A Performance Comparison Of Laboratory-Scale eHPCC Against Conventional Comminution

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Abstract. This paper presents the first formal test-work of a novel *laboratory-scale* comminution device, eHPCC, and compares its performance against *full-scale* conventional comminution. eHPCC is one machine combining existing and proven comminution types of high-pressure-rolling-surfaces and high-intensity-attrition. This combination is reportedly more efficient than conventional comminution circuits (proven by others). eHPCC is the acronym for eccentric-High-Pressure-Centrifugal-Comminution. The laboratory-scale eHPCC was designed for feed-top-size (f100) of 30mm. The nominal absorbed power during test-work was 10kW. The grinding chamber volume was 2.5litres, resulting in absorbed-power-intensity of 4kW per litre (4MW/m3). The outside diameter of the largest machined element was 350mm. Feed particles and conventional comminution data of dry-magnetite-concentrate, with 80% of particles less than (f80) 9mm, were used for the comparison. eHPCC produced a product with 80% of particles less than (p80) 120μm (with p50 40μm, and p20 18μm); this was achieved in a choke-fed dry open circuit without grinding media. A nominal energy saving of 15% was achieved (without accounting for differences in scale). This paper supports the decision for scale-up and proving commercial reliability, availability and complimentary extractive processes.

Keywords: High pressure rolls, high intensity, stirred attrition, energy, efficiency, inert, dry, autogenous, and comminution.

INTRODUCTION

This paper compares the performance of a novel device called eccentric-High-Pressure-Centrifugal-Comminution (eHPCC) against a conventional comminution circuit whilst addressing the subjects of sustainability and energy efficiency upstream, downstream and within comminution and classification. eHPCC has previously proven to operate dry, wet, autogenously and semi-autogenously. The metric system of units are used herein.

History of eHPCC

Conceived in 2012/13, only one apparatus of eHPCC has been manufactured. It was designed for proof of concept and subjected to numerous developmental modifications, the work of which was conducted within a third-party factory environment, in the city of Almaty, Republic of Kazakhstan. Successively, test-work was planned and executed with intent to compare its specific energy demand and capabilities against equivalent conventional-comminution-circuits. A minor portion of this test and development work is the subject of this paper.

Background

Conventional comminution circuits are renowned for extreme inefficiency; having energy demands in the order of 53-80% of the overall mineral extraction process (Drozdiak, J.A., Klein, B., Nadolski, S., & Bamber, A., 2011). It has been estimated that energy efficiency ranges from 0.1% to 2% for the conventional grinding process, based on the generation of new surface area (Fuerstenau & Abouzeid, 2002,; Tromans & Meech, 2004; Whittles et al., 2006) (as cited by Wang, C., 2013). Recirculation inside tumbling mills is not readily quantifiable, and comminution relies on sporadic and uncertain attrition and impact events. Oversize particles from tumbling mill discharges are normally separated with cyclones, which are fed by slurry pumps (wet) or airflow (dry), and re-circulated to the mill feed, with a mass flow, in the order of 100 to 300% of the mill feed stream. This is common knowledge for those skilled in the industry. In recent times, high pressure grinding rolls (HPGR) were reported to increase overall energy efficiency (Fuerstenau and Kapur, 1995) (as cited by Drozdiak et al., 2011). HPGR handle particle sizes nominally 70mm to 4mm. Size reduction of the process particle is attributed to inter-particle abrasion and compression causing micro-cracking. The specific-compression-pressure (SCP) between the rolls is typically within the range of 3 to 5 MPa. Micro-cracking of the process particles are claimed to benefit downstream comminution. HPGR feed and product sizes and moisture content are limited; caused by roll geometry and loss of friction on the rolls (Wang, C., 2013). Another technology, known as horizontal (or vertical) high intensity stirred milling, adapted from the pharmaceutical and related industries, helps process fine grained ore effectively. This method consists of a cylindrical tube with centrally-rotating shaft, mounted with evenly-spaced grinding discs, and loaded with small ceramic grinding media (typically 2 - 6 mm) whilst operating at high speeds, the equipment utilizes high-intensity attrition to reduce the size of particles. The combination of small grinding media and high media velocity has been shown to improve the energy efficiency of grinding to fine particle sizes (Burford & Clark, 2007) (as cited by Drozdiak et al., 2011). Inert-comminution, resulting from non-steel grinding media, is desirable for protecting and enhancing the chemical activity of fresh particle surfaces with process reagents. Within conventional circuits, this demands the elimination (or substitution) of traditional steel grinding media, a significant site of oxidative reaction, causing iron hydroxide coatings on mineral surfaces. Xstrata has achieved this with IsaMill by substitution of steel grinding media with other inert grinding media in a much smaller grinding chamber volume (Pease, J.D., Curry, D.C., Barns, K.E., Young, M.F., & Rule, C. 2004). Xstrata Technology and Xstrata Zinc, report this has a profound and compelling impact on the flotation of fine-grained ore bodies. Furthermore, Xstrata conclude, "The availability of large-scale efficient inert grinding mills could have profound impact on circuit design for many ore bodies." (Pease et al., 2004). Xstrata have successfully scaled up their IsaMill to accommodate courser grain sizes and larger throughputs with an inert-comminution environment. The feed size to these mills remain relatively small despite their successful scale up.

The power intensity of different grinding devices is an interesting subject and well defined - also by Xstrata. Their publication indicates the following nominal intensities: Autogenous Mill 18kW/m3; Ball Mill 21kW/m3; Regrind Ball Mill 19kW/m3; Tower Mill 42kW/m3; High-Intensity-Stirred Mill 280kW/m3 (Pease, J.D., Young, M.F., & Curry, D.C., 2004). Two stage HPGR – stirred mill circuits have energy savings of 15-36% as compared to AG/SAG – ball mill circuit (Wang, C., 2013).

Grinding media is an energy intensive consumable, traditionally manufactured of steel using forging with free-energy-change in the order of 19,800 kWh/t (converted to metric units) of steel; this is the sum of free-energy-change of coking, smelting, production of ferroalloys, manufacture of raw steel and then forging (Berry, R.S., & Fels, M.F., 1973).

Noteworthy (paraphrased): "Grinding power accounts for 26% and media 22% of total costs; the two are related, because media wear is generally proportional to the power consumed in grinding" (Jameson, G.J., 2013).

Philosophy 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 controlled discrete classification. This is enhanced by counter-flow sweeping of product particles from the grinding chamber with process fluid.

eHPCC, schematically shown in figure 1, has two frustum roll surfaces, one inside the other, eccentric, and rotating in the same direction; their axes are vertical, offset and parallel. The annulus between these rolling surfaces, the grinding chamber, is open at the top to receive feed, and restricted and/or closed at the bottom so as to selectively control the maximum size of product; the bottom of the grinding chamber may be closed using alternative geometry. The rotational speed of the grinding chamber is sufficient to separate particles according to size and density using centrifugal force within the fluidized particle bed on the non-pressure side of the chamber (Stokes Law).

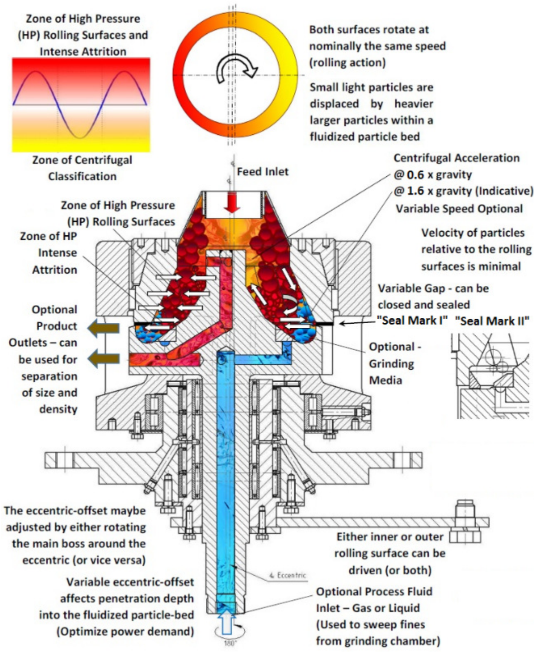

FIGURE 1. eHPCC Process Schematic.

All particles are certain to receive cyclic high-pressure and high-intensity attrition as they flow from the top to the bottom of the rotating chamber. The grinding chamber compresses its content once per revolution with a sinusoidal high pressure wave; the opposite side of the axis of rotation opens the grinding chamber annulus permitting fluidized forced particle flow. When the lower grinding chamber annulus is closed (optional), the fine and/or less dense product is displaced by the coarser and/or denser product and separates toward the central axis, according to Stokes Law, and is swept, with process fluid, to the top of the grinding chamber, where it then overflows into the cavities of the inner frustum then out of the machine. The retention-time/ number-of-cycles the particles are ground can be controlled by adjusting the feed rate of particles and/or fluid into the grinding chamber. The selectively adjustable variables are feed rate, eccentric offset between axes, rotational speed, particle characteristics (size, density, unconfined-compressive-strength (UCS), Poisson's ratio) and fluid viscosity. Process fluid may be forced into the bottom of the grinding chamber, via an inner passage of the grinding element shaft, so as to sweep the grinding chamber of product particles. eHPCC may be operated with or without grinding media; the density of which must be greater than the bulk density of the feed particles, and the diameter of which must be less than 1/3 the minimum roll gap. eHPCC is tolerant of tramp metal due to the minimum roll gap being greater than the feed top size (f100).

The energy demand of eHPCC can be calculated on the basis of the rolling resistance force (similar to a wheel on a flat surface). This rolling resistance translates into resistance-torque whilst the inner grinding element penetrates the grinding-chamber-bed-of-particles. The limit of resistance is dictated by UCS of feed particles and Poisson's ratio. Calculations rely on host rock UCS being converted to point load index (PLI) as defined by The International Society of Rock Mechanics (ISRM). PLI is assumed equivalent to SCP. SCP is used in conjunction with a defined ratio of particle size reduction per cycle, volume per cycle, rotational speed and an empirical form of the grind-ability laws (influenced by high probability of comminution events - not published herein or peer verified). Centrifugal force and consequential hindrances to particle flow were ignored. The grinding-chamber nip-angles remain less than 5 degrees for all settings and geometric locations within the grinding chamber (radial and axial). A fluid pressure gradient from inside to outside the grinding chamber is required for product flow: with air this is established using a dust extraction system; with water this is achieved naturally by centrifugal force.

Laboratory-scale eHPCC

The laboratory-scale eHPCC was designed for typical mineral-bearing-ore types. The design SCP was 16MPa (particles with UCS up to 355MPa). Figures 2 to 5 show the assembly of eHPCC, complete with auxiliaries. The installed motor was 22kW 8 pole (740RPM) with belt transmission ratio of 2.45. Electrical variables were controlled and measured using Goodrive-200-Inverter, a constant-torque variable-frequency-drive (VFD).

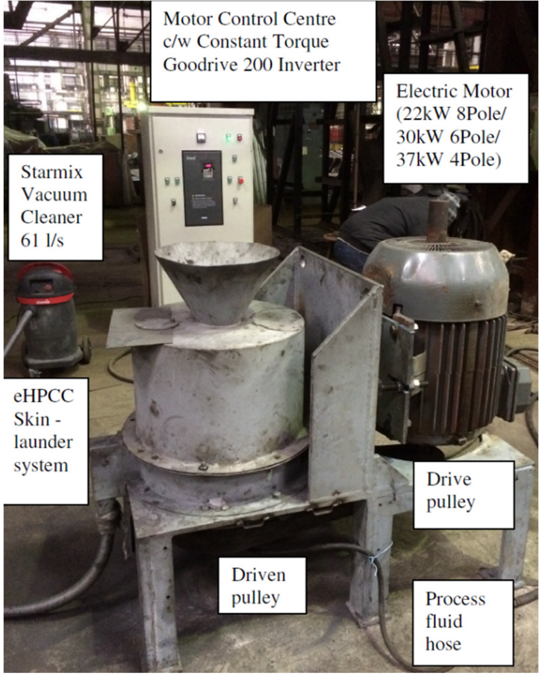

FIGURE 2. Laboratory-scale eHPCC.

Seal Mark I, as shown in Figure 1, was used during the initial testing campaign, and later Seal Mark II was created and tested during a subsequent campaign. Commissioning and development work concluded eHPCC has a threshold of speed, above which efficiency is hindered. This is demonstrated in Figure 7 herein below. The cause is assumed to be centrifugal force settling and hindering particle flow inside the grinding chamber (Stokes Law). As a consequence, there is a need to change the speed-reduction-ratio from motor to the eHPCC by a magnitude of 2. However, there was insufficient real-estate on the present belt-driven machine to do this modification. The speed was limited using the said VFD, and the motor operated in a compromised range of its performance curve.

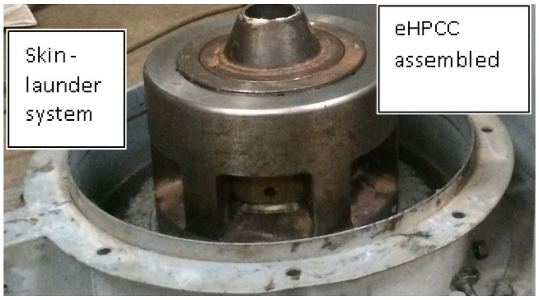

FIGURE 3. Laboratory-scale eHPCC without top skin showing the launder system.

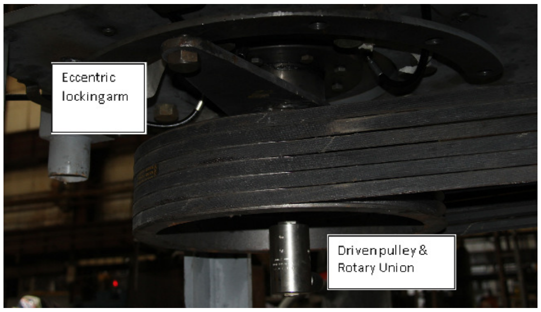

FIGURE 4. Laboratory-scale eHPCC showing eccentric locking system underneath base-frame.

FIGURE 5. eHPCC – Electric motor nameplate.

METHOD

Conventional Circuit

A dry concentrate of magnetite ore containing 53%-Fe with 80% of particles less than (p80) 9mm was tested and reported. The magnetite concentrate originated from iron ore of the Bapy deposit, care of BAPY Mining LLC, Kazakhstan. It is monogenic magnetite. The magnetite content of the run-of-mine varies from insignificant fractions in poor ore, and up to 80-90% in rich ore. The rock forming minerals include diopside and serpentine, the content of which varies considerably. Other abundant mineral is talc. The UCS of the host rock ranges from 20MPa to 50MPa.

Prior to the wet grinding circuit, the run-of-mine magnetite ore undergoes crushing, screening and dry magnetic separation resulting in p80 9mm containing 53.8% Fe in the form of Fe_2O_3 and FeO in the form corresponding to magnetite.

BAPY Mining LLC use a conventional wet process for comminution of their concentrate; consisting of open-circuit rod-mill with vibrating-sizing-screen in series with a closed-circuit ball-mill coupled with hydro-cyclones catering for a 300% recycle load and resulting in 80% of particles less than 74μm. The combined energy demand is reported to be 40kWh/t at 40tph. This specific energy demand shall be converted to an equivalent motor-shaft power basis for direct comparison with eHPCC test-work; assume a conservative power factor of 0.88 and motor efficiency of 89% resulting in an equivalent 31.3kWh/t to be used for comparison purposes. The actual grinding media consumption rate was not available; hence we shall use data as follows: 0.55kg and 0.40kg of steel grinding media per tonne of magnetite feed to each of their rod and ball mills respectively (totaling 0.95kg/t) (Myklebust, J. (Ed.) 2012). This equates to 18.7kWh/t of throughput (19,800kWh/t of free-energy-change in producing the steel balls, multiplied by consumption rate of steel balls, 0.95kg/t of magnetite throughput (p.2 c.1 herein above)). The total energy demand of the conventional comminution circuit is 50kWh/t (31.3kWh/t plus 18.7kWh/t).

eHPCC Test-Work Outline

All test work reported herein, unless noted otherwise, were conducted with eHPCC discharge gap dynamically-sealed, the eccentric offset at 120° (6mm displacement between rotating axes), the use of air as the process fluid, dry and autogenous (DryAG). No-load variables of the electric motor, with and without eHPCC, were measured at three speeds i.e. hertz, amperes, and volts. All other test-work was conducted at the same three speeds. The speed of eHPCC is reported in revolutions per minute (RPM).

Feed sample mass, electrical variables, and observable comminution-time were measured for each configuration. Samples of resultant product were collected for laboratory determination of particle size distribution (PSD). An industrial vacuum cleaner (Starmix – HS AR-1645 EWS) was used to contain and collect 100% of the product; it has a capacity of 40 litres and volumetric air-flow capacity of 61 litres per second. Compressed air was delivered to the rotary union at the base of the eHPCC from the workshop compressed air system; the volumetric flow rate was not measured but restricted so as to be less than the airflow of the vacuum-cleaner; determined by observable dust containment. Each test commenced and finished with the eHPCC grinding chamber primed and full of feed sample.

Feed quantities for each test were measured using a plastic bucket on digital bathroom-type scales (to the neatest 0.1 kg). A typical 'feed' sample was grabbed for measuring PSD. 'Product' samples were 'hand-grabbed and contained', from the vacuum cleaner contents, with an inverted plastic sample collection bag covering the hand.

Laboratory Standard

Feed and product samples were delivered to and analyzed by certified laboratory, Central Laboratory (CL) – "CL GeoAnalitika" LLC, Almaty, Kazakhstan. The PSD measurement procedure was carried out in accordance to: GOST 21216.2-93 "Raw materials clay. Method of definition of fine fractions". Two specific methods: a) PSD using a pipette method for less than 500μm and b) sieve method for greater than 500μm.

RESULTS AND DISCUSSION

No-load data of motor (wired Δ-Delta) were collected. Note: a) the constant-torque-VFD has the inherent characteristic whereby output voltage is linearly proportional to the output frequency, and b) the speed reduction of the belt transmission was 2.45:1.

TABLE 1. No-load of electric motor only

VFD (Hz)	Motor (RPM)	Current (A)	Voltage (V)
15	222	38.3	109
25	370	38.5	180
35	518	38.7	254

TABLE 2. No-load of eHPCC and motor

VFD (Hz)	eHPCC (RPM)	Current (A)	Voltage (V)
15	91	39.4	113
25	151	40.0	183
35	211	40.0	254

TABLE 3. Calculated losses (difference of Tables 1 and 2)

VFD (Hz)	eHPCC (RPM)	Losses (kW)
15	91	0.008 (8 Watts)
25	151	0.008 (8 Watts)
35	211	0.000 (Nil)

Table 3 demonstrates eHPCC and its transmission has negligible power losses. The measured and then calculated mechanical output of the electric motor shaft is affected by its power factor and efficiency; and is misrepresented when the motor operates at low loads. This is demonstrated in publically available electric motor performance charts of a) Power-factor versus % of full-load-current (%FLC), and b) % of Full-load-efficiency (%FLE) versus %-full-load (McCoy, G.A., Litman, T., Douglass, J.G. (2011) Energy-Efficient Electric Motor Selection Handbook, Revision3, January 1993, DOE/CE-0384) (as cited by (Bennet, S., 2013). The interpolated value of %FLE was based on %FLC (rather than % of full-load). The shaft power for each test was calculated using VFD output current (I) and voltage (V), the motor rated full-load efficiency (η), the interpolated values of motor power factor (Cos ∅) and % of full-load motor efficiency (%FLE) as follows:

$$\sqrt{3} \,.\, I \,.\, V \,.\, \eta \,.\, \mathrm{Cos}\, \emptyset \,.\, \%FLE = P \qquad (1)$$

Figure 5 shows the motor full-load current rating of 49.3A. The motor whilst under no-load used 38.5A (Table 1) (78% of the full-load current). The VFD was a constant-torque inverter; in hindsight, it would have been more correct to interpolate the %FLE based on % of full-load power. In the majority of tests, the electric motor was loaded 20 to 50% of full-load power; the interpolated value for %FLE would be less than actually used herein, further-enhancing the reported performance of eHPCC.

Furthermore, note the significant difference in scale of the equipment; throughput of laboratory-scale eHPCC is nominally 0.3 tph, compared to 40tph for the conventional equipment. This is a factor of 133 times. We have not accounted for "economies of scale" herein. Hence, the reader shall consider the possibility of eHPCC specific energy demand being lesser again than reported herein.

TABLE 4. PSD Data of Feed – Seal Mark I

	% Feed passing particle size mm								
mm	20	10	5	2	1	0.5	0.2	0.1	0.05
%	100	86	41	13	8	6	4	3	3

TABLE 5. PSD Data of Product – Seal Mark I.

	% passing particle size mm						
RPM\mm	5	2	1	0.5	0.063	0.01	0.005
91	100	98	87	76	36	6	2
151	100	100	95	90	20	7	2
210	100	100	94	80	31	19	4

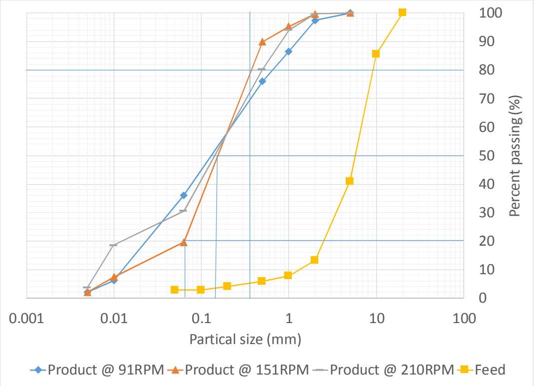

FIGURE 6. PSD - Product – Seal Mark I.

TABLE 6. Electrical - Product – Seal Mark I.

eHPCC (RPM)	**VFD (Hz)**	**VFD (A)**	**VFD (V)**	**% FLC**	**Cosϕ**	**% FLE**
91	15	68	124	138%	0.75	88%
151	25	43	190	87%	0.75	88%
210	35	42	260	85%	0.75	88%

TABLE 7. Calculated Result - Product – Seal Mark I.

eHPCC (RPM)	**Mass (kg)**	**Time (min)**	**Flow (tph)**	**Power (kW)**	**S.E. (kWh/t)**
91	10.3	1.62	0.381	9.6	25
151	10.3	1.83	0.338	9.3	28
210	10.3	5.25	0.118	12.4	106

Power was calculated using equation 1. Specific energy (S.E. kWh/t) is the result of power (kW) per unit throughput (tph). The lowest p80 achieved by eHPCC Seal Mark I was 400µm (with p50 125µm and p20 63µm) (Fig.6). This was achieved with specific energy demand at the motor shaft of 28kWh/t, choke-fed dry open circuit and without grinding media.

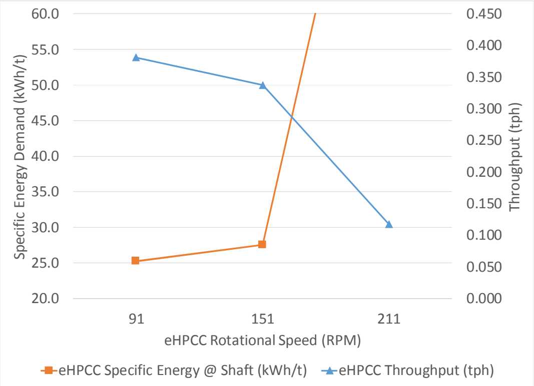

FIGURE 7. Calculated Result - Product – Seal Mark I.

eHPCC dynamic seal was then modified from Seal Mark I to Seal Mark II, as shown in Figure 1. This increased the depth and volume of the grinding chamber whilst improving the seal geometry. One additional test was conducted with magnetite concentrate yielding the following results. Note: the eccentric offset was reduced from 120° (6mm) to 60° (3mm) to cater for the additional grinding volume (and torque) within the compromised limits of the transmission and motor.

TABLE 8. PSD Data of Feed – Seal Mark II

	% Feed passing particle size mm								
mm	20	10	5	2	1	0.5	0.2	0.1	0.05
%	100	94	46	24	17	14	9	6	3

TABLE 9. PSD Data of Product – Seal Mark II.

	% passing particle size mm						
RPM\mm	5	2	1	0.5	0.063	0.01	0.005
151	100	99	97	94.2	62.2	4.8	3.3

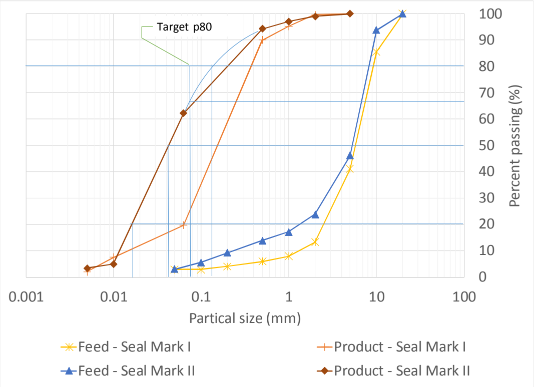

FIGURE 8. PSD - Product – Seal Mark II.

Seal Mark II achieved p80 of 120μm (with p50 40μm and p20 15μm) choke-fed dry open circuit and without grinding media (dribble-feeding would have resulted in a lower p80). The specific energy used was 36.7kWh/t (Table 11).

TABLE 10. Electrical - Product – Seal Mark II.

eHPCC (RPM)	VFD (Hz)	VFD (A)	VFD (V)	% FLC	Cosϕ	% FLE
151	25	46	189	93%	0.75	88%

TABLE 11. Calculated Result - Product – Seal Mark II.

eHPCC (RPM)	Mass (kg)	Time (min)	Flow (tph)	Power (kW)	S.E. (kWh/t)
151	15	3.33	0.270	9.9	36.7

The conventional circuit achieves p80 of 74μm whilst consuming a total equivalent specific energy of 50kWh/t. There is an energy gap to account for corresponding to the p80 gap between 120μm and 74μm; this energy gap is 7.5kWh/t; determined by applying the general form of Bond's equation with Wi = 30kWh/t (Bond (1952) (as cited by Jankovic, A., Dundar, H., and Mehta, R. (2008)). By crediting this energy gap to the conventional circuit; such that equivalent conventional circuit p80 is 120μm, its equivalent specific energy demand will be (50 - 7.5) = 42.5kWh/t.

Hence, the overall energy difference between the conventional circuit and laboratory-scale eHPCC is: ((42.5 – 36.7) / 42.5) x 100% = 13.6%; nominally 15% in favour of eHPCC.

eHPCC liner duty and life ought to be considered equivalent to HPGR. The plain surface of the outer-liner displayed evidence of autogenous buildup.

The nominal shaft power of eHPCC was 10kW; the grinding-chamber volume was 2.5litres; equating to absorbed-power-intensity of 4kW per litre (4MW/m3); this is significantly greater than conventional ball mills and high-intensity-stirred-mills (p.2 c.1) i.e. eHPCC has smaller relative footprint. Scaling-up eHPCC, will proportionally increase its f100; it is feasible for eHPCC to be fed primary crushed rock or run-of-mine. These characteristics offer potential reductions in real-estate, equipment and consumables; offering potential for in-pit/ under-ground comminution and the resulting alternative materials handling options.

Furthermore, whilst dry and autogenous, eHPCC offers inert comminution and its intrinsic benefits (p.2 c.1). Dry product could be conditioned with reagents and/or hydrated, if desired, within the eHPCC housing immediately after comminution.

CONCLUSION

Laboratory-scale eHPCC saves nominally *15%* specific energy whilst offering elimination (or significant reduction) of grinding media and water as compared against *full-scale* conventional comminution and classification; it offers opportunity to improve upstream and downstream processes; and scaled-up, will certainly improve sustainability and energy efficiency. This conclusion supports the decision to scale-up eHPCC and prove commercial reliability, availability and complimentary extractive processes.

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