Cone Crusher	1	-	933 kW
5	Coarse Ore Stockpile	1	7,500 t	-
7	High Pressure Grinding Roll	1	2.0 m x 1.65 m	3,200 kW
8	Ball Mill	1	6.7 m x 10.4 m	8,500 kW
	Feeders	4	Various	30 kW
	Conveyors	9	Various	1,126 kW

* Unit power value for main equipment and total power for feeders and conveyors

The following are the positives and drawbacks of the Alternative circuit proposed for Project #2.

Positives:

- **Smaller footprint** – the reduction in ancillary equipment and the installation of high-angle conveyors can reduce the footprint of the plant and decrease the capital costs associated with building size.
- **Elimination of the fine ore bin** – the use of a lower cost stockpile for a coarser material (secondary crushing system product) replaces the expensive capital cost of a fine ore bin feeding the ball mill.
- **Smaller ball mill** – a finer product size generated by the HPGR would reduce the size of the ball mill. This smaller mill would enable the use of a single drive system, resulting in significant capital cost savings. Depending on ore hardness and final grind size, the total power requirements and grinding media consumption rates may also be considerable lower.
- **No tertiary screening** – dry fine screening is usually the weakest point in a 3-stage crushing / ball mill circuit and in many operations it can create excessive downtime, insufficient screening efficiency and a bottleneck for tertiary crushing. To compensate for this constraint, operations sometimes relax the aperture size on the tertiary screen, compromising grinding efficiency and product size.

Drawbacks:

- **Reduction in similar equipment** – the Base Case 3-stage crushing circuit incorporates three cone crushers of similar size. This similarity provides an advantage in stocking common spares and assessing circuit performance. In contrast, each stage of comminution in the Alternative circuit utilizes different types of equipment, requiring additional spares and a more complex maintenance program.
- **Increased maintenance complexity** – the use of an HPGR requires more specialized maintenance procedures. The HPGR requires the replacement of roll tyres and a dedicated maintenance facility located within a reasonable distance. Cone crusher liner replacement, although more frequent, is much simpler to coordinate.
- **Lower grinding availability** – operating the ball mill in tandem with the HPGR results in a lower availability when compared with the ball mill operating after a fine ore bin.
- **Advanced instrumentation and control systems** – the operation of the Alternative circuit will require more instrumentation, advanced control systems and better trained operators to efficiently run the HPGR / ball mill circuit.
- **Edge recycle classification efficiency** – the application of HPGR edge recycle may not fully capture the benefits associated with operating an HPGR in closed circuit with high efficiency classification. Since high efficiency classification seldom occurs in conventional screening circuits, this drawback should have little impact.

Layouts / 3D Models

One of the high capital costs associated with the installation of HPGR-based circuits is the increased footprint and the corresponding inflated building costs. Our case studies focus on projects in remote regions with harsh winters, amplifying the corresponding building costs. The alternative circuits we propose in this study are meant to alleviate this problem by shrinking the overall footprint and making the capital costs more competitive.

Project #1

A general layout for the Base Case HPGR circuit is presented in Figure 8 and the corresponding 3D models for the secondary crushing, HPGR and grinding circuits are shown in Figure 9 and Figure 10.

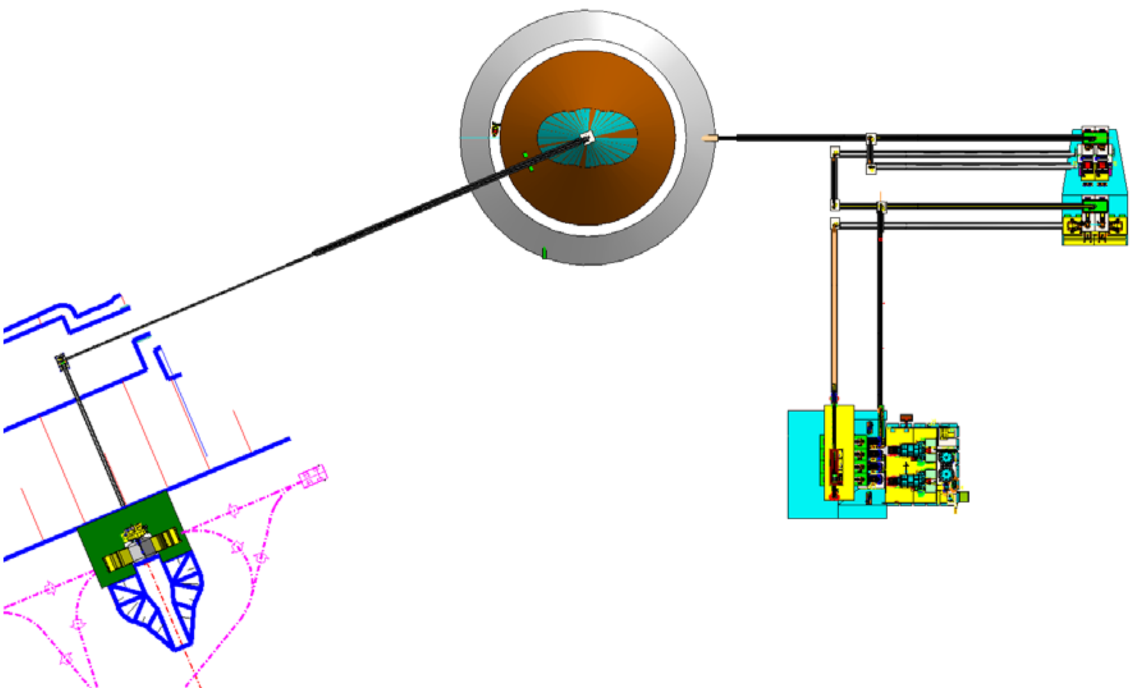

Figure 8 – Project #1 Base Case general layout

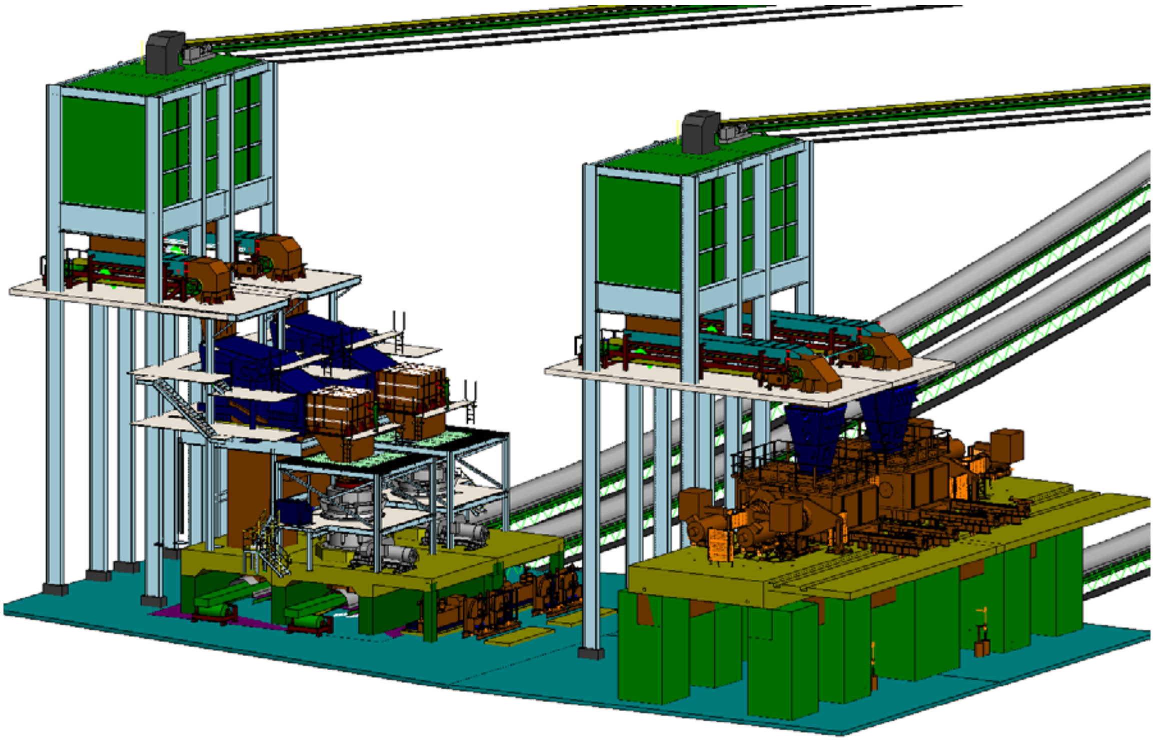

Figure 9 – Project #1 Base Case secondary crushing and HPGR circuit 3D model

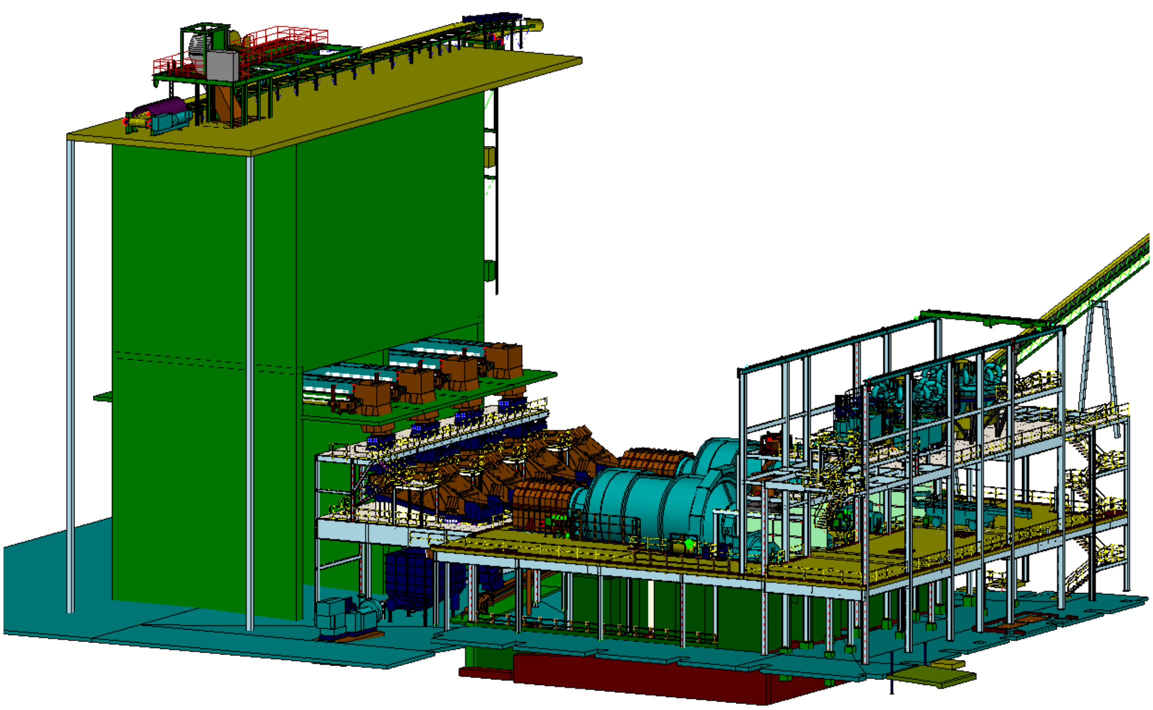

Figure 10 – Project #1 Base Case grinding circuit 3D model

The general layout for the Alternative circuit is presented in Figure 11 and the corresponding 3D models for the primary and secondary crushing, HPGR and grinding circuits are shown in Figure 12 and Figure 13. The integrated primary and secondary crushing circuits, coupled with the integrated HPGR and ball mill circuits have allowed for a substantially reduced footprint. In cold climates, this reduction in footprint can result in considerable capital cost savings.

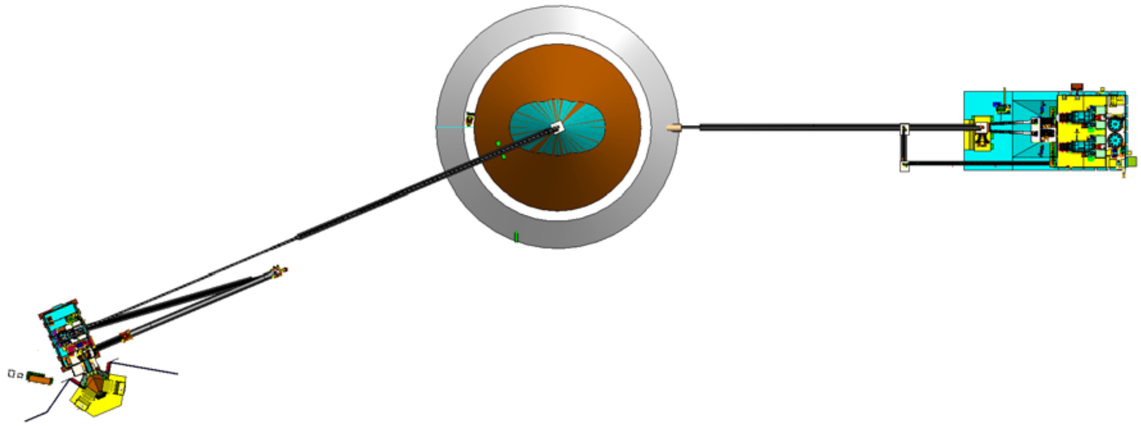

Figure 11 – Project #1 Alternative general layout

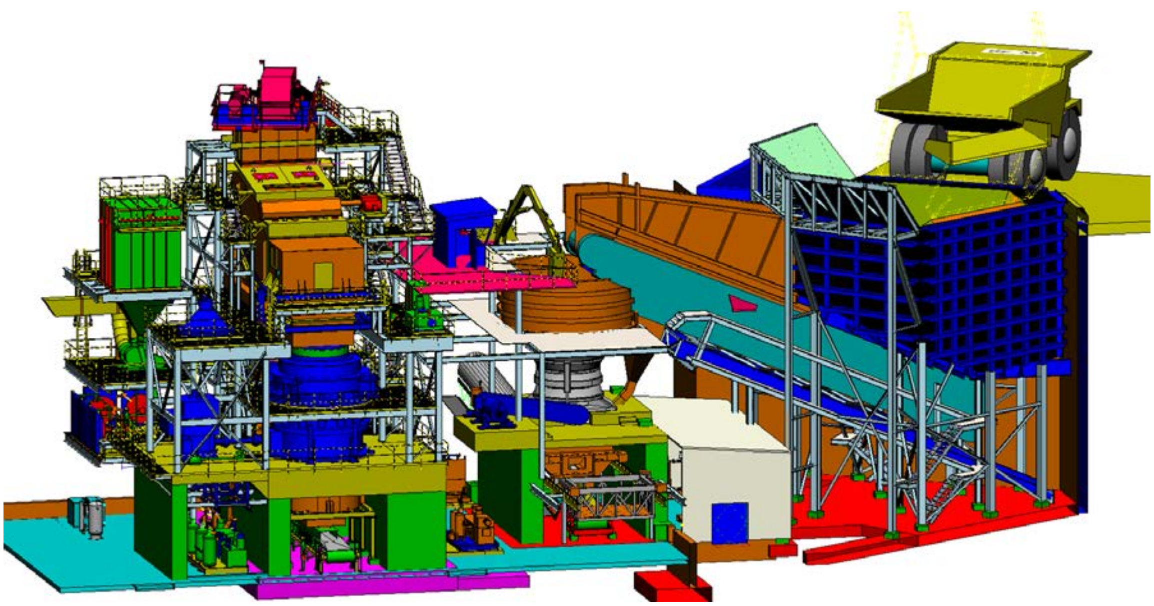

Figure 12 – Project #1 Alternative primary and secondary crushing circuit 3D model

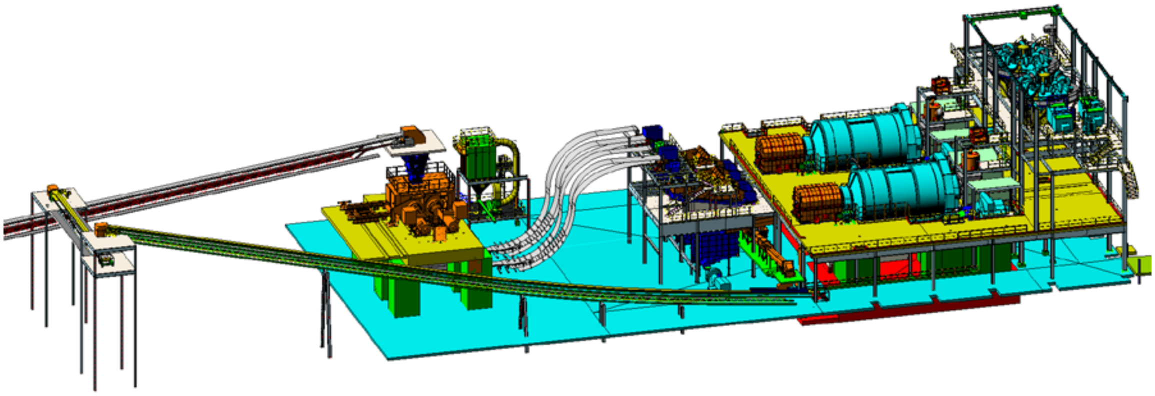

Figure 13 – Project #1 Alternative HPGR and grinding circuit 3D model

Project #2

A general layout for the Base Case 3-stage crushing circuit is presented in Figure 14 and the corresponding 3D models for the secondary and tertiary crushing, and grinding circuits are shown in Figure 15 and Figure 16. With conventional conveyors and multiple crushers, the resulting footprint is substantial and the corresponding building capital costs in a cold climate would be considerable.

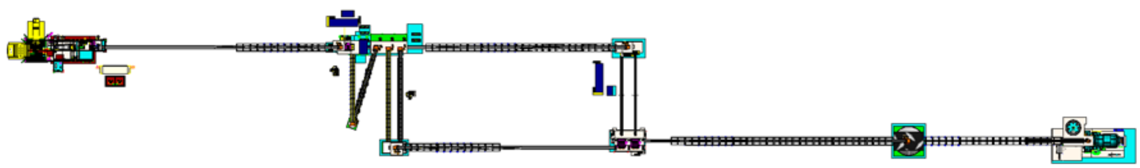

Figure 14 – Project #2 Base Case general layout

Figure 15 – Project #2 Base Case secondary and tertiary crushing circuit 3D model

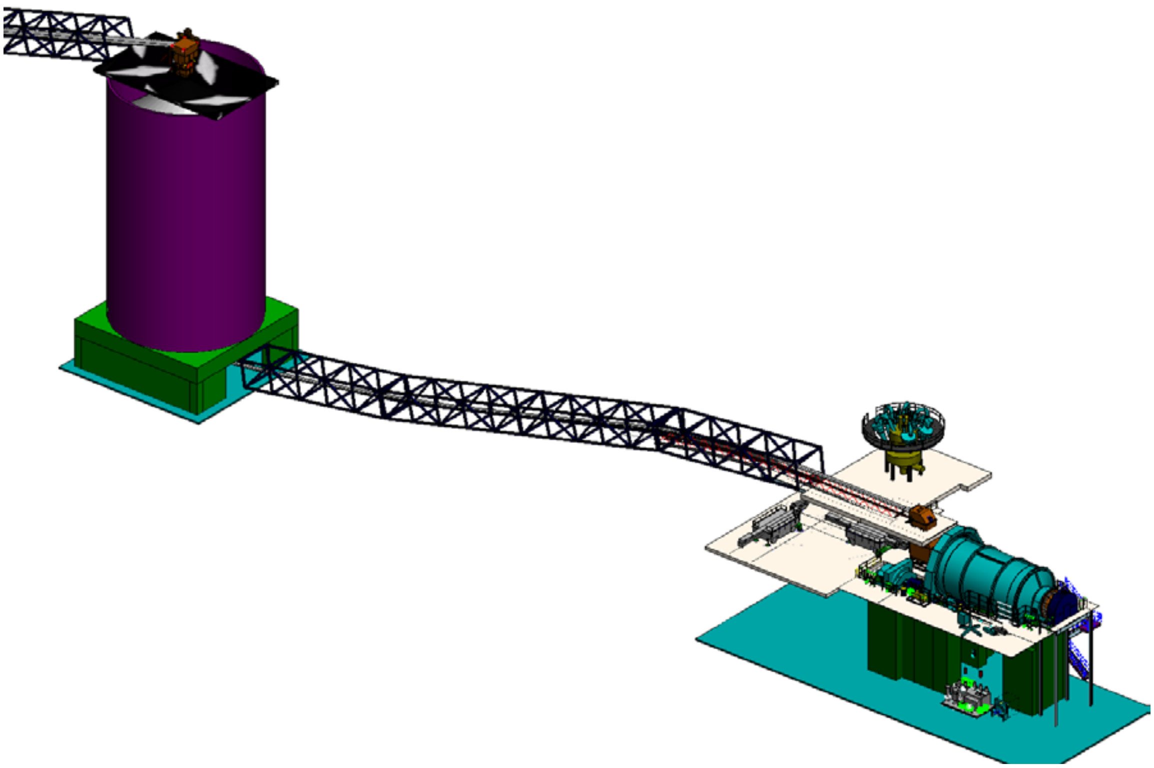

Figure 16 – Project #2 Base Case fine ore bin and grinding circuit 3D model

The general layout for the alternative circuit is presented in Figure 17 and the corresponding 3D models for the primary and secondary crushing, and HPGR and grinding circuits are shown in Figure 18 and Figure 19. The use of high-angle conveyors and modified layout design results in the reduction in footprint and overall building requirements.

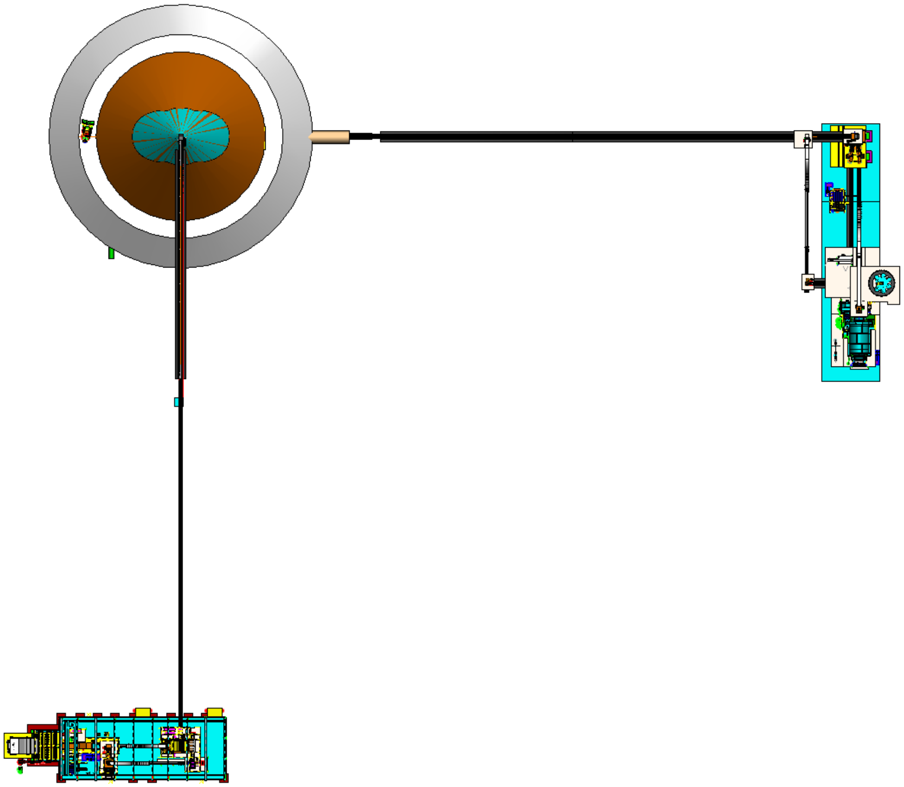

Figure 17 – Project #2 Alternative general layout

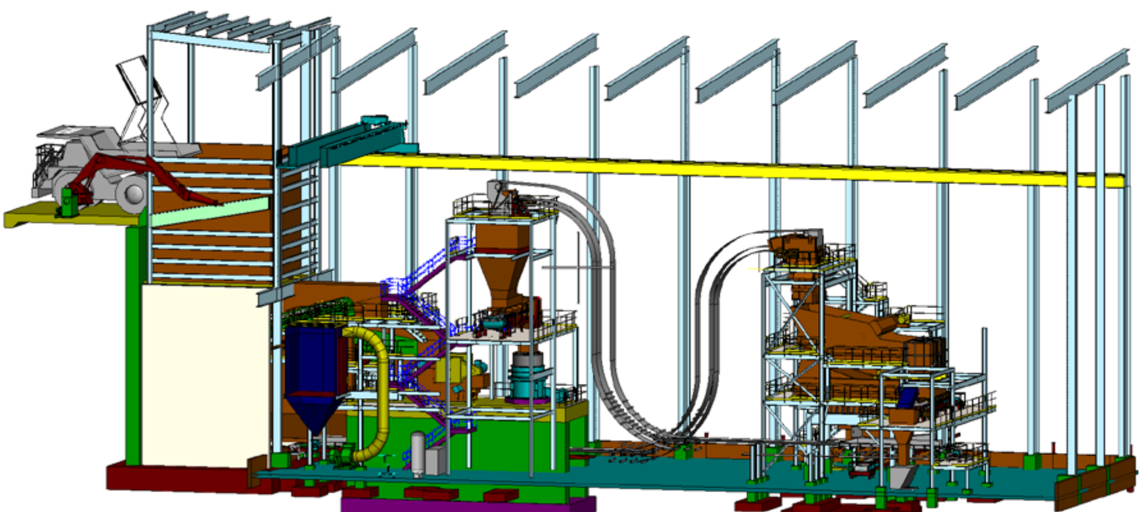

Figure 18 – Project #2 Alternative primary and secondary crushing circuit 3D model

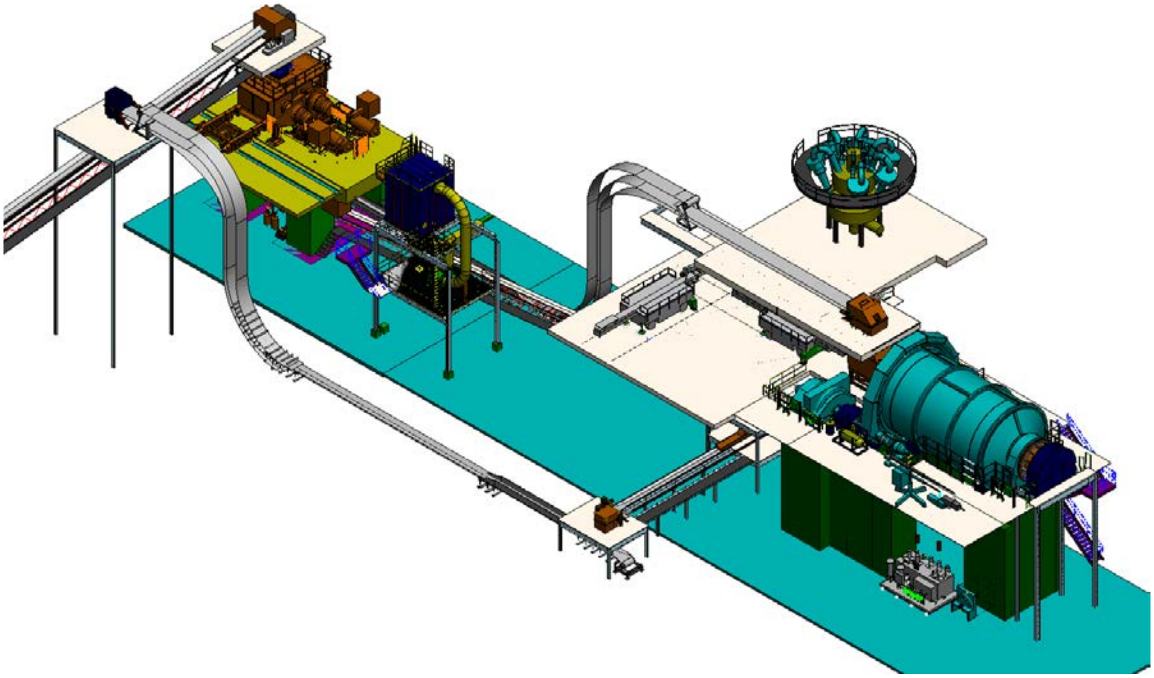

Figure 19 – Project #2 Alternative HPGR and grinding circuit 3D model

CAPITAL COST ESTIMATE

An order-of-magnitude capital cost estimate for the two projects is summarized in Table 6. The estimate was based on a combination of budgetary quotes and in-house factors. In both cases, the circuit modifications we proposed in this study resulted in a lower CAPEX. For Project #1, compared with traditional HPGR-based circuits currently installed in industry, the Alternative circuit reduced overall CAPEX by 17%. For Project #2, the Alternative HPGR circuit reduced CAPEX by 15% over a traditional 3-stage crushing circuit. In both cases, the substantial drop in CAPEX should make for a more favourable comparison with standard SABC circuits.

Table 6 – Order of magnitude cost comparison

	Direct Cost (,000 CAD)	Indirect Cost (,000 CAD)	Total Capital Cost (,000 CAD)
Project #1 – Base Case Circuit	$240,200	$154,400	**$394,600**
Project #1 – Alternative Circuit	$197,600	$129,400	**$327,000**
Difference	***$42,600***	***$25,000***	***$67,600***
Project #2 – Base Case Circuit	$89,800	$56,800	**$146,600**
Project #2 – Alternative Circuit	$75,400	$48,900	**$124,300**
Difference	***$14,400***	***$7,900***	***$22,300***

CONCLUSION

The two alternative HPGR-based circuits we propose in this paper are not revolutionary, but have achieved the stated objective of decreasing the overall capital costs for the project. For the 50,000 t/d option (Project #1), by shifting the coarse ore stockpile to after secondary crushing, operating secondary crushing in open circuit, utilizing the largest commercially available HPGR unit and eliminating large surge bins, the Alternative circuit reduced capital costs by 17% compared with traditional circuit configurations currently installed in industry. For the 15,000 t/d option (Project #2), the application of HPGR technology, elimination of a fine ore bin and the reduction in footprint with high-angle conveyors resulted in a decrease in capital costs of 15% compared with traditional 3-stage crushing. With the current capital cost sensitivity for most Greenfield projects, the modifications summarized in this paper should help make HPGR-based circuits more competitive.

ACKNOWLEDGEMENTS

The authors wish to thank Hatch senior mechanical designer Scott Perkins for the well-thought out layouts and corresponding 3D models, Hatch mechanical engineer Mike Kaplan for assistance in conveyor sizing and S&PC designer Arbelle Laguador for the assistance in generating flowsheets.

REFERENCES

Broeckmann C., & Gardula A. (2005). Developments in high-pressure grinding technology for base and precious metal minerals processing. *Proceedings of the 37th Annual Meeting of the Canadian Mineral Processors*, Jan. 18-20 2005, Ottawa, Canada.

Dunne, R., Hart, S., Parker, B., & Veillette, G. (2007). Boddington gold mine – an example of sustaining gold production for 30 years. *Proceedings of World Gold 2007 Conference*. Oct. 22-24 2007, Cairns, Australia.

Gruendken, A., Matthies, E., & van der Meer, F.P. (2008). Flowsheet considerations for optimal use of high pressure grinding rolls. *Proceedings of MEI Comminution '08 Conference*. June 17-20 2008, Falmouth, Cornwall, UK.

Hart, S., Parker, B., Rees, T., Manesh, A., & Mcgaffin, I. (2011). Commissioning and ramp up of the HPGR circuit at Newmont Boddington Gold. *Proceedings of the 2011 International Conference on Autogenous, Semi-Autogenous and High Pressure Grinding Technology.* Vancouver, Canada.

Jacobson, D., & Lamminmaki, N. (2013). Pilot study on the influence of eccentric speed on cone crusher production and operation. *Proceedings of the 2013 SME Annual Meeting.* Denver, CO, USA.

Jankovic, A., Valery, W., Sonmez, B., & Oliveira, R. (2014). Effect of circulating load and classification efficiency on HPGR and ball mill capacity. *Proceedings of the XXVII International Mineral Processing Congress.* Santiago, Chile.

Morley, C. (2006). Flowsheets for HPGR. *Proceedings of the 2006 International Conference on Autogenous and Semi-Autogenous Grinding Technology, 4*, 172-189. Vancouver, Canada.

Morley, C., & Daniel, M. (2009). HPGR Flowsheets – The Next Generation. *Proceedings of PROCEMIN 2009.* Santiago, Chile.

Pincock, Allen & Holt Consultants. (2011). *Technical Report for the Sierra Gorda Project, Chile.* Prepared for Quadra FNX Mining Ltd. Retrieved from www.sedar.com.

Rosario, P.P., Boyd, K., & Grundy, M. (2009). Recent trends in the design of comminution circuits for high tonnage hard rock mining. In D. Malhotra, P.R. Taylor, E. Spiller, & M. Levier (Eds.) *Recent Advances in Mineral Processing Plant Design* (pp. 347-355). Society for Mining, Metallurgy and Exploration, Inc. (SME).

Rotzinger, R.J., & Major, K.W. (2011). Gibraltar Mine SAG mill expansion grinding circuit design. *Proceedings of the 2011 International Conference on Autogenous, Semi-Autogenous and High Pressure Grinding Technology.* Vancouver, Canada.

Seidel, J., Logan, T.C., LeVier, K.M., & Veillette, G. (2006). Case Study – Investigation of HPGR suitability for two gold/copper projects". *Proceedings of the 2006 International Conference on Autogenous and Semi-Autogenous Grinding Technology, 4*, 140-153. Vancouver, Canada.

Vanderbeek, J. (2006). HPGR implementation at Cerro Verde. *Proceedings of the 2006 International Conference on Autogenous and Semi-Autogenous Grinding Technology, 4*, 45-61. Vancouver, Canada.