High voltage breakage: A review of theory and applications

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ABSTRACT

High voltage breakage is a novel comminution technology that shows considerable potential for various applications in mineral processing and recycling. It relies on highly energetic electrical pulses to induce electrical explosions in rocks, causing the formation of plasma channels and powerful shockwaves that result in fracturing and fragmentation of particles. There has been considerable interest in this technology for its ability to weaken rocks and preferentially liberate target minerals, as previously demonstrated by other authors. Weakening has the potential to significantly reduce energy consumption during comminution, or alternatively, increase throughput of a circuit. Better liberation may yield an improved concentrate grade and/or recovery, reduce fines losses to tailings or increase the grind size required for liberation, thereby also reducing energy requirements.

This review aims to increase general awareness of this technology, and promote further research into it by providing a general summary of the theory underlying high voltage breakage, as well as the envisaged applications of this novel technology. A brief history of the technology is presented before progressing onto the physics underlying the electrical and geomechanical aspects of high voltage breakage. Key results regarding weakening and liberation are discussed, and some mention is made of current challenges and planned developments to increase the throughput of high voltage breakage units to the level where it can be integrated into new and existing processing circuits.

INTRODUCTION

Comminution is one of the major energy consumers at most mine sites (Curry, Ismay & Jameson, 2014), whilst also being a notoriously inefficient process (Tromans, 2008; Fuerstenau & Abouzeid, 2002). Consequently, there is considerable focus on improving existing comminution processes, as well as identifying new technologies that transform current comminution practices. High voltage breakage (HVB) is a novel comminution technology that fits very well into this step change framework. Although pioneered in the 50's, it only recently received serious attention. The key benefits of this technology compared to conventional comminution are its high level of selectivity (Wang, Shi & Manlapig, 2012) and its ability to weaken ore, enabling significant energy savings in the further comminution (Wang, Shi & Manlapig, 2011).

The relative novelty of the process is due to the multiple disciplines of complex physics at work during HVB. This paper aims to review the history of the technology, electrical and geomechanical processes at work during HVB, as well as an overview of key results, and a brief outline of planned developments for implementation of HVB technology in the mining industry is included.

HISTORY OF HIGH VOLTAGE BREAKAGE

Marx generators, developed by Erwin Otto Marx in 1924, are the main type of generator used to produce high voltage pulses for electrodynamic fragmentation. Prof. Yutkin from the St. Petersburg University, Russia was the first to utilize high voltage pulses for the fragmentation of rocks (Yutkin, 1955). Yutkin's unit was different from current technology in that it did not use Marx generators, and it produced shockwaves in the water rather than inside rock, i.e. it was an electro-hydraulic crusher, rather than electrodynamic fragmentation unit. His work led to further investigation into mining applications, with research at Tomsk Polytechnical University in 1960, indicating a higher voltage and shorter rise times forces the electrical discharge into the solid, marking the first research into electrodynamic fragmentation. This technology was kept a military secret until a former member of the Tomsk group emigrated and published the first article on electrodynamic fragmentation (Andres, 1977).

After the fall of the Soviet Union, the predecessor of the Karlsruhe Institute of Technology (KIT) bought an electrodynamic fragmentation unit from Tomsk. Research at KIT between 1995 and 2005 included several other units being built, including a continuous plant. The key publication from KIT is by Bluhm *et al.* (2000), who reported on HVB fragmentation mechanisms, efficiency and possible applications. The work at KIT culminated in a license agreement with the Ammann Group (Switzerland) in 2003, ultimately resulting in the formation of SelFrag who presently market a Lab system for geological research and a 2 – 3 tph continuously operating system is available for pilot planting and research. There are a number of competing systems to SELFRAG, but very limited research has been published using these technologies (see Rudashevsky *et al.*, 1995 and Saini-Edukat & Weiblen, 1996 for examples), and with the exception of CNT Mineral Consulting and their Spark-2 unit, they maintain a very low profile.

ELECTRICAL ASPECTS OF HIGH VOLTAGE BREAKAGE

Dielectric theory

Dielectrics are non-conducting materials that are capable of accommodating a propagating, alternating electromagnetic field (Cassidy, 2009). All minerals fall in this category, with the exception of some highly conductive minerals and native metals. The interaction between electromagnetic fields and dielectric solids is described using Maxwell's theory, which involves a number of vectors related to conductivity, magnetic permeability and permittivity, and it is the latter that is most relevant to HVB.

Permittivity (also known as dielectric constant, κ) is a measure of a material's ability, under the influence of an external electric field, to limit the degree of polarization or restrict flow of charge as a result of this field (Cassidy, 2009). During a high voltage pulse, a material will experience polarization at an atomic level, causing a charge to shift from its original position (dipole moment). Permittivity is a measure of proportionality between electrical field strength and the energy stored in this dipole moment (Cassidy, 2009). It is measured in Farads per meter, but often reported as relative permittivity, calculated by dividing a material's permittivity by that of a vacuum. Permittivity consists of a real component (ε') related to how strongly a material is affected by an electrical field, and an imaginary component (ε'') that describes the physical interaction between charges (Cassidy, 2009). Permittivity displays frequency-dependent behavior (see Figure 1) which includes a number of polarization mechanisms at different

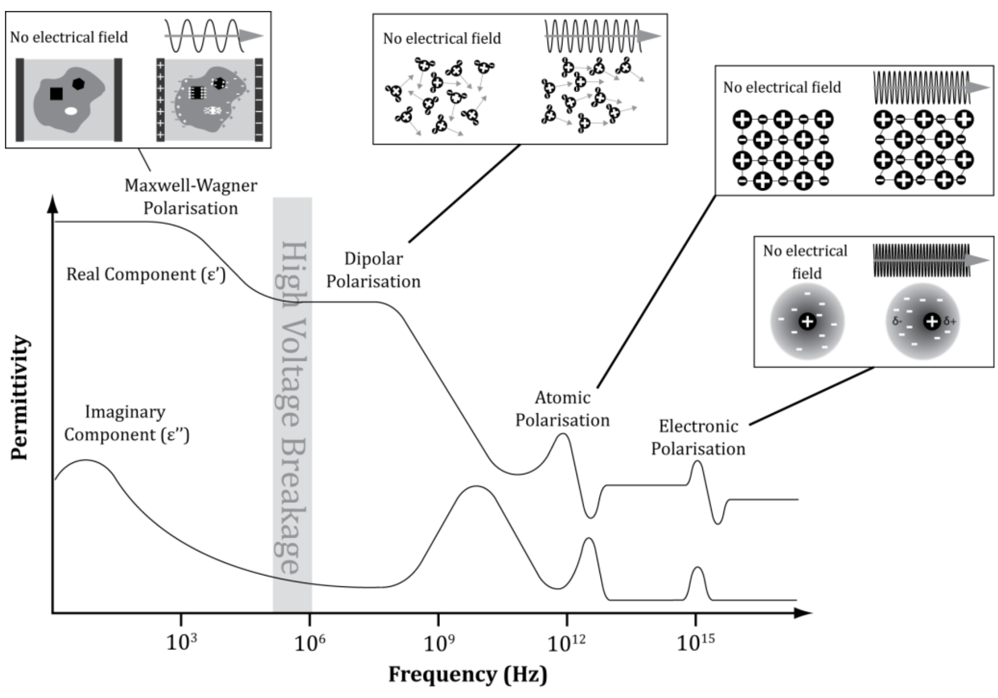


Figure 1 Schematic of frequency-dependence of permittivity including an illustration of the different polarisation mechanisms (adapted from van der Wielen, 2013; Cassidy, 2009).

frequencies. Therefore, when modelling interactions between electrical fields and dielectrics in HVB equipment it is important to use mineral permittivities measured in the 0.1 – 1 MHz frequency range (such as Olhoeft, 1979).

Electrical Breakdown

Electrical breakdown occurs when an electrical field is sufficiently strong to make a dielectric lose its resistive properties to such an extent that permanent changes occur in the atomic structure of the dielectric (Cardarelli, 2008; Budenstein, 1980). It is important to make a distinction between thermal electrical breakdown and pure electrical breakdown. The former occurs on far longer time scales (>1 s range) than pure electrical breakdown (<1 μs range), and is not relevant to HVB. Pure electrical breakdown occurs when a local electrical field exceeds the breakdown voltage. The steps in electrical breakdown involved can be subdivided into the following steps (after Budenstein, 1980; Bluhm *et al.*, 2000):

1. Application of an electrical field (i.e. a high voltage pulse) results in local re-distribution of electrical charges due to polarization, collisional ionization, and atomic displacement. Areas of high permittivity contrasts experience the strongest field enhancement and hence the largest charge imbalances. Importantly, this charge imbalance can occur inside dielectrics, for instance on grain-boundaries at the cross-cut of a chalcopyrite vein and a later quartz vein.
2. Electrical breakdown occurs where charge imbalances exceed the electrical breakdown strength. This result in the formation of a fractal-shaped plasma 'tree' whose shape is guided but not determined by local field enhancements. Multiple propagating trees and/or tips can exist during a pulse, all forming plasma streamers that are self-sustaining, displacing more and more electrons in an 'avalanche'-effect, resulting in their ever more rapid propagation.
3. Once a plasma streamer bridges the gap between discharge and ground electrode, a highly conductive path forms, and at this stage the electrical pulse from the generator forms an electrical discharge. This low-Ohmic discharge path carries very high currents, causing extremely rapid heating and expansion of the plasma channel. During this phase, vast amounts of energy are deposited over a very short period, sending very powerful shockwaves through the material.

Stage 2, initiation of electrical breakdown requires electrons that can be accelerated by an external electrical field. This field needs to be sufficiently strong to accelerate electrons, and the electrons need a mean collision free path long enough for that electron to gain ample energy to hit another electron out of its atomic orbit (Budenstein, 1980). This causes an 'avalanche' effect that, once started, is self-sustaining provided the field strength is strong enough and there is enough 'driving force' behind the streamer in the form of pulse energy (Küchler, 2005). Streamer propagation in both liquids and complex dielectrics are still poorly understood. It is thought liquid electrical breakdown is a relatively slow mechanism compared to that in solids, and in the former streamers do not react as strongly to increased field strengths. Therefore, below a certain ramp-up rate of the voltage during an electrical pulse, propagation in solids will exceed that in water. Essentially, streamer paths through the liquid and the solid are competing to reach the counter electrode. If the voltage is high enough or the rise time of the voltage is fast enough, the channel in the solids will outcompete that in the liquid, resulting in breakdown in the solids before the liquids.

During stage 2, insufficient energy may sometimes be available for a streamer to self-propagate, or too many branches exist that 'dilute' pulse energy driving the individual streamers. In this case it is possible the streamer(s) extinguish without making it to stage 3, i.e. the pulse does not cause a full discharge. Some damage may be done to the solid but the total energy deposited is insufficient to cause the desired damage for weakening/liberation. This is the major inefficiency in HVB, and the reason for the recommendation in van der Wielen *et al.* (2013) that the discharge ratio should always be as high as possible.

Electro-hydraulic crushing vs. electro-dynamic fragmentation

A continuous flow of electricity cannot efficiently deliver a sufficient amount of energy quick enough to cause pure electrical breakdown, so a pulsed technology such as a Marx generator is required. These are essentially a bank of capacitors that charge in parallel and discharge in series. Each capacitor builds up a large amount of energy and deposits it in a single pulse, adding up the energy stored in each individual capacitor to yield a pulse intense enough to cause pure electrical breakdown.

There is a crucial difference between earlier electrohydraulic crushing units (Yutkin, 1955) and later electrodynamic fragmentation units first reported by Andres, 1977. The former uses slower pulses with lower voltages (20 – 50 kV) to cause electrical breakdown in water, resulting in a shockwave that may crush rock, but limited electrical damage occurs inside the rock. Electrodynamic fragmentation uses higher voltage rise times (<1 μs) and higher voltages (>90 kV), allowing streamers to propagate faster inside the rock than in water, causing an electrical explosion inside rock. Electrohydraulic crushing is markedly less efficient than electrodynamic fragmentation due to shockwave reflection at the water/rock interface rather than penetration from water into rock, and due to shockwave energy dropping rapidly with distance from the electrode.

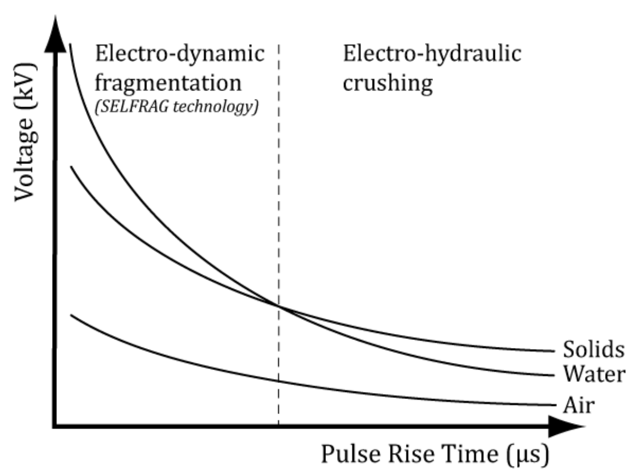


Figure 2 Schematic of the voltage – pulse rise time relationship and the type of fragmentation induced (from van der Wielen et al., 2013).

GEOMECHANICAL ASPECTS OF HIGH VOLTAGE BREAKAGE

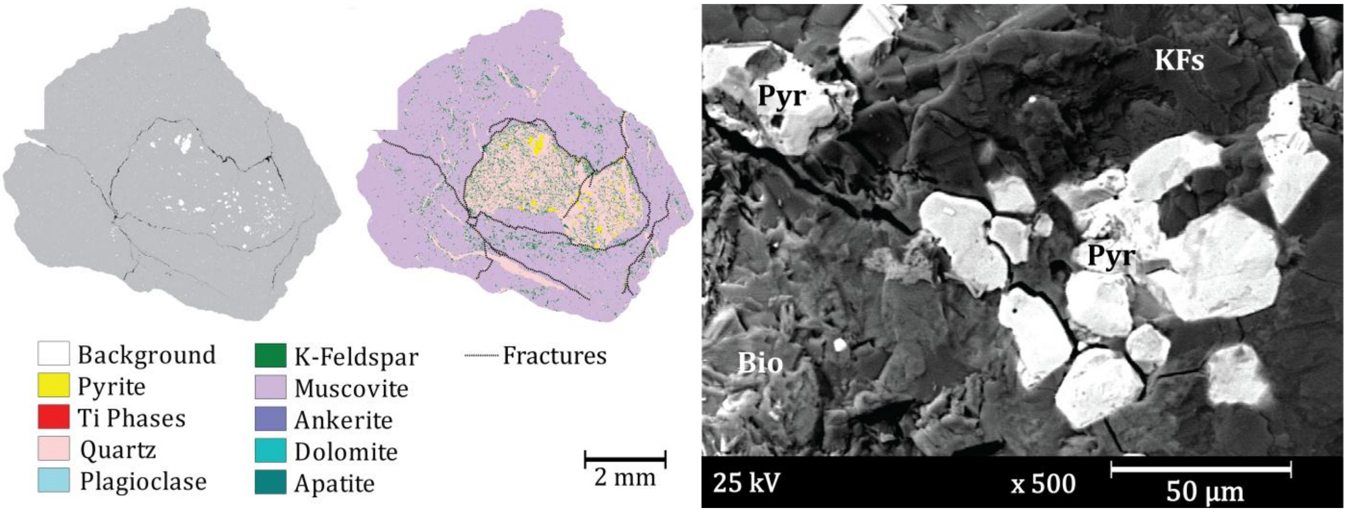
Influence of equipment settings and rock properties

Total high voltage energy input is determined by the number of pulses per mass of rock and the energy per pulse, with the latter determined by voltage as well as the internal setup of the generator. Voltage also interacts with the electrode gap, particle properties and particle geometry to determine the electrical field strength in the process zone. Total energy input is the key parameter influencing fragmentation results, and the electrical field strength is important in that it influences the discharge ratio and therefore electrical efficiency of high voltage processing (van der Wielen *et al.*, 2013). Optimum equipment settings are rock-specific, but a general recommendation is that energy inputs in the 0.5 – 5 kWh/t range using pulses discharged at an electrical field strengths above 2.5 kV/mm are most efficient (van der Wielen, 2013). Further experience with a range of weakening projects at SELFRAG showed pulse energies exceeding 200 Joule per pulse, at total energy inputs below 3 kWh/t to be most feasible for weakening applications.
Of the material properties investigated, acoustic impedance, porosity, tensile strength and permittivity were found to be the key properties related to fragmentation results. A relationship including the former two was found to be related to the decrease in P_{80} of HVB products with energy input, and the latter two gave a very good correlation to the decrease of particles remaining in the feed size fraction (-20 +14 mm) after high voltage processing at increasing energy levels (van der Wielen, 2013).

Selectivity of fragmentation

One of the key advantages of HVB is its ability to fragment selectively, which is related to the way energy is deposited during an electrical discharge. Firstly, many ore minerals have electrical properties quite different from most gangue minerals. The field distortions caused by these minerals may attract streamers or even act as an initiation point, giving rise to a selective energy deposition mechanism which assist preferential liberation (Bluhm *et al.*, 2013). Secondly, electrons are less tightly bound along grain boundaries and they also provide a longer collision-free path, making it more likely plasma streamers follow them. Lastly, depending on their geomechanical properties minerals respond differently to mechanical stresses induced by the shockwaves, giving rise to complex wave interactions that create local stress fields exceeding the strength of the rock. These interactions are strongest at grain boundaries between minerals of contrasting properties, giving rise to further selective fragmentation.

Figure 3a and 3b show clear examples of inter-granular selective fragmentation, where liberation has effectively occurred despite the weakened rock matrix still being intact. Both particles were treated at below 2 kWh/t high voltage energy input (van der Wielen, 2013), demonstrating that liberation benefits can coincide with the weakening energy input range. This synergy is further substantiated by Wang, Shi & Manlapig, (2012) who reported comparatively better liberation at a lower energy input, and van der Wielen (2013) who found better liberation and selective pre-concentration of sulphides in the -355 +2 µm fractions at HVB energy inputs below 5 kWh/t.



a) b)

Figure 3 QEMSCAN® Image of selective fracture around quartz hosted in muscovite in a massive sulphide gold ore (a), and selective fracture around pyrite in a granodiorite-hosted gold ore (b) (from van der Wielen, 2013).

Optimum feed size

Van der Wielen *et al.* (2013) reported a strong feed size effect, with coarser feed sizes (>14 mm) producing a considerably finer product than finer feed sizes (<14 mm) at equivalent energy inputs. Further investigation showed this to be due to the number of pulses available for a given number of particles, and the fact that particles unaffected by a discharge will not experience fragmentation (van der Wielen, 2013). High voltage pulses represent a very discrete form of energy application compared to, for instance, a ball mill and the HVB pulse energy operates in a narrow band with the maximum pulse energy less than an order of magnitude larger than the lowest pulse energy. Conversely, the number of particles in a volume increases exponentially with a decrease in size. In the 10 – 15 mm range a threshold is reached below which the number of particles in the volume increases so strongly with decreasing size that it is impossible to affect all particles with the available number of pulses. This has an important implication for industrial HVB units, as particles smaller than 10 – 15 mm in size are significantly less suited for HVB processing.

Plasma vs. shockwave breakage

Plasma streamers and the subsequent shockwave can both cause damage to a rock being fragmented. A 'deep' liberation effect by very fine branching of plasma streamers was implied by some authors (Andres, Jirestig & Timoshkin, 1999; Andres *et al.*, 2001), whilst others have argued for shockwave-damage being the dominant fragmentation mechanism (Bluhm *et al.*, 2000; Burkin, Kuznetsova & Lopatin, 2009; van der Wielen *et al.*, 2013).
The behaviour of the plasma channel is similar to that of an explosive as it can exceed generate transient pressures in the GPa range and temperatures exceeding 10,000 K (Bluhm *et al.*, 2000), and most evidence

now indicates plasma-generated shockwaves rather than pervasive plasma 'trees' are the major fragmentation action. Firstly, the correlation between fragmentation and acoustic impedance/tensile strength, as well as a close similarity between high voltage and blasting fragmentation patterns has led to the conclusion that shockwaves are the dominant fragmentation mechanism (van der Wielen *et al.*, 2013; van der Wielen, 2013). Secondly, there is a clear cause for the relative susceptibility of coarser feeds to HVB, but the explanation above does not elucidate why coarser feeds actually yield a finer product than finer feeds. To explain this, a whole-volume effect needs to take place, fracturing particles before full fragmentation takes place (i.e. weakening). An intensive fracture zone (<2 mm) around a plasma channel in weakened ore particles is often visible by the naked eye. Plasma-related effects also stand out in an SEM image, and even in the immediate vicinity of a plasma channel (<50 μm) these effects are not observable in terms of mineral texture or alteration (van der Wielen, 2013). Therefore, the level of plasma percolation required for this 'whole-body' fragmentation effect is not consistent with available evidence, making it unlikely that an intensively branched plasma 'tree' is responsible for the majority of the fragmentation. It should be noted that though shockwaves are likely the dominant fragmentation action, the energy-fragmentation relationships reported in van der Wielen (2013) also incorporate porosity and permittivity. The latter is an electrical property of rocks, whilst the former is related to void space filled by air/water, which affects electrical breakdown strength of a rock. These properties influence the location and intensity of electrical breakdown and hence plasma formation within the rock, which in turn affects shockwave patterns so this evidence is not inconsistent with the shock-wave theory.

APPLICATIONS OF HIGH VOLTAGE BREAKAGE IN MINING

Liberation

Wang, Shi & Manlapig (2012) used a Mineral Liberation Analyzer (MLA) for a comparison of ores fragmented using a SELFRAG Lab to ore milled at the same specific energy. They found that HVB products had a lower fines generation, as well as a significantly higher proportion of >95% liberated ore minerals in the >53 μm fractions, demonstrating that high voltage breakage liberates better and coarser than conventional milling. Furthermore, they also found deportment was comparatively better at 8.9 kWh/t than 21.9 kWh/t HVB energy, suggesting there may be an optimum energy input for liberation. Based on this, Wang, Shi & Manlapig. (2012) calculated high voltage breakage would only require approximately 4.8 kWh/t to match liberation by conventional milling at 8.9 kWh/t, representing a possible energy saving in the range of 46%.

Andres *et al.*, (2001) assessed grade/recovery increases after HVB (full fragmentation) for an iron ore (hematite), a copper ore (chalcopyrite), a nickel ore (pentlandite) and two platinum group elements (PGM) ores. For the iron ore recoveries from the HVB and control sample were similar, but impurity (P_2O_5 and SiO_2) contents were significantly lower in the HVB sample (Andres *et al.*, 2001). Liberation (QEM*SEM) data for the copper and nickel ore presented by Andres *et al.*, (2001) is consistent with Wang, Shi & Manlapig, (2012) in that it showed better and coarser liberation. For the copper ore this translated into a better concentrate grade but lower recovery, whilst the situation was the other way around for the nickel ore (Andres *et al.*, 2001). Considerable improvements were also reported for the PGM ores in terms of grade whilst recovery remained constant (Andres *et al.*, 2001).

Weakening

The first mention of weakening using high voltage pulses was by Andres & Bialecki (1986), who reported a 400 – 500% increase in cutable emeralds from a 10 kg pegmatite lump subjected to a single high voltage pulse but this was not investigated further. The first full study using HVB equipment for weakening was by Wang, Shi & Manlapig (2011). They compared weakening of high voltage products to the same size fractions in a control sample for four different ores. Weakening values between 9% and 52% were found in the A*b size range, combined with Bond rod mill work index reductions of up to 24%. In addition, for one of the ores they also reported a porosity increase from 3.2 to 13.7% which they attributed to micro-cracking. This strength reduction represents a considerable potential overall energy saving, calculated to be 24% for one of the ores investigated (Wang, Shi & Manlapig, 2011).

The second paper looking in detail at weakening is by Shi, Zuo & Manlapig (2013). They developed a single particle test method to compare weakening in the form of a pre-weakening index (PWi), defined as % pre-weakening per kWh/t of high voltage energy input. An example test showed an A*b increase from 31 to 84 using 1.6 kWh/t HVB energy, which equates to a PWi of 106%/kWh/t. This paper represents a crucial first step towards a standardized weakening assessment. However, it should be noted it neglects efficiency of processing, and does not take into account fragmentation occurring concurrent with weakening and hence it is not yet a holistic assessment.

Future developments

The focus in the development of HVB equipment is currently on weakening to aid comminution, though recycling applications are also receiving considerable interest. Given the feed size effect, better liberation at lower energy inputs, and to take most advantage of the weakening benefits of high voltage breakage, the most suitable location in most processing circuits is prior to the SAG mill or similar comminution stage. A 2 – 3 tph continuous processing unit is operational, whilst a scalable 10tph pilot plant unit is in the final design stage, with the ultimate goal of producing 100 - 2000 tph units. Current developments to achieve these throughputs include research into processing of larger feed sizes in the range of 100 – 200 mm, as well as a push towards higher pulse rates and equipment availabilities in the 92 – 97% range.

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