INTRODUCING eHPCC TO INTERNATIONAL MINERAL PROCESSING COMMUNITY

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ABSTRACT

This paper introduces novel comminution flowsheet concepts involving a novel apparatus, eccentric-high-pressure-centrifugal-comminution (eHPCC), and forthcoming advantages to the international mineral processing community. eHPCC is one-machine synergising high-pressure-rolling-surfaces, high-intensity-attrition and centrifugal classification. eHPCC has demonstrated: an absorbed-power-intensity of 4 MW/m^3; receipt of lump feed whilst producing 80% of product particles less than (p80) 120 µm (choke-fed, dry, open circuit without grinding media; an inert comminution environment); tramp metal tolerance, and a minimum embodied-free-energy saving of 15% as compared against conventional comminution (this comparison withstanding 133-times difference in throughput). Furthermore, this paper introduces: process design and operating characteristics of eHPCC (wet, dry, with and without grinding media); reline considerations (vertical-lift without confined-space). The international mineral processing community is invited to consider eHPCC as an alternative to conventional comminution circuits and/ or complimentary so as to enhance existing process flow sheets.

KEYWORDS

High-pressure, high-intensity, stirred-attrition, energy-efficient, inert, dry, wet, autogenous, comminution, grinding-media, ROCKY DEM

INTRODUCTION

Eccentric-high-pressure-centrifugal-comminution (eHPCC) was conceived in 2013 (Patents pending) and has the potential to eliminate the in-efficiencies and complexity of conventional tumbling mill circuits. During the development and testing phase eHPCC demonstrated improved energy efficiency and sustainability offsets.

eHPCC will compliment any upstream feed source, be it run-of-mine (ROM), primary crushed rock, or any other conventional comminution stream such as tumbling mill oversize. Another novel-emerging technology, Conjugate Anvil-Hammer Mill (CAHM) (Nordell and Potapov, 2011), receiving ROM, will be a complimentary open-circuit feed to eHPCC for very high throughput flow-sheets.

eHPCC may compliment downstream process requirements through selective mineral liberation. Selective mineral liberation is entirely feasible as the ore is comminuted upon itself (autogenously) in the high pressure zone caused by the synchronous rotating components.

To date, a laboratory scale eHPCC has been manufactured and tested. This machine has demonstrated to receive ore less than 30 mm and comminute the ore within a dry, media free environment to approximately 80% passing 120 µm. The feed is choke-fed dry with internal classification of liberated minerals as soon as they are produced. This promotes the concept of selective mineral liberation in an open-circuit inert comminution environment. The feed size will scale up with eHPCC.

The energy efficiency of the novel device has been compared to full-scale conventional mills in the laboratory and has been shown to be 15% more energy efficient (Roper, 2015). The energy efficiency at the laboratory scale takes into consideration the benefit arising from eliminating embodied-free-energy associated with not having to use steel grinding media. Laboratory tests tend to have high motor in-efficiencies, so these reported scale up energy benefits are expected to improve (Roper, 2015).

In addition to the physical testing of eHPCC in the laboratory, modern discrete element modelling (DEM) via Rocky Inc. software is improving understanding of the breakage mechanism and process within the grinding chamber.

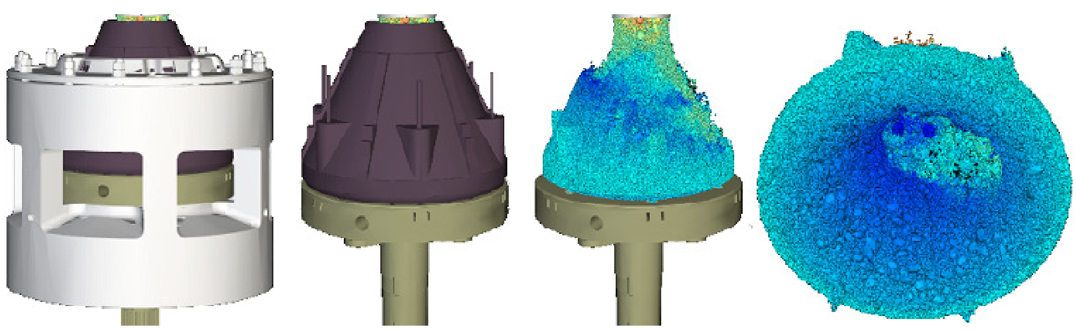

Figure 1 – DEM snapshots of eHPCC grinding chamber being charged

eHPCC DESIGN PHILOSOPHY

eHPCC utilises the mechanism of low-velocity particle-bed breakage; similar to that of vertical-roller mill and high-pressure-grinding-roll (HPGR) technology whose geometries are schematically depicted in figure 2.

eHPCC is an evolution of the same, except the opposing surfaces (or rolls) rotate around the same axes, which are parallel to each other, vertical, and selectively offset depicted in figure 3.

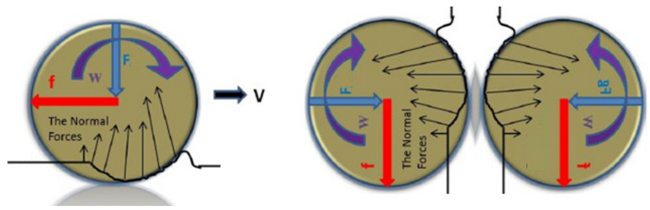

Figure 2 – Schematic geometries of vertical roller mill (left) and HPGR (right) - horizontal side view

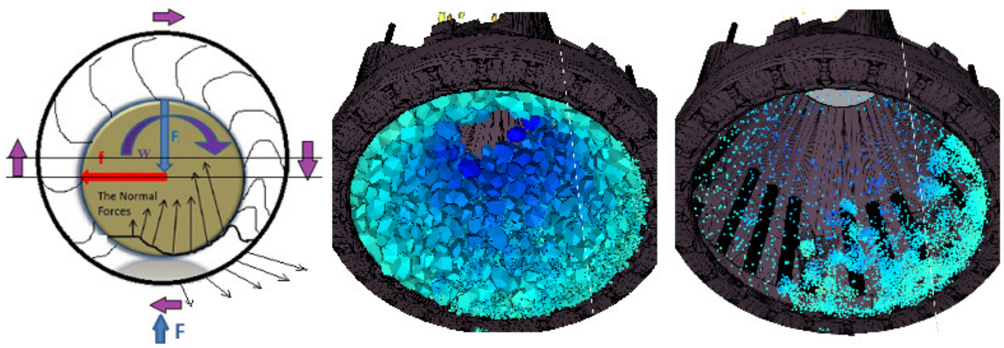

Figure 3 – Schematic of eHPCC (left), eccentric-particle-bed (middle) and particle fracture sites (right)

The notable differences in the geometry of eHPCC, shown in figure 3 (left) as compared against figure 2, are: a) the angle between the tangents of each rolling surface (otherwise known as nip-angle) never exceed nominally 5 degrees; and b) the minimum distance between rolling surfaces exceed the top size of particles entering the machine. The benefits in favour of eHPCC are that of enhanced engagement of compressive forces normal to the rolling surfaces (minimizing motion of particles on the roll surface in the nip zone; minimizing skiving and wear) and tolerance of tramp metal inside the machine (the tramp metal never bridges the gap between rolling surfaces; and will aid comminution). The DEM modelling images in figure 3 (middle and right) show the result from rotating the particles and machine elements in sync 1/3 of a turn around their axes; the high pressure zone is on the right of the axes.

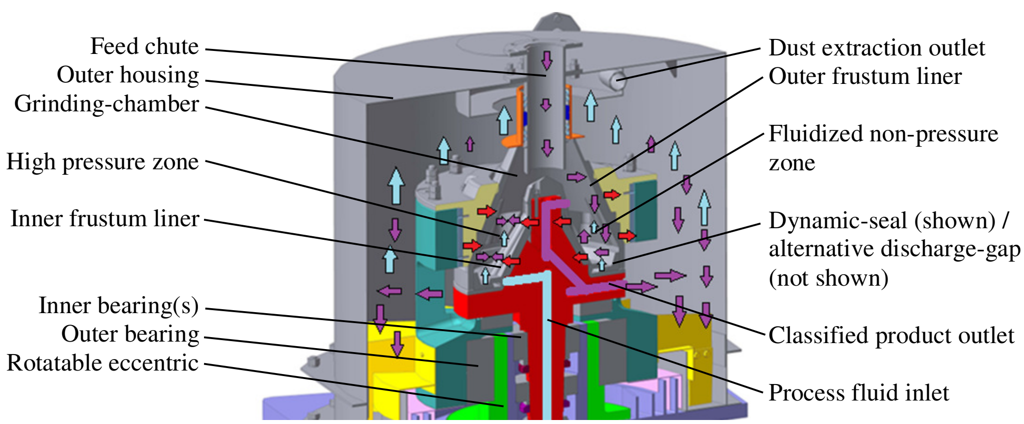

Figure 4 – Sectional view of eHPCC

eHPCC synergises high-pressure-rolling-surfaces with high-intensity-attrition in a continuous sinusoidal action. The fluid-flow dynamics within the eHPCC, and its capability of selectively retaining oversize particles, enables discrete classification. This is enhanced by optional counter-flow sweeping of product particles from the grinding chamber with process fluid via the shaft (Roper, 2015).

A pressure gradient from inside to outside the grinding chamber establishes product flow. With air this is established using a dust extraction system drawing air from the outer housing, and with water this is achieved by centrifugal force (similar to an impeller). This is partially demonstrated in figure 4 (the process fluid in this case is gas; note the colour of fluid versus that of particles). Feed particles enter by gravity through the top feed chute, air is drawn from the top of the housing, and product falls to the bottom.

We have designed eHPCC with intent of eliminating the time-consuming, obscure, hazardous, lifting, handling and fastening practices used to re-line conventional equipment (I.e., horizontally in and out of the confined space of tumbling-mills). Figure 5 presents a story-board of eHPCC design philosophy adopted so as to remove confined space, minimise the number of lifts and time to achieve a grinding-chamber re-line. Note: the rotatable-spare grinding-element-assembly (complete with the highest loaded bearings in the machine), and the vertical lifting method.

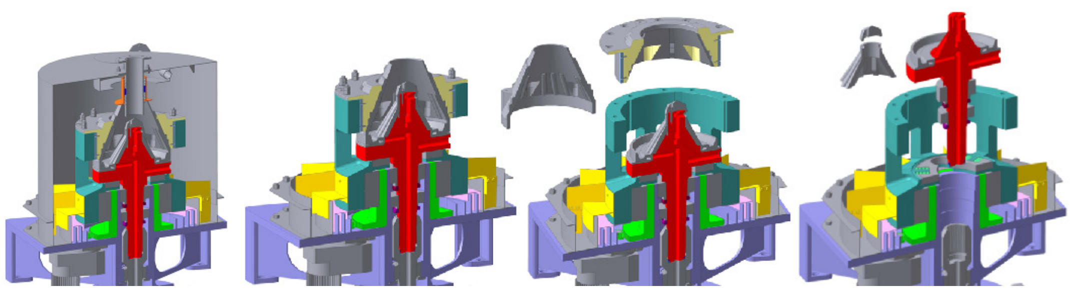

Figure 5 – Story-board of eHPCC reline - showing liner change design philosophy

Let us consider the two options of discharge-gap and/or dynamic-seal at the bottom of the grinding chamber, shown in figure 6 (at relative rotational positions 0°, 180°, and 360°). The outer/upper frustum liner(s) oscillate relative to the inner/lower frustum liner(s) as they rotate around their static offset axes. The distance between the rolling frustum surfaces reduces on one side and increases on the other side of the axes. The inner and outer liners oscillate in the radial direction, parallel and in the opposite direction to each other. There is no relative movement in the axial-direction.

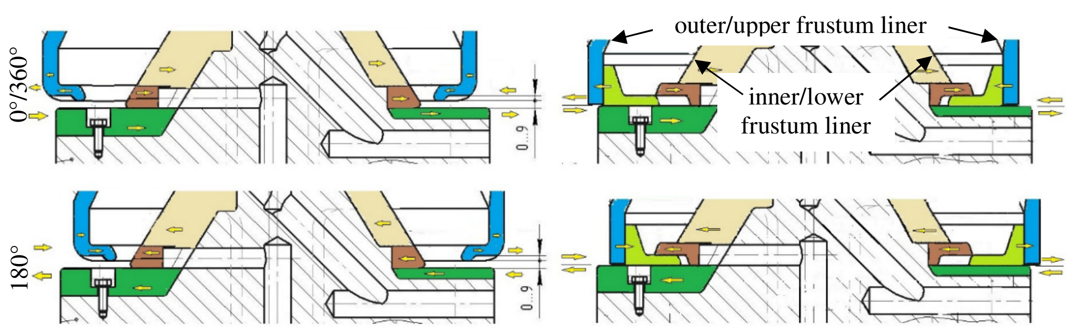

Figure 6 – Sectional-views of liners - discharge gap (left) and dynamic seal (right) – shown eccentric

With regard to the discharge gap (figure 6 (left), product particles small enough to have exited the bottom of the grinding chamber will free-flow (by centrifugal force) or roll between the upper and lower surfaces (aided by process fluid); and with regard to the dynamic seal (figure 6 (right) the process fluid entering the zone of the dynamic seal will continually clean the seal of product particles. The maximum relative velocity between the liners is 0.5 m/s for our proof of concept machine.

eHPCC CAPABILITIES

Our proof-of-concept and subsequent developmental test-work was routinely measured, documented and reported (Roper, 2014) and (Roper, 2015). An overview of outcomes and conclusions are documented here below.

The nomenclature:

f(100) 100% of feed particles less than (otherwise known as "top-size" of feed);
f(80) 80% of feed particles less than;
p(80) 80% of product particles less than;
p(50) 50% of product particles less than; etc.

The combinations of eHPCC machine setup and feed materials tested have been:

1. eHPCC grinding-chamber dynamically-sealed:

   - Magnetite-concentrate (53%-Fe) f(80) 9 mm: wet, dry, with and without steel grinding media;
   - Copper-nickel sulphide ore f(80) 13 mm: wet, dry, with and without grinding media;
   - Wolfram-clay ore f(80) ~13 mm: dry only without grinding media;
   - Wolfram-clay ore f(80) 2 mm: dry only with steel grinding media (2mm beads); and
   - Mountain-granite f(80) 9 mm: wet, dry, with and without grinding media.

2. eHPCC grinding-chamber discharge-gap open (without grinding media):

   - Magnetite-concentrate (53%-Fe) f(80) 9 mm: dry;
   - Copper-nickel sulphide ore f(80) 13 mm: dry;
   - Wolfram-clay ore f(80) ~13 mm: dry;
   - Mountain-granite f(80) 9 mm: wet, dry; and
   - Marble f(80) 18 mm: dry

Feed Capabilities

eHPCC comminuted all feed-material that arrived into its grinding chamber, that being wet, dry, hard or soft. The exceptions and/or limitations of feed were:

Feed Size

The following feed size limitations were observed (note: they scale-up linearly):

1. Feed chute dimensions: We designed our proof-of-concept eHPCC grinding-chamber with intent of f(100) 30 mm. Irrespective, our feed chute inside-diameter was 62 mm; hence we experienced free-flow feed into eHPCC with f(100) less than nominally 20 mm. This agrees with the industry rule-of-thumb for free-flow of material through chute openings (I.e., the largest particle-size shall be less than 1/3 of the smallest opening size, or visa-versa; 62 mm / 3).
2. The minimum distance between grinding-chamber rolling-surfaces ("minimum roll gap") dictates the tolerable size of tramp metal; this also dictates the f(100). Our proof of concept machine had a minimum roll gap of 18 mm; eHPCC tolerated steel grinding-media with diameter 18 mm (note: it did not tolerate a bed of 18mm grinding media; this is discussed further here below).
3. The maximum grinding media size, for deliberate semi-autogenous grinding (a bed of grinding media) is dictated by the same industry rule-of-thumb for free-flow of material (I.e. the smallest roll-gap is 18 mm, therefore the largest grinding media size for semi-autogenous grinding was 6 mm; 18 mm / 3)

Wet or Dry

Repeating the statement above, "eHPCC comminuted every material that arrived into the grinding chamber, that being wet or dry and hard or soft"; the moisture content of the feed was never measured during our test-work. However the following anomalies are noteworthy:

1. The wolfram-clay sample with f(80) ~13 mm, evidently containing moisture, was fed into the machine and promptly consolidated in the feed chute and in the grinding chamber; then
2. The same wolfram-clay sample, after being dried in ambient conditions of nominally 23 degrees Celsius, was free-flowing throughout all tests.

Product Size Capabilities

The following certain conclusion have been drawn with respect to product size distribution:

1. Particles are retained inside the grinding-chamber until the desired product size is achieved (true for target p80 greater than nominally 120 µm and choke-feeding); note: controlled dribble-feeding and controlled process-fluid flow are yet to be tested);
2. Product particle size distribution (PSD) is influenced by:
    a. Rotational speed (note: there is evidently an optimum speed for classification); and
    b. Wet or dry comminution (note: dry has much more discrete classification than wet).
3. Grinding media (versus not using grinding media):
    a. Did not significantly improve particle size reduction ratio; but
    b. Did improve rate of throughput.
4. Secondary classification was achieved inside the outer-housing by drawing air from the top of the housing (dust extraction). This test was done twice with wolfram-clay (the result was the same: a) with 2mm steel balls (beads) and b) without steel balls. The result was: 21% of the product (by weight) was extracted from the top of the housing with p(80) 30 µm; the balance discharged from the bottom of the housing with p(80) 120 µm.
5. When using open discharge gap (as opposed to the dynamic seal), the product p80 is similar to the gap.

Liberation Capabilities

The repetitive sinusoidal particle-bed compression/fluidization cycle is shown in figure 7. Softer species of feed (yellow) will fail under compression preferentially to the harder species (black). Harder species will remain intact and will concentrate at the lower outer circumference of the grinding chamber (centrifugal acceleration will cause them to flow and displace smaller species). Machine variables will offer ability to selectively liberate minerals and minimize energy. Figure 8 shows the larger harder quartz remaining intact (right). The concentration of these harder larger species ought to enhance comminution.

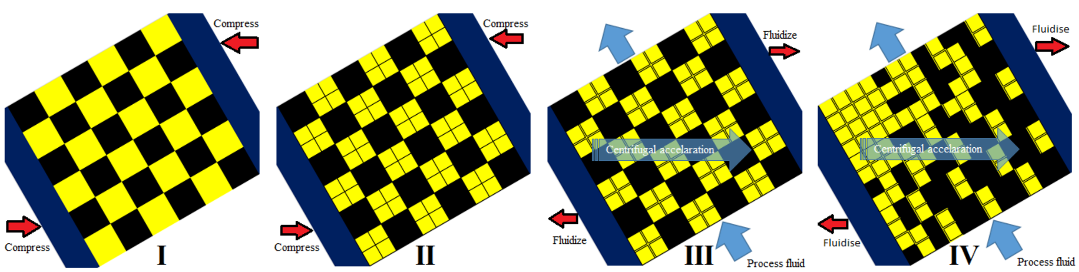

Figure 7 – eHPCC particle-bed breakage and liberation cycle

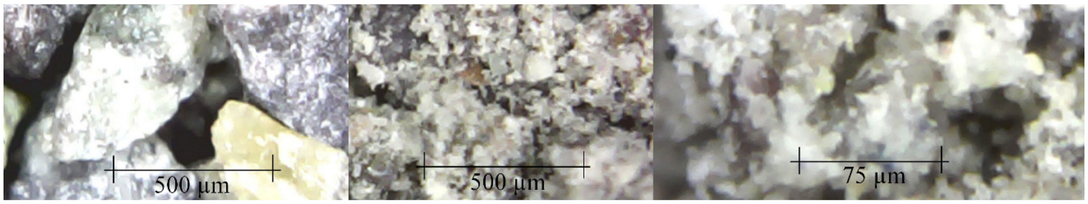

Figure 8 – mountain-granite: 1 mm to 500µm screened (left); and unscreened (middle and right)

Energy Consumption and Sustainability Capabilities

The mechanical properties of feed particles affect the specific energy demand of eHPCC. eHPCC specific energy consumption was compared against that of a conventional-comminution-circuit (Roper, 2015). The following conclusions were drawn:

1. The absorbed power intensity achievable in eHPCC grinding chamber was 4 MW/m^3 (4 kW/l) as compared to nominally 21 kW/m3 for the conventional circuit;
2. eHPCC operated choke-fed, open-circuit, dry and without grinding media as compared to the closed-circuit, wet, steel-grinding-media-consuming conventional-circuit; 15% less embodied-free-energy consumption was measured and determined; and
3. eHPCC operated with a comparably inert comminution environment.

Financial Capabilities

A discounted average cost comparison of eHPCC against a conventional 20 tph copper-sulphide ball mill grinding circuit concludes eHPCC, in lieu of the conventional circuit, will result in capital cost savings of 44%, operating cost savings in the order 24% and IRR of 70% (in lieu of the base case conventional circuit IRR of 15%) (Borissenko, V., Roper, L., 2015).

These cost benefits are achieved by: elimination of grinding media, high-intensity-high-pressure comminution that improves the unit energy consumption, reduced capital costs of auxiliary equipment (elimination of cyclones, and cyclone feed pumps, etc.), and an open-circuit with no recirculating load (Borissenko, V., Roper, L., 2015).

Scale-up Capabilities

Figure 10 presents indicative scale-up capabilities of eHPCC. This chart has been derived from empirical relationships and actual results obtained from the proof-of-concept eHPCC (1-times scale). The chart shall be considered indicative only and to be used to forecast nominal scale-up capabilities. The constants used in its derivation are: solids specific gravity (s.g.) 2.7; and target product size p(80) 150 µm.

The scale-up capabilities known to be certain are feed size and throughput. Feed size will scale-up in a linear manner with the machine size; and throughput will scale-up with a function involving an exponent of 3 (for volume). The rotational speed will reduce during scale-up by another function catering for the need to limit centrifugal-acceleration on the particles (as the grinding chamber radius increases).

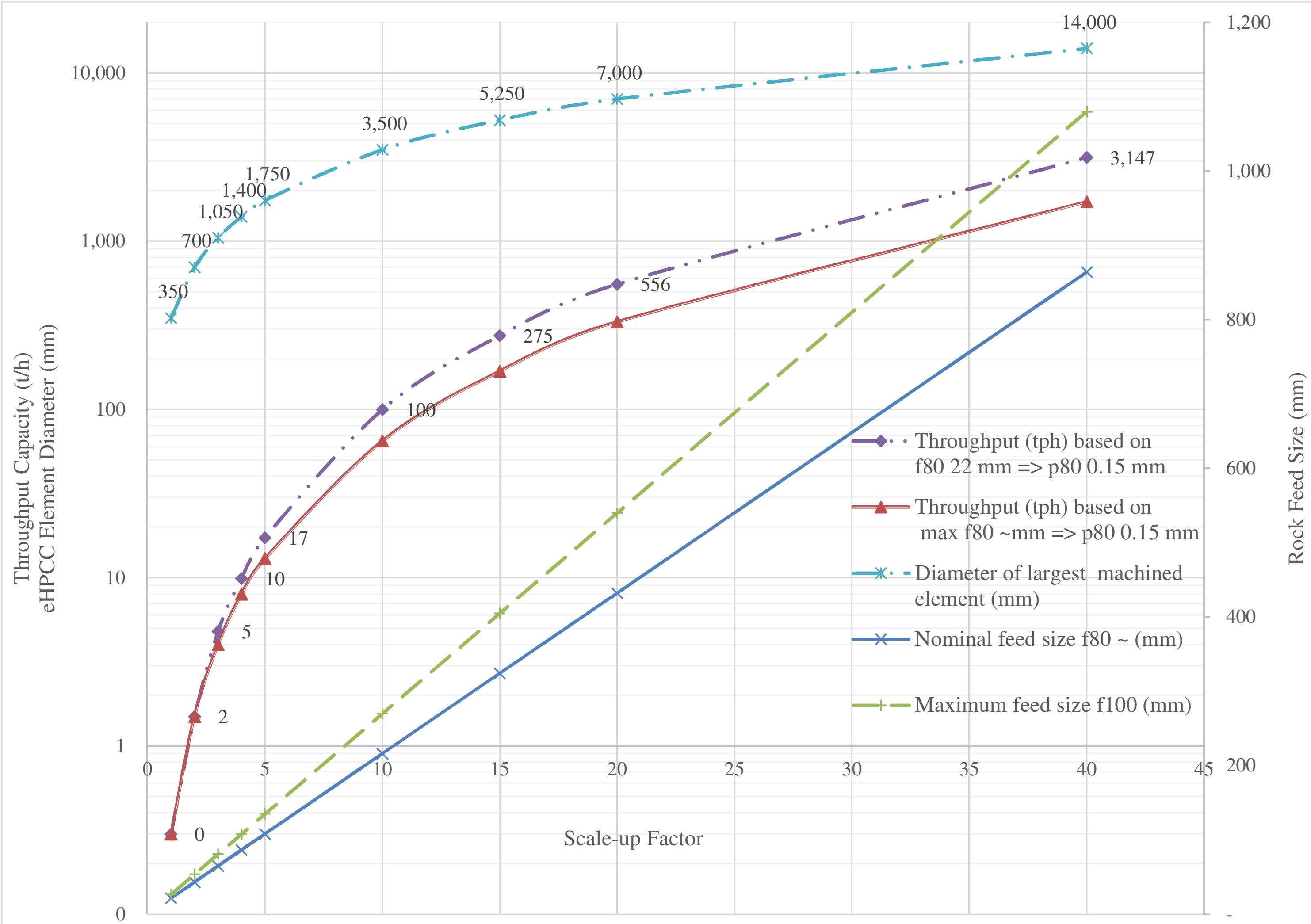

Figure 10 – eHPCC Indicative Sizing Criteria (Scaled-up)

Unexplored Capabilities

The following prospective capabilities showed promise with the proof-of-concept machine, albeit require a controlled commercial environment to be conclusive:

1. Varying eccentric-offset so as to optimise liberation and specific-energy-consumption kW.hr/t;
2. Dribble feeding with steady-state conditions so as to achieve a smaller product size;
3. Dry or wet regrinding (e.g. rougher concentrate) with steady-state conditions;
4. Grinding matte and slag;
5. Roller bearing life; and
6. Wear-liner life-expectancy; the proof-of-concept machine utilized untreated cast-steel with hardness not greater than 255HB (GOST 1050-88 Grade 45). Figure 9 shows the unworn condition of the outside receptacle (left) and worn condition of grinding-element (right) at the same operating life. Evidently the receptacle retains an autogenous protective layer whilst the grinding element does not.

Figure 9 – eHPCC grinding-chamber receptacle (left) and grinding-element (right)

PROCESS FLOWSHEET POSSIBILITIES

eHPCC is a potential alternative to conventional SAG and Ball Mill circuit(s); superseding tumbling mills, pebble crusher recycle circuits, and hydro-cyclone recycle classification circuits. eHPCC will certainly scale up to receive conventional primary crushed rock of less than 150 mm or CAHM product of less than 20-30 mm (figure 11) or ROM (figure 12) whilst offering a dry, open-circuit inert direct flotation feed (DFF; or other comparable process feed).

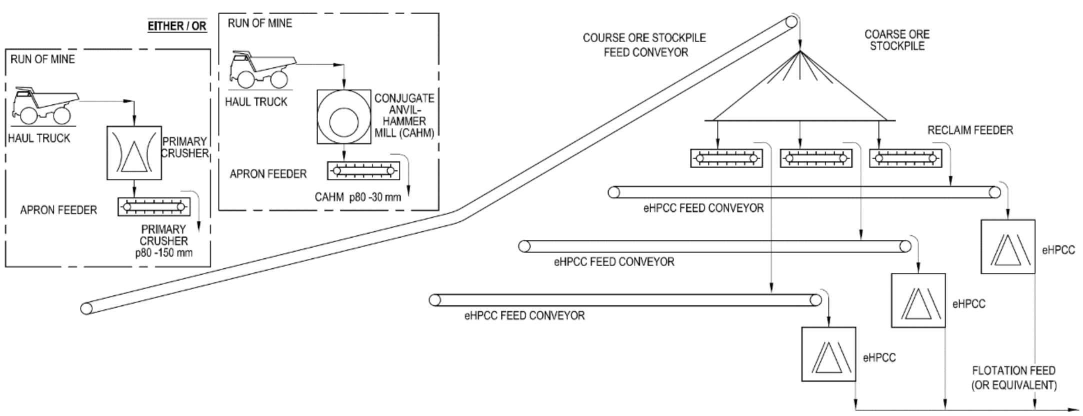

Figure 11 – eHPCC receiving primary crushed rock (minus 150 mm) or CAHM product (minus 20-30 mm)

The CAHM has potential to replace conventional crushers and SAG mill circuits with improved comminution efficiency but dry, open-circuit, and with high capacity (Nordell and Potapov, 2011); hence will certainly complement eHPCC resulting in a very high capacity efficient flowsheet for DFF.

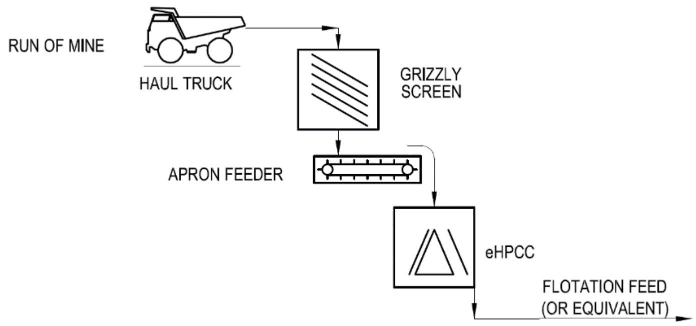

Figure 12 – eHPCC receiving ROM and producing DFF

CONCLUSIONS

Conventional SAG and ball mill circuits are well understood. Their performance has arguably reached their limit. This paper presented novel eccentric-high-pressure-centrifugal-comminution (eHPCC), its design philosophy, capabilities, and novel flowsheet concepts. The improvements/benefits of these new dry, inert, open-circuit flowsheet concepts are directly applicable and comparable to conventional process flowsheets. Engineering layout and maintenance cost-benefits are apparent I.e. less equipment, open-circuit and less overall footprint. Process-benefits include reducing water, energy, and grinding-media consumption and improving chemistry. Coarser mineral liberation and reduced liner wear require more test-work in a commercial environment to quantify benefits; this is a necessary next step.

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REFERENCES

Borissenko, V. and Roper, L., (2015). A Discounted Average Cost Comparison of eHPCC Against Conventional Cu-S Grinding Circuit. Retrieved on 16th December 2015, from https://onedrive.live.com/redir?resid=20822455E3CAB6A4%21192

Nordell, L. and Potapov, A. (2011). Novel Comminution Machine May Vastly Improve Crushing-Grinding Efficiency. Retrieved on 16th December 2015, from http://conveyor-dynamics.com/wp-content/uploads/2015/02/Novel-Comminution-Machine-May-Vastly-Improve-Crushing-Grinding-Effiency_081911_.pdf

Roper, L (2014). A Proof of Concept and Comparison of Laboratory-Scale eHPCC Against Conventional Comminution (Nov 2014) (revised 2015, July). Retrieved on 16th December 2015, from https://onedrive.live.com/redir?resid=20822455E3CAB6A4!198&authkey=!ADziuJW4z7GqzQI&ithint=file%2cpdf

Roper, L. (2015). A Performance Comparison of Laboratory-Scale eHPCC Against Conventional Comminution. In M. Evertsson (Chair), *14th European Symposium on Comminution and Classification (ESCC2015)*. Symposium conducted at Chalmers University of Technology, Gothenburg.