A Standardised Methodology for the Assessment of the High Voltage Breakage Characteristics of Ores

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Abstract
High voltage breakage is an emerging comminution technology with demonstrated advantages in terms of particle weakening and improved liberation. However, up till now a holistic optimisation assessment was lacking.
In this work a number of relationships are presented to describe high voltage breakage behaviour of an ore. Based on these relationships a standardised methodology is outlined for single particle testing that allows for assessment of weakening and size reduction and the optimum generator setup. A relationship similar to the drop weight test breakage function allows determination of the weakening-energy relation, and the pre-weakening index helps ascertain the most efficient pulse energy. Weibull distributions can be used to describe the probability of electrical breakdown occurring. It is shown 69% weakening can be achieved using 2 kWh/t at an optimum pulse energy of 385 Joule and an electrical field of 5.5 kV/mm. Scale-up from single particle to continuous tests is also demonstrated.

Introduction
Energy savings in comminution have become an increasingly important topic in mineral processing research (Bearman, 2012). Research into this subject has followed a number of different routes, including modelling to better understand dynamics during comminution (Weerasekara et al., 2013), improvements to existing equipment design and operation to improve performance (Rybinski et al., 2011), mine-to-mill optimisation (Djordevic & Michaux, 2005) and design/implementation of new technologies such as HPGR and Isamill.
High voltage breakage falls into the latter category, being a novel technology that offers significant potential for energy savings as well as improvements in liberation. High voltage breakage (HVB) units use very short (<1 ns) electrical pulses at very high voltages (>90 kV) to cause electrical breakdown inside dielectric materials such as rocks. Electrical breakdown is a phenomenon in dielectric materials that occurs when an electrical field is intensive enough to cause a dielectric material to lose its resistive properties (Cardarelli, 2008; Budenstein, 1980). During this process electrons are displaced, resulting in permanent changes to its atomic structure in the form of the formation of a plasma tree. This plasma tree behaves similar to conventional explosives, causing localised crushing near the plasma channel and extensive shockwave damage throughout the affected volume (Bluhm et al., 2000; van der Wielen et al., 2013).
High voltage breakage can be used as a pre-treatment for, or replacement of conventional comminution. Andres et al. (2001) have demonstrated the possibility to increase grade and/or recovery of copper, nickel and platinum group element into concentrates after flotation, which they attributed to improved liberation. Wang et al. (2012) used a Mineral Liberation Analyser (MLA) to compared liberation after HVB to samples comminuted conventionally using similar energy inputs. They found that sulphide liberation was improved, with up to over an order of magnitude more sulphide minerals deported into >53 μm size fractions.

On top of liberation advantages, HVB can also be used to weaken rocks, making it possible to achieve significant energy savings in the comminution process (Shi et al., 2014). Weakening values of $A{\times}b$ values of up to 52% were reported by Wang et al. (2011) after batch processing of ores in a SELFRAG Lab HVB unit. Shi et al., (2013) demonstrated substantially higher weakening percentages can be achieved using a single particle test approach (64% for batch tests vs. 171% for single particle tests). Based on this method they proposed a pre-weakening index, which is calculated by dividing the weakening percentage by the SELFRAG energy input required to achieve this value. This paper represents an important step forward in describing the weakening behaviour of rocks, but has several shortcomings. Firstly, there is no consideration for the evolution of weakening with SELFRAG specific energy input. The pre-weakening index implies a linear relationship but this paper will demonstrate this is not the case. Moreover, Shi et al. (2013) did not provide any means of optimising generator setup in terms of Joule per pulse and conditions required to achieve electrical breakdown, as well as the amount of fragmentation induced as a side-effect of the weakening treatment. This paper expands on the pre-weakening index and further investigates the relationship between weakening, size reduction and SELFRAG energy input. Based on observations a holistic methodology is formulated that provides all basic design criteria for generator setup for weakening applications.

Fundamental Relationships

Weakening

Weakening is the result of a discharge-induced fracture network inside a particle that is pervasive enough to cause a measurable strength reduction, whilst not being so pervasive that the integrity of a particle is reduced sufficiently to cause it to fragment completely. Essentially, weakening should be viewed as the precursor to full fragmentation of a particle. It may consist of anything from a small number of fractures of limited extent inside an otherwise intact particle matrix, to a set of almost discrete product particles that are only loosely held together by their interlocking geometries and some remaining particle-particle cohesion. The fracture mechanics of weakening, and more specifically the reason why HVB is very efficient at it, are not yet fully defined. It is likely due to shockwaves created as a result of Ohmic heating during the conduction phase of a discharge. Consequently, the high voltage treatment process can be viewed as a small-scale equivalent of blasting. The unique aspect of HVB is that the fragmentation energy is generated by a plasma channel whose location inside a particle is governed by mineral properties, rather than a randomly located drill-hole inside a rock mass without consideration for its properties.

Shi et al. (2013) define the percentage of weakening (*% PW*) of a particle by high voltage treatment using equation 1:

$$\%\,PW = \frac{Ab_{sf} - Ab_{ut}}{Ab_{ut}} \tag{1}$$

Where Ab_{sf} = $A{\times}b$ value of the SELFRAG product
Ab_{ut} = $A{\times}b$ value of the control (untreated) sample

This equation is only valid for grindability indicators such as the $A{\times}b$ value, whose value increases with a decrease in hardness. For grindability indices such as the Bond work index or drop weight index, where higher values indicate harder material, equation 2 should be used. In the case of equation 1, there is no theoretical limit to the percentage of pre-weakening that can be achieved, whereas equation 2 can never yield more than 100% weakening.

$$\% PW = \frac{Wi_{ut} - Wi_{sf}}{Wi_{ut}} \quad (2)$$

Where Wi_{sf} = Work index of the SELFRAG product
Wi_{ut} = Work index of the control (untreated) sample

Due to this fundamental difference, equations 1 and 2 will give different weakening percentages that will affect fitting of equations discussed later. To avoid confusion during reporting of weakening values, it is imperative that the analysis method is mentioned.

Vogel and Peukert (2003) showed through consideration of dimensional analysis by Rumpf (1973) and a fracture mechanical model that the probability of breakage (S) during impact breakage can be described using equation 3.

$$S = 1 - e^{(-f_{mat}\, x\, k\, (W_{m,kin} - W_{m,min}))} \quad (3)$$

Where S = probability of breakage
f_{mat} = material breakage property (kg/J/m)
x = initial particle size (m)
k = successive number of impacts
$W_{m,kin}$ = mass-specific kinetic impact energy (J/kg)
$W_{m,min}$ = threshold energy required for fragmentation (J/kg)

Shi and Kojovic (2007) pointed out the similarity between this breakage probability function and the JKMRC prior art breakage model (equation 4) used for determining the $A{\times}b$ ore impact breakage parameters, and adapted it to describe product size (t_{10}) generation from impact tests (equation 5):

$$t_{10} = A(1 - e^{(-b\, E_{cs})}) \quad (4)$$

$$t_{10} = M(1 - e^{(-f_{mat}\, x\, k\, (E_{cs} - E_{min}))}) \quad (5)$$

The term M in equation 5 is the same as A in equation 4, $-f_{mat}\, x$ equals b, and $k(E_{cs}\text{-}E_{min})$ corresponds to E_{cs}. This adaptation was shown by Shi and Kojovic (2007) to better describe drop weight test results than the JKMRC prior art model.

To calculate the high voltage treatment specific energy (E_{sf}) the pulse energy, total number of pulses and the particle mass are required. The electrical energy contained in a single high voltage pulse can be calculated using the following formula:

$$E_p = \tfrac{1}{2} C U^2 \quad (6)$$

Where E_p = Pulse energy (J)
C = Capacitance (F)
U = Voltage (V)

This equation can be used to calculate the total energy charged into the capacitors in a Marx generator, and therefore is a direct measure of the energy contained in a high voltage pulse. Given this equation, E_{sf} can be calculated from equation 7:

$$E_{sf} = \frac{d\ E_p}{3.6\ m} \tag{7}$$

Where E_{sf} = SELFRAG specific energy input (kWh/t)
d = number of discharges
m = particle mass (g)

Figure 1 shows the percentage of $A{\times}b$ increase (i.e. weakening) as a function of SELFRAG specific energy input. A strong increase in weakening is visible between 0 and 4 kWh/t before weakening levels off. Both voltage and capacitance can be used to vary the energy applied to a particle (see equation 6), and together with size (i.e. particle mass), they are all means of varying HVB specific energy. Independent sample t-tests showed these three data series did not show significantly different weakening. This demonstrates that it is total energy input, rather than any of these individual parameters, that is the key variable influencing weakening results.
The data in Figure 1 closely resembles the general trend described by Vogel and Peukert's breakage probability equation. Shi and Kojovic (2007) already showed this general breakage probability relationship can be adapted to describe more specific comminution scenarios. Weakening is a form of fragmentation, and therefore it is not surprising the Vogel and Peukert model can describe it as well. Given this plausibility, an adaptation of equation 5 is proposed to describe weakening as a function of energy input for high voltage treatment:

$$\%\ PW = H\left(1 - e^{f_{matSF}\ x\ k\ (E_{sf} - E_{min})}\right) \tag{8}$$

Figure 2 shows the data presented in Figure 1 as a function of f_{matSF} x $(E_{sf}\text{-}E_{min})$ rather than E_{sf}. This improves the correlation coefficient (r^2) from 0.79 to 0.88. This better correlation, and the fact that both van der Wielen et al. (2013) and Shi et al. (2013) reported that larger particles are considerably more amenable to HVB, demonstrate that the particle size term x should not be omitted during fitting of the pre-weakening model. Single particle tests should be based on single discharges, meaning the term k in equation 6 can usually be set to 1.
According to Vogel and Peukert (2003) f_{mat} is a material-specific parameter that describes the resistance against the applied load. For HVB the nature of the function f_{mat} has not been determined, and it may incorporate other aspects such as the way a material interacts with the electrical field (hence notation as f_{matSF}). Van der Wielen (2013) showed there is a reciprocal aspect to HVB, where material properties influence the amount of energy deposited before it is applied. This makes it possible that f_{matSF} for HVB incorporates more than the resistance against the applied load as with impact tests. Consequently, the nature of f_{matSF}, and which material properties it relates to, are aspects of the proposed weakening-energy relationship that warrant further research.
Following Shi and Kojovic (2007), and to ease reporting of the pre-weakening model results, the term f_{matSF} x is set to equal a new term: v (see equation 9).

$$\%PW = H(1 - e^{(-v\ (E_{cs} - E_{min})}) \tag{9}$$

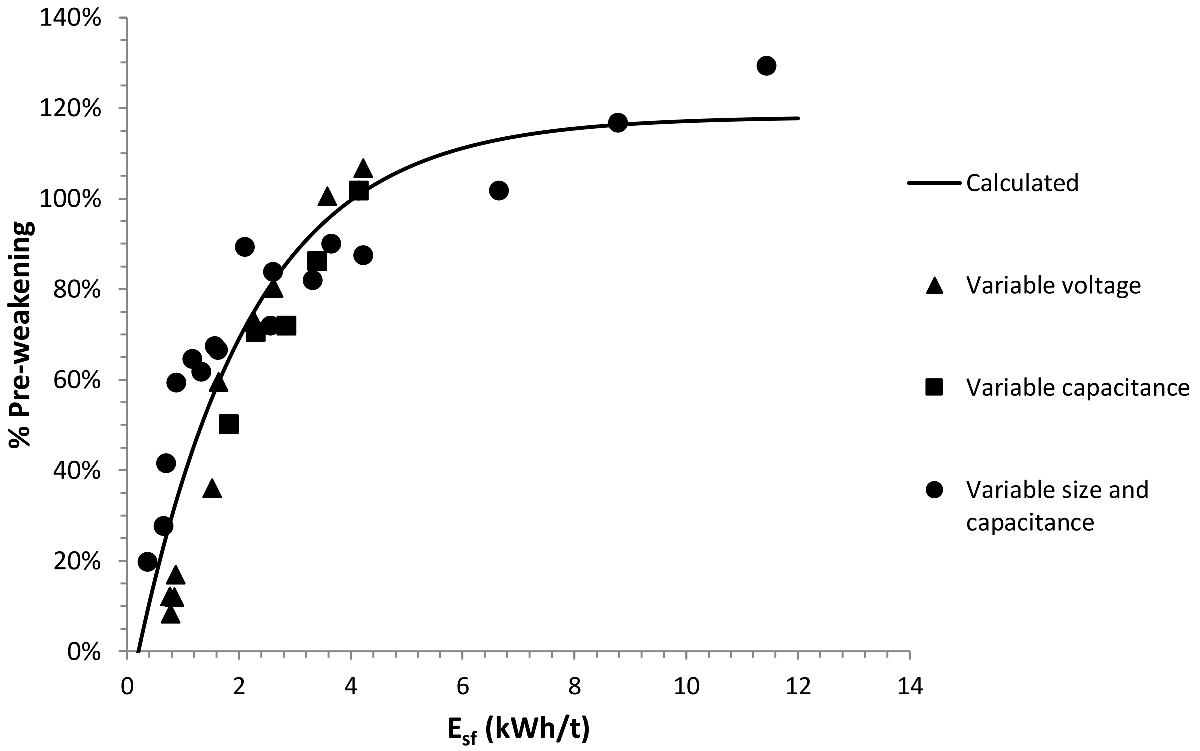

Figure 1 – Weakening as a function of high voltage energy input.

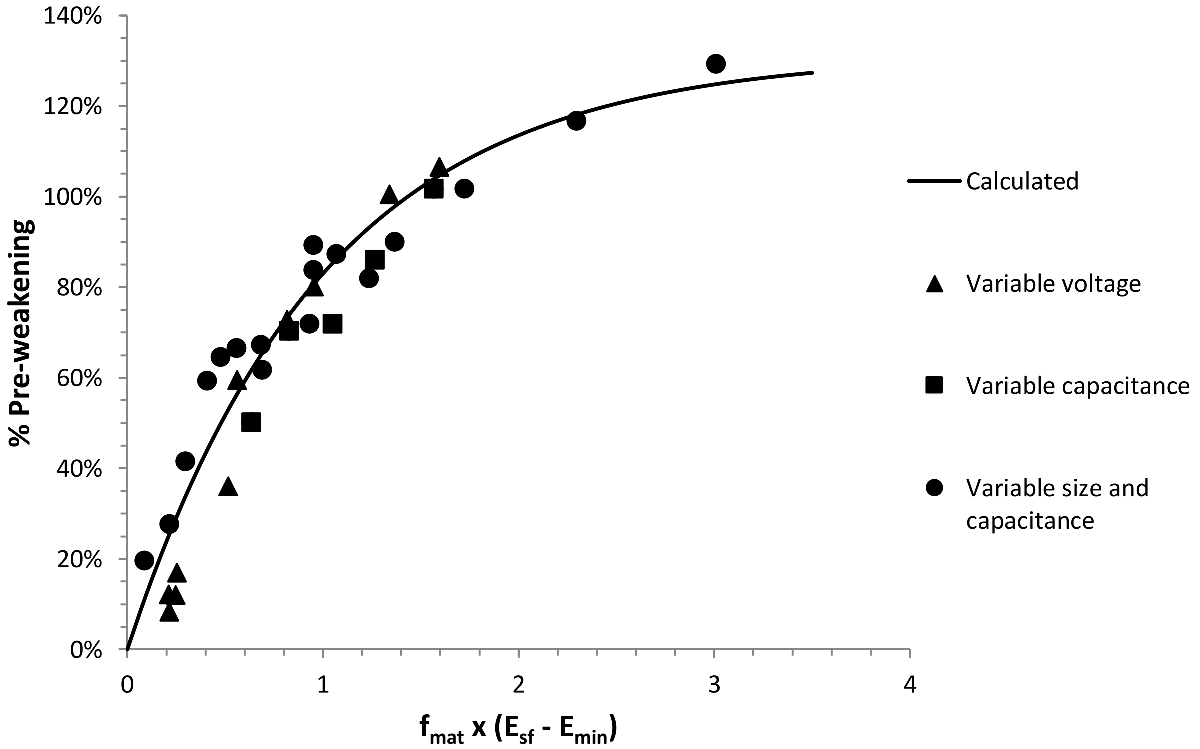

Figure 2 – The more extensive weakening model (equation 8) applied to data presented in Figure 1.

This makes the results more recognisable to process engineers as they closely resemble the JKMRC $A \times b$ parameters. To avoid confusion, it was chosen to rename A to H, and b to v, giving $H \times v$ as the weakening equivalent of the $A \times b$ ore breakage parameters. Use of the $H \times v$ weakening parameters is a versatile representation of the weakening – energy relationship that overcomes one of the main shortcomings of the Pre-Weakening Index proposed by Shi et al. (2013): it gives an indication of weakening that can be expected at any energy input within the SELFRAG specific energy range used to determine the $H \times v$ parameters.

Figure 1 demonstrates there is a minimum energy input below which no weakening occurs, meaning the total high voltage input is higher than the net energy available for fragmentation. This effect has been observed using several test methods (drop weight test, point load test, Bond work index) on a range of different rock types, and is therefore not an artefact of the test method or a peculiarity of a specific rock type. There are several possible scenarios which may contribute to this minimum energy requirement. Firstly, like with impact testing a certain amount of energy may be required to supply sufficient strain energy to overcome elastic deformation. Secondly, propagating and sustaining streamers requires a certain amount of energy. This energy is not available for fragmentation, which may be reflected partly in the presence of E_{min}. Lastly, there is likely some inefficiency in the electrical-mechanical coupling of the plasma channel and the rock, i.e. not all electrical energy is actually transformed into shockwave energy available for fragmentation. Typically, the high voltage specific energy inputs for weakening are between 1 and 3 kWh/t, so an E_{min} of 0.2 kWh/t can represent an inefficiency of 6.7 to 20%. Consequently, further research is recommended to establish which factors contribute to E_{min}, and whether there are means of reducing it.

Pulse Energy

Equation 6 demonstrates that a given high voltage energy input can be reached using different combinations of pulse energy and number of discharges. There are two fundamentally different philosophies with regards to the energy balance between these two variables. Firstly, it is possible to design a system to apply discharges sufficiently powerful to provide enough energy to overcome elastic deformation in the largest particle. Alternatively, a system can be designed with a lower pulse energy and higher number of discharges to ensure there are enough pulses to give each particle a reasonable chance of being affected by a discharge regardless of size. The latter is the preferable design strategy as larger particles hit by multiple discharges will still receive sufficient energy to cause weakening, whilst the low pulse energy/large number of discharges is better suited to the higher number of particles in the finer end of the feed.

Use of single pulses of different energies on the same sized particles will inevitably result in different HVB specific energies being applied. This in turn means different pulse energies will inherently produce different degrees of weakening. Consequently, normalisation of data is required to allow comparison of weakening at different HVB specific energy inputs. This can be achieved using the Pre-Weakening Index (*PWi*, see equation 10) formulated by Shi et al. (2013):

$$PWi = \frac{\%PW}{E_{sf}} \tag{10}$$

For assessment of the pulse energy it is logical to consider weakening results as a function of pulse energy rather than high voltage specific energy input. Substituting the percentage of pre-weakening in equation 9 with equation 11 gives:

$$PWi = \frac{H(1-e^{f_{matSF}x(E_p-E_{p,min})})}{E_p} \tag{11}$$

Figure 3 shows the general relationship described by this equation. It demonstrates there is a maximum pre-weakening index that can be achieved. Obtaining the second-order derivative of

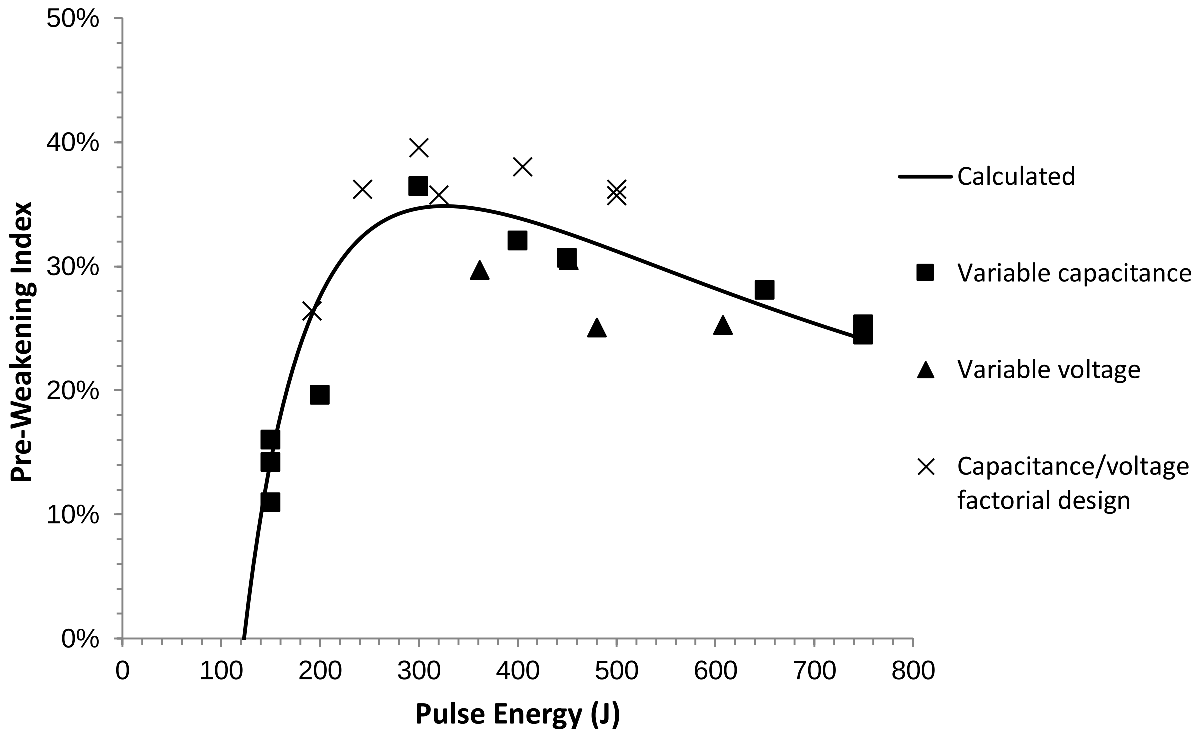

Figure 3 – Pre-weakening index as a function of pulse energy including the best fit of equation 11 to available data.

the best fit for a given dataset, or solving it numerically will yield the pulse energy where the highest pre-weakening index is achieved.

Size reduction

Some degree of size reduction occurs simultaneously with weakening during high voltage treatment, which may affect the influence of HVB equipment on a comminution circuit. It is important that the measurement of the degree of size reduction should not interfere with the weakening analysis. Consequently, representation of size reduction is recommended through the t_{10} value rather than the P_{80}, as the former is measured on size fractions smaller than the drop weight test size range whereas the latter will likely require sieving of weakening analysis feed material.

It was already shown that the weakening – energy relationship for high voltage breakage can be described by an adaptation of the breakage probability reported by Vogel and Peukert (2004). As an extension to this, it is logical to expect that the degree of size reduction after high voltage treatment can also be described using this relationship. As mentioned above, the preferred representation of size reduction is through the t_{10} value, so equations 4 or 5 can be fitted directly to data. However, to avoid confusion it is necessary to add a suffix to the ore breakage parameters, i.e. A_{Hv} and b_{Hv} (making $A \times b_{Hv}$) instead of just A and b. Figure 4 shows t10 values as a function of HVB energy input, including best fit of equation 11. The fragmentation data shows some scatter due to difficulties in retrieving particles from the high voltage treatment unit but nonetheless the correlation coefficient of the best fit of equation to the data is good ($r^2 \approx 0.86$).

Discharge Ratio

High voltage pulses represent very discrete events of energy introduction into the fragmentation environment compared to many other comminution devices, where the energy is applied far more frequently or even continuously. Due to the stochastic nature of the process a high voltage

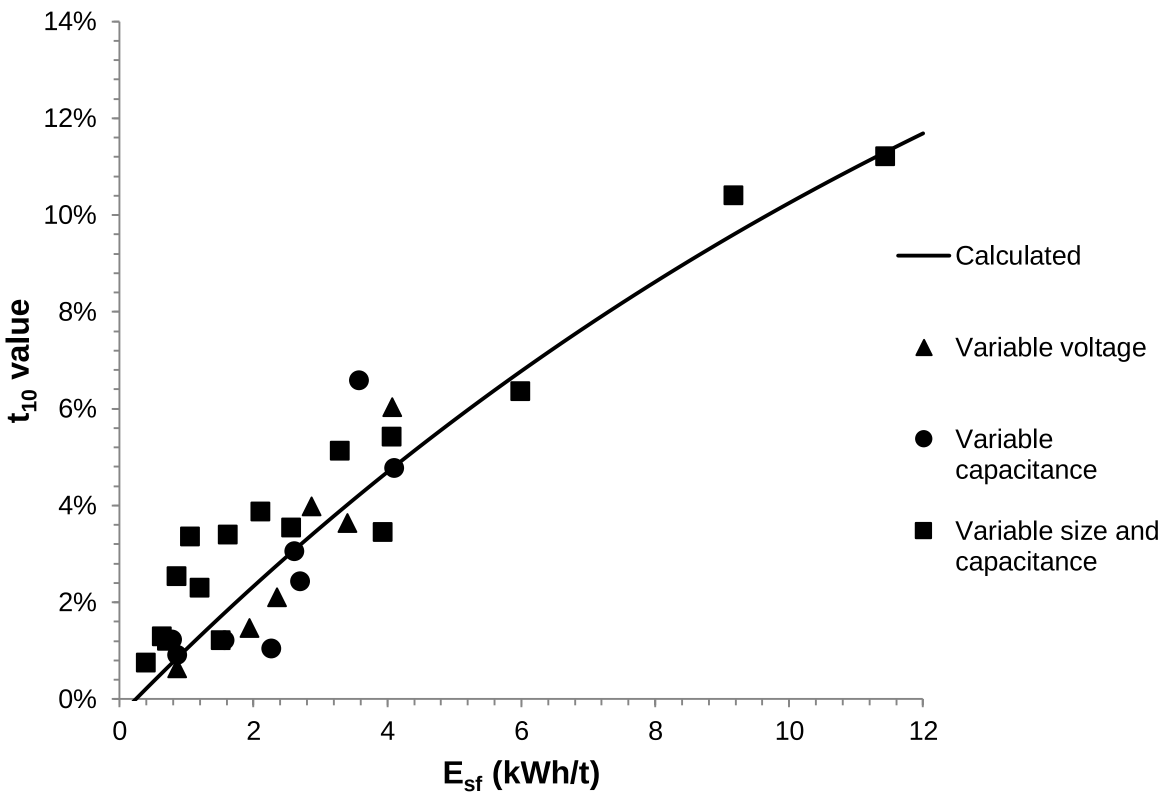

Figure 4 – Size reduction as a function of high voltage energy input, including the best fit line for equation 4.

pulse from the generator may not form a full discharge where electrical breakdown has bridged the gap between the discharge and counter electrode. the pulse energy is insufficient to propagate the plasma channel resulting from electrical breakdown.

The ratio of discharges to pulses (equation 12) is defined as the discharge ratio (van der Wielen et al., 2013).

$$r_{dp} = \frac{d}{p} \tag{12}$$

Where r_{dp} = Discharge ratio

d = Total no. of discharges applied to a sample

p = Total no. of pulses applied to a sample

The difference between discharges and pulses is audibly different for operators, and also recognised by HVB SCADA software. It was demonstrated by van der Wielen et al. (2013) that the discharge ratio is related linearly to HVB efficiency. Therefore it is crucial this ratio is as close to 1 as possible and it is one of the key attributes to assess when characterising the high voltage breakage behaviour of an ore.

The discharge pulse ratio is essentially the probability of electrical breakdown occurring, and it is often described using a Weibull distribution (Kuechler, 2005; Fabiani & Simoni, 2005). In the context of HVB the probability of fracture is replaced by the discharge ratio r_{dp}, and the electrical field strength (E, in kV/mm) and characteristic electrical breakdown strength ES_s (kV/mm) substitute the mechanical strength indicators σ and σ_s respectively.

$$r_{dp} = 1 - e^{\left\{-\left(\frac{ES}{ES_s}\right)^{\beta_{ES}}\right\}} \tag{13}$$

The general consensus in literature regarding electrical breakdown is that the field strength is the only influencing factor. However, inspection of available data shows both capacitance and electrical field strength influence the discharge ratio during HVB. This is due to the fact that a minimum electrical field strength is required to initiate electrical breakdown, whilst a certain proportion of energy is also required to maintain self-propagation of the streamer and prevent it from dying out. Therefore, a comprehensive equation is required that takes into account both streamer initiation (i.e. field strength) and streamer propagation (i.e. pulse energy).
The evolution of voltage as a function of time during a high voltage discharge can be described by the following equation:

$$U = U_{max} e^{-\frac{t}{RC}} \tag{14}$$

Where t = time (s)
R = Resistance (Ω)

Figure 5 shows three typical voltage-time evolutions represented by equation 14. There is a voltage threshold (U_{th}) below which electrical breakdown will not occur in HVB. Furthermore, a minimum amount of energy needs to accumulate inside a particle during a high voltage pulse to allow plasma channels to fully develop and cause a discharge. This is represented by a specific threshold area (A_{sp}) of a voltage-time profile (U_p) above the threshold voltage. This threshold area is material specific, giving rise to a discharge development time (t_{sp}) at which A_{sp} is sufficient for a plasma streamer to bridge the gap between discharge and ground electrode. The time spent by a high voltage pulse for depositing electrical energy (A_p) is influenced by both voltage (i.e. higher peak value for U_p) and capacitance (rate of decrease of equation 14). Therefore, the larger the charging voltage (proportional to U_{max}) and/or the higher the capacitance, the longer U_p is above U_{th}. This means there is more time for A_p to accumulate electrical energy to the point where A_p can exceed A_{sp}, making it more likely a discharge occurs. In Figure 5 the alternative high voltage pulse scenarios represent the following pulse conditions: U_{max} for *P1=P2>P3*, and *C* for *P1=P3>P2*. This produces three alternative pulse evolutions:

1. *P1* will experience electrical breakdown as $U_{max}>U_{th}$ and the pulse energy is sufficient for A_{P1} to exceed A_{sp}, resulting in the formation of an electrical discharge from the electrical pulse. This voltage-time profile would result in weakening.
2. *P2* will experience electrical breakdown as $U_{max}>U_{th}$, but there is insufficient pulse energy available for propagation till $A_{P2}>A_{sp}$. The end-result is that the plasma streamers extinguish. This voltage-time profile would not result in weakening though the particle may accumulate some plasma-induced damage that makes it more likely further pulses develop a discharge.
3. *P3* will not develop electrical breakdown as U_{max} for *P1* never exceeds U_{th}. No damage is done to the particle.

For ease of derivation, the term *1/RC* in equation 14 is substituted by a new factor, *a*. In order to determine A_p it is necessary to solve equation 15 for the time to the threshold voltage (t_{th}), which gives:

$$U(t) = -\frac{Log\left(\frac{U_{th}}{U_{max}}\right)}{a} \tag{15}$$

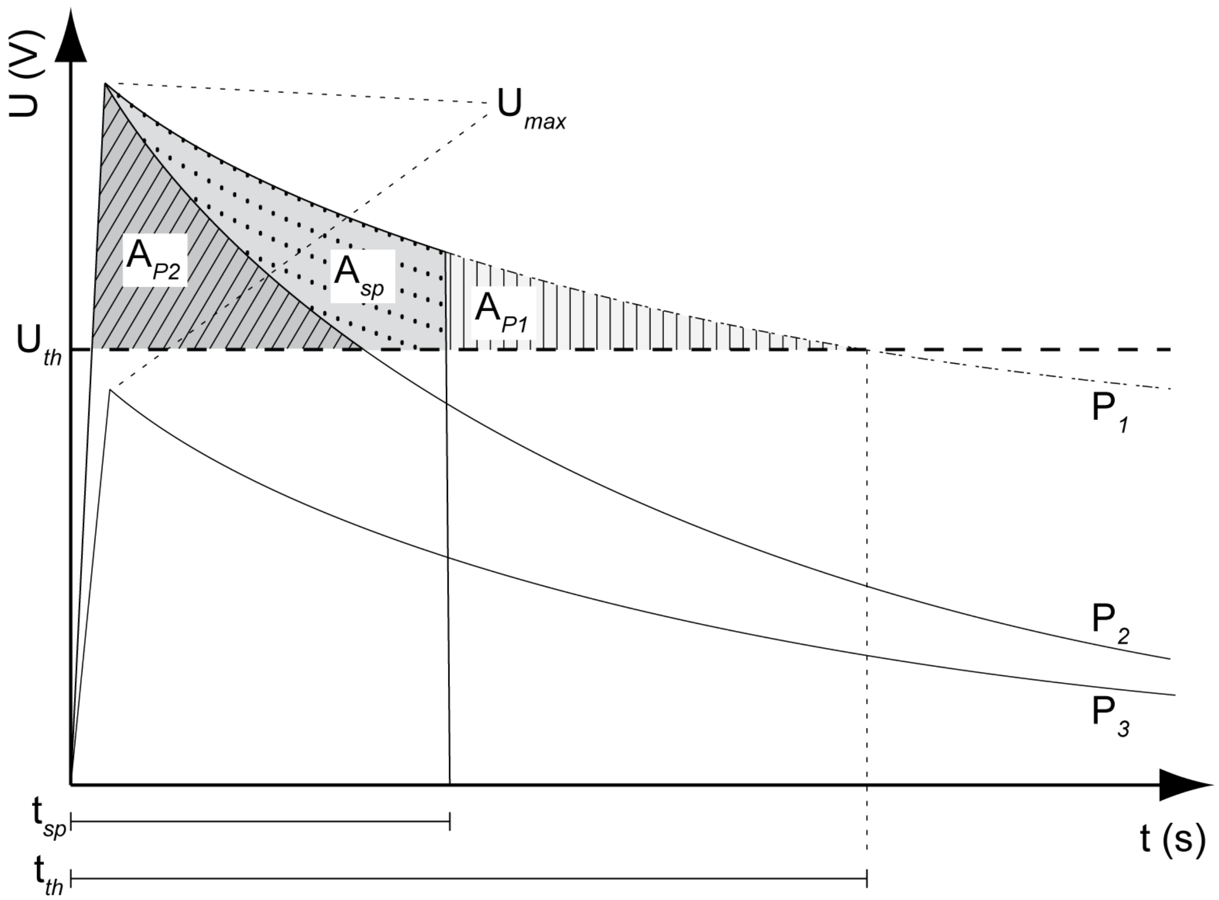

Figure 5 – Schematic of the various voltage-time profiles during a HVB pulse. U_{max} for *P1=P2>P3*, and *C* for *P1>P2=P3*.

The area A_p is denoted by the integral of U_{th} between 0 and t_{th}.

$$A_p = \int_0^{t_{th}} U_{th} dt \qquad (16)$$

Solving this integral and replacing a with $1/RC$ yields equation 17:

$$A_p = \frac{2RE_p}{U_{max}} \left(1 - \frac{U_{th}}{U_0}\right) \qquad (17)$$

This equation is only valid for situations where the charging voltage is varied and where the gap between electrodes is constant. By replacing voltage with electrical field strength (*kV/mm*), equation (17) becomes more generally applicable:

$$A_p = \frac{2RE_p}{\overrightarrow{E_{max}}} \left(1 - \frac{\overrightarrow{E_{th}}}{\overrightarrow{E_{max}}}\right) \qquad (18)$$

During the streamer propagation phase of a high voltage pulse, resistance is mostly governed by process water properties, the transmission system and electrode geometry. For single particle testing these can be assumed to remain constant. Likewise, when the charging voltage is not varied, U_0 will remain constant. Lastly, the threshold voltage is a material property and is therefore considered constant as well. This means equation 19 can be simplified to:

$$ES \propto A_p \propto \frac{E_{pulse}}{\vec{E}} \quad (19)$$

The area (A_p) in figure 5 denotes time available for streamer propagation. If a streamer cannot bridge the gap between initiation point and ground electrode within the time denoted by A_p, it will die out. Therefore, A_p is proportional to the electrical strength (ES) of material, enabling it's use in the Weibull distribution for electrical breakdown probability (equation 13). However, the scenario outlined above is only valid if the entire electrode gap is filled by a single material. In the case of HVB the electrode gap will contain both water with a relative permittivity (ε_w) of 80, and rock with an ε_m ranging from 4.5 to 15 (average ≈ 7.0). Due to the large permittivity distance between water and rocks, the electrical field is forced almost completely into the rock, meaning that the effective electrical field strength (E_{mat}) can be approximated using equation 20.

$$\vec{E}_{mat} = \frac{U}{x} \quad (20)$$

Where U = charging voltage (kV)

Using this effective field strength in equation 19 instead of the total electrical field strength over the total electrode gap allows analysis of discharge ratio as a function of electrical strength in a way that also considers particle size. Figure 6 shows the discharge ratio as a function of this approximation of electrical strength. The correlation coefficient for the Weibull fit to this data is 0.87, which shows the analysis approach and assumptions outlined above do not affect goodness of fit for this relationship.

Standard HVB Test Method

Test Rationale

The comparison of batch and single particle tests by Shi et al. (2013) demonstrates the advantages of single particle testing for high voltage breakage. Therefore, the single particle test mode is adopted for the test procedure in this paper.

The sources of energy in HVB units and drop weight test equipment are different, but both technologies apply a well-defined amount of energy to a particle in a single event. Furthermore, the drop weight test is a well-recognised and industry-standard test. Therefore the drop weight test procedure, as outlined in Napier-Munn et al. (1996), made a convenient starting point for the formulation of a standardised test method for HVB. However, the drop weight test only yields a relation between fragmentation (t_{10} value) and specific energy input, whereas for high voltage breakage several relationships are of interest:

1. % Weakening as a function of SELFRAG specific energy input
2. % Weakening as a function of energy per pulse
3. Fragmentation as a function of SELFRAG specific energy input
4. Discharge ratio as a function of electric field strength

The goal of the proposed test procedure is to serve as an exploratory weakening assessment that covers these four aspects. It should provide indications regarding the degree of weakening and fragmentation that can be attained at different SELFRAG energy inputs (points 1 and 3), and how the electrical energy is most effectively applied (points 2 and 4). Given this data, it is possible to make first-order estimations to determine effects on a comminution circuit, with the aim of establishing feasibility of implementation of HVB technology treating materials to different

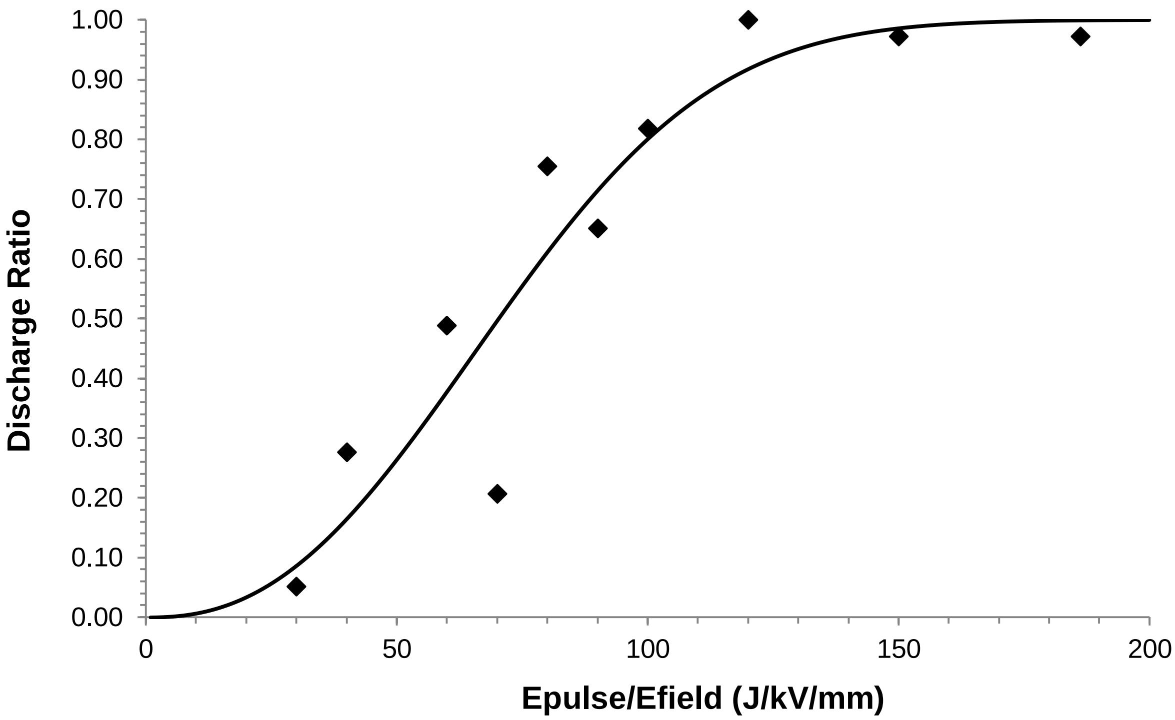

Figure 6 – Discharge ratio as a function of the pulse energy/field strength ratio, including the best fit Weibull distribution.

specific energy levels. Once the most feasible specific and pulse energy have been determined, further testing on larger batches or in continuous mode are required for verification of the data. Other attributes, such as improved liberation, can in principle be tested using the same test approach, but these are not considered in this paper.

High voltage breakage equipment

The proposed test procedure is designed for the SELFRAG Pre-Weakening Test Station (PWTS), which is a purpose-built R&D machine at the SELFRAG pilot plant that offers considerable flexibility in terms of generator setup, as well as the possibility to process continuously. Specification for the PWTS are listed in table 1. Importantly, the PWTS can vary voltage and capacitance independently, allowing testing of a larger range of pulse energy and electrical field strength combinations. In principle the proposed test procedure should also be possible on the SELFRAG Lab, but this unit can only vary pulse energy by changing the voltage. Further work is recommended to compare weakening performance of the SELFRAG Lab and PWTS.

Table 1 – Specifications of the Pre-Weakening Test Station

Voltage	45 – 200 kV
Pulse energy	5 – 750 J
Electrode gap	20 – 80 mm
Pulse rate	1 – 70 Hz†
Throughput	3 tph‡

†) Dependent on pulse energy
‡) Dependent on high voltage treatment energy

Feed size

Table 2 outlines recommended feed sizes for this test procedure. The PWTS can work on particles between 10 and 75 mm in size. The feed sizes tested in this test procedure are narrowly defined so as to minimise the variation in particle mass. The current upper size limit is defined by the process zone geometry inside the high voltage treatment unit, and is not a limitation of the high voltage treatment process. There is a minimum electrical field strength required to cause electrical breakdown (van der Wielen et al., 2013), but this depends on electrical properties and geometry of the rocks being treated, as well as process water conditions, pulse energy and electrode geometry. The lower size limit stems from a trade-off between the number of pulses required to achieve a given energy input, and the number of particles in a volume relative to the number of particles affected by a discharge (van der Wielen, 2013). This explains the feed size effect reported in van der Wielen et al. (2013) and is also reflected in circuit design considerations reported in Shi et al. (2014).

Equipment settings

The goal of the test procedure is to define the relationship between fragmentation (both weakening and size reduction), and specific energy input, pulse energy and discharge ratio. To achieve this, the number of pulses, voltage and capacitance can be varied. Discharges may cause particle movement, and therefore it is preferable to use single discharges for single particle testing. Consequently, it is advisable to only use 1 discharge per particle but more discharges can be applied if necessary. Voltages below 140 kV are unlikely to be of interest due to disproportionately low discharge ratios, and the capacitance range can be tailored to a rock type to ensure a convenient distribution of pulse energies and specific energy inputs. The pulse rate is set at 1 Hz for operational convenience, and an electrode gap of 40 mm is recommended but this is not a fixed requirement and may be changed if the largest particles cannot be accommodated in this electrode gap. Particles up to 55 mm can be accommodated under a 40 mm gap because the smallest axis of these particles mostly falls below 40 mm. Not every high voltage pulse from the generator will cause electrical breakdown, so a total of 50 pulses may be used to achieve a single discharge. If no discharge is achieved after 50 pulses the particle should be exchanged. The particles that cannot be discharge into may be investigated separately to establish whether there is a particular geometrical, mineralogical or other aspect that causes the difficulty. The pulse/discharge effect is further discussed in the section on the discharge ratio.
Table 1 outlines estimated energy inputs for different sizes and pulse energies. For a rock type with a density of 2,700 kg/m^3 this yields high voltage energy inputs between approximately 0.4 and 11.4 kWh/t. This specific energy range provides a comprehensive cover of the high voltage energy input range that is most likely to be economic. Higher and lower energy inputs are

Table 2 – Example of approximate SELFRAG specific energy inputs for a rock type with a density of 2,700 kg/m^3.

	SELFRAG Specific energy input (kWh/t)			
	300 J/pulse	*450 J/pulse*	*600 J/pulse*	*750 J/pulse*
-55 +50 mm	0.4	0.6	0.8	1.3
-45 +40 mm	0.8	1.2	1.7	2.1
-35 +30 mm	1.5	2.6	3.3	4.2
-25 +20 mm	3.6	5.3	9.6	11.4

possible, but will require treatment of smaller or larger particles, or the application of multiple pulses.

Test procedure

High voltage treatment features a stochastic aspect, in that it is governed by physical laws but also maintains a random component. To account for particle-to-particle variability in process response and to achieve a more representative sample, treatment of a minimum of 30 particles is recommended.

Prior to testing each particle must be weighed and the mass recorded individually. This is done since the pulse energy for a given sample series is set, but the particle mass varies so each particle receives a specific amount of electrical energy. Recording of the exact mass of each particle tested allows back-calculation of a weighted total high voltage energy input. Placement of the particle in the process vessel should be such that it is centred below the top electrode. The exact electrical breakdown path cannot be set a priori, but the recommended particle position makes it most likely the discharge will enter the particle.

The product from each treatment should be collected and retained separately. Data to collect after the treatment include the actual voltage as reported by the HVB unit, the number of pulses required to achieve the specified number of discharges.

Weakening analysis

High voltage breakage will likely be implemented as a pre-treatment prior to SAG milling (van der Wielen et al., 2013; Shi et al., 2014). Therefore, a weakening analysis used for SAG mill sizing, such as the drop weight test, is recommended. If required, additional weakening analyses such as (comparative) Bond tests may also be carried out on the sample if weakening data is required for a finer size range.

High voltage pulses result in varying degrees of weakening and size reduction depending on where in a particle the discharge occurs and how intense this discharge was. This unpredictable aspect of HVB represents the biggest complication for this test procedure because some SELFRAG-treated particles are retrieved more or less intact whilst others are almost completely disintegrated during treatment. This complicates the analysis, as strictly speaking the different particles should be analysed at different t_{10} sizes. However, sieving of the product will disintegrate some particles through attrition, and thereby bias results. Furthermore, the differing degrees of size reduction may also produce a bias as some particles only produce one progeny particle in the drop weight test range, whereas others may produce several progeny particles in a single size fraction suitable for drop weight test analysis causing this particle to have a disproportionate influence on the measured weakening.

For consistency purposes, and to maintain the exploratory character of this test procedure, the t_{10} value for analysis of the high voltage-treated drop weight test product is determined at the size based on the pre-SELFRAG feed size, regardless of post-treatment product size. Given these considerations, the test procedure specifies that the largest progeny particle after SELFRAG treatment is collected for drop weight test analysis, and the rest of the progeny removed from the process area for size reduction analysis.

Shi et al. (2013) demonstrate through differentiation of the standard t_{10} vs. E_{cs} formula how $A \times b$ values can be approximated based on a single drop weight test (equation 21).

$$A \times b = \frac{t_{10}}{E_{CS}} \tag{21}$$

This method allows for estimation of the $A \times b$ value of an ore without the need for a full drop weight test. The exploratory weakening assessment proposed in this paper requires a significant number of tests. Therefore to reduce the total number of tests required for a weakening assessment this abbreviated $A \times b$ test approach is adopted. Analysis of the drop weight test results is done according to the weakening – energy relationship outlined above (equation 9). It should be noted that equation 9 only gives the $H \times v$ values, which can be used to estimate the percentage of weakening at any E_{sf}. Establishing the most feasible overall SELFRAG energy input requires comminution circuit modelling combined with a wider view of beneficial effects, including size reduction, and possibly liberation or grade/recovery studies.

Pulse energy analysis

The $H \times v$ values are adequate for determination of the weakening vs. energy trend, but will not provide any indication of the optimum pulse energy to achieve the weakening. To establish the pulse energy – weakening relationship the percentage of weakening needs to be normalised for energy input, which can be achieved using the Pre-weakening Index (Equation 11). For a given rock type, pre-weakening indices will vary significantly between feed sizes regardless of pulse energy. The feed size fraction for planned industrial HV treatment units is loosely defined as ranging from 10 to 200 mm. Therefore, it is not possible to define a single optimum pulse energy that suits all particle sizes in a feed. The test series outlined in table 2 requires treatment of four feed sizes at four different pulse energies. To find the optimum pulse energy for this size range, it is recommended to average the PWi values obtained at identical capacitances for the different feed sizes, and plot these as a function of pulse energy. Fitting of equation 11 to this data and determining the maximum gives the pulse energy that will, on average, deliver the highest pre-weakening index for the tested feed size range.

Size reduction analysis

The amount of size reduction caused concurrent with weakening needs determination to fully appraise the influence of HVB on a comminution circuit. For the size reduction analysis, the remaining SELFRAG product not used for drop weight testing should be collected, dried and sieved using a suitable $\sqrt{2}$ series of sieves. From the sieve data the t_{10} value of the SELFRAG product can be determined following the standard procedure outlined by Napier-Munn et al. (1996). It is highly likely all particles used for drop weight testing are considerably larger than the t_{10} size, so their combined mass can be added to the largest sieve size fraction used for the t_{10} measurement without affecting the t_{10} calculation. The increase in t_{10} value of the SELFRAG product can be plotted as a function of HVB specific energy input. Weakening is the primary goal of high voltage treatment, so once a preferable energy input has been defined for weakening, the size reduction – energy plot can be used to estimate the t_{10} value of the high voltage treated product at the required high voltage energy input.

Discharge ratio

The main goal of the discharge ratio assessment is to determine the minimum electrical field strength required for a discharge ratio larger than 0.95 at the pulse energy selected based on the pulse energy – weakening assessment. An upper limit to the electrical field strength is dictated by durability of generator components, and there is no need to establish it as part of this test procedure. The discharge ratio goal of 0.95 was set empirically and does not represent a rigidly fixed value.

The discussion of the relationship between discharge ratio and electrical setup of the high voltage generator showed the time available for streamer propagation, and hence probability of developing a discharge, is proportional to the ratio of the pulse energy to the effective field strength inside a particle. Using this relationship to fit equation 13 to discharge ratio data gives a continuous distribution which can be solved to determine pulse energy/field strength ratio that give as discharge ratio of 0.95. Solutions of the Weibull distribution for r_{dp} = 0.95 will differ depending on particle size as the relative length of streamers in the particle and water will change for a fixed electrode gap. However, in a continuous processing scenario the material bed being treated at any given time will be approximately equal to the diameter of the larger particles in the feed. Based on the shape (*ES'*) and scale parameter (β) from the Weibull fit for the largest feed particles it is possible to determine the pulse energy/field strength ratio required for r_{dp} = 0.95. Subsequently, at a fixed pulse energy it is possible to calculate

Case Study

A case study following the methodology outlined above was done on a granite sourced from a quarry in the Schwarzwald in Germany. This material does not contain any noteworthy concentrations of ore minerals, and was chosen for this study as it represents a readily available source of homogeneous rock for research and development purposes. All high voltage treatments were done in the PWTS, and capacitance was varied to give a range of electrical field strengths and pulse energies. Weakening percentages were calculated based on $A{\times}b$ values determined using an Instron Drop Weight tester. To minimise the error induced by the variation in particle mass, each particle was weighed prior to impact testing to determine the exact impact energy required for a specific energy input of 0.5 kWh/t.

H×v Weakening Parameters

Figure 7 shows the results from the tests outlined in table 3. Equation 9 was fitted to the data using the least squares method, and the H, v and E_{min} values for each of the size fractions, as well as regression statistics can be found in table 3. The tested granite has a H×v value of 57.7, and from Figure 7 it becomes clear that weakening percentages in the 65 – 75% range can be achieved for this material using only 2 kWh/t.

Table 3 – High voltage weakening parameters for Schwarzwald Granite

H	118%
v	0.488
E_{min}	0.20 kWh/t
%PW @ 2 kWh/t	69%
r^2	0.91

Pulse Energy

All feed sizes were tested at four different pulse energies. Averaging of the *PWi* values for each of the capacitances gives the relationship shown in figure 8. The second-order derivative of equation 11 gives 385 J/pulse as the optimum pulse energy. The closest pulse energy that can be attained based on flexibility of capacitor configuration in the high voltage generator is 400 J/pulse.

Size Reduction

The increase in t_{10} value achieved during high voltage treatment of the Schwarzwald granite is plotted as a function of high voltage energy input in Figure 9. Table 4 tabulates the $A{\times}b_{Hv}$ values determined from the best fit of equation 4 to this data. The goal is to determine the degree of size reduction achieved concurrent with weakening, so taking an E_{sf} of 2 kWh/t and entering the $A{\times}b_{Hv}$ values into equation 4 gave an expected t_{10} of 2.64% for the HVB product.

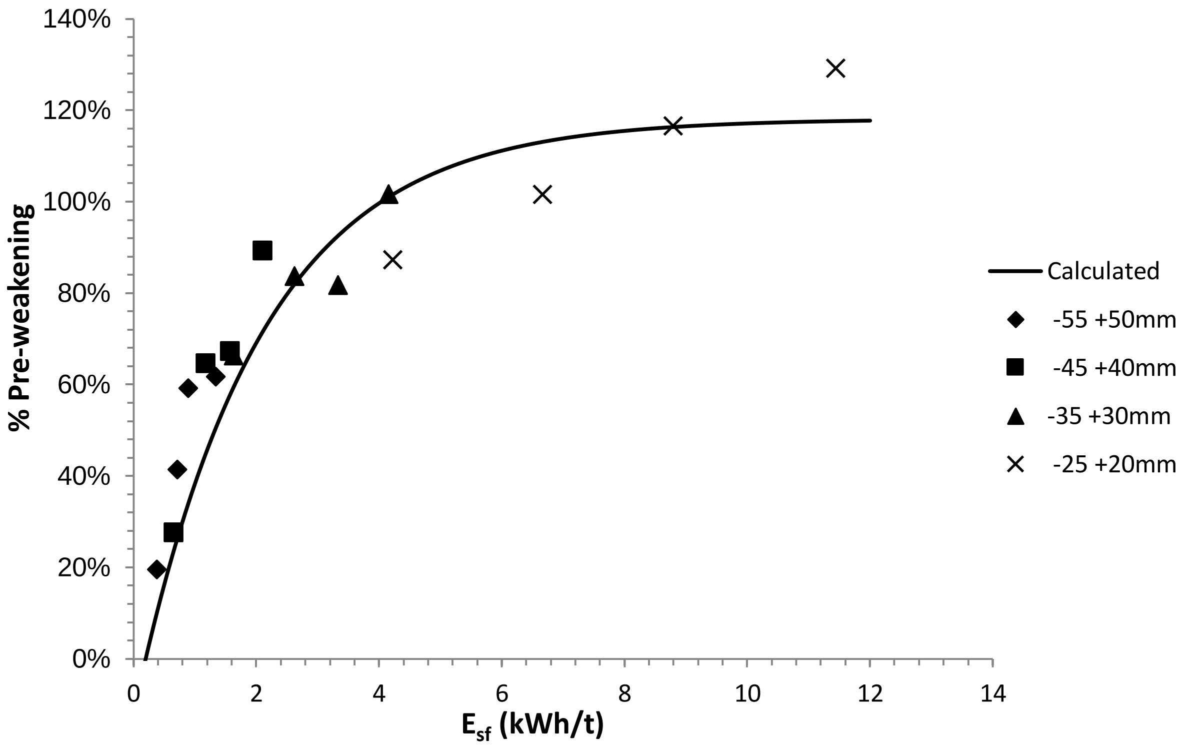

Figure 7 – Discharge ratio as a function of the pulse energy/field strength ratio, including the best fit Weibull distribution

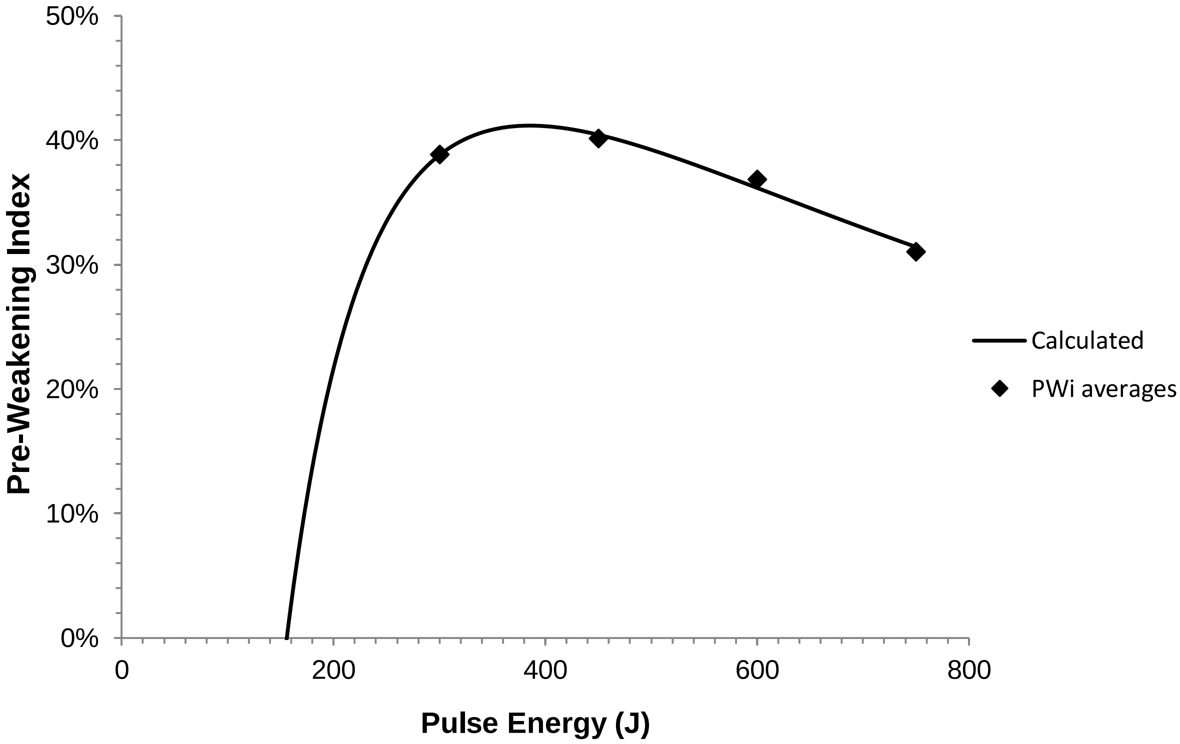

Figure 8 – Discharge ratio as a function of the pulse energy/field strength ratio, including the best fit Weibull distribution.

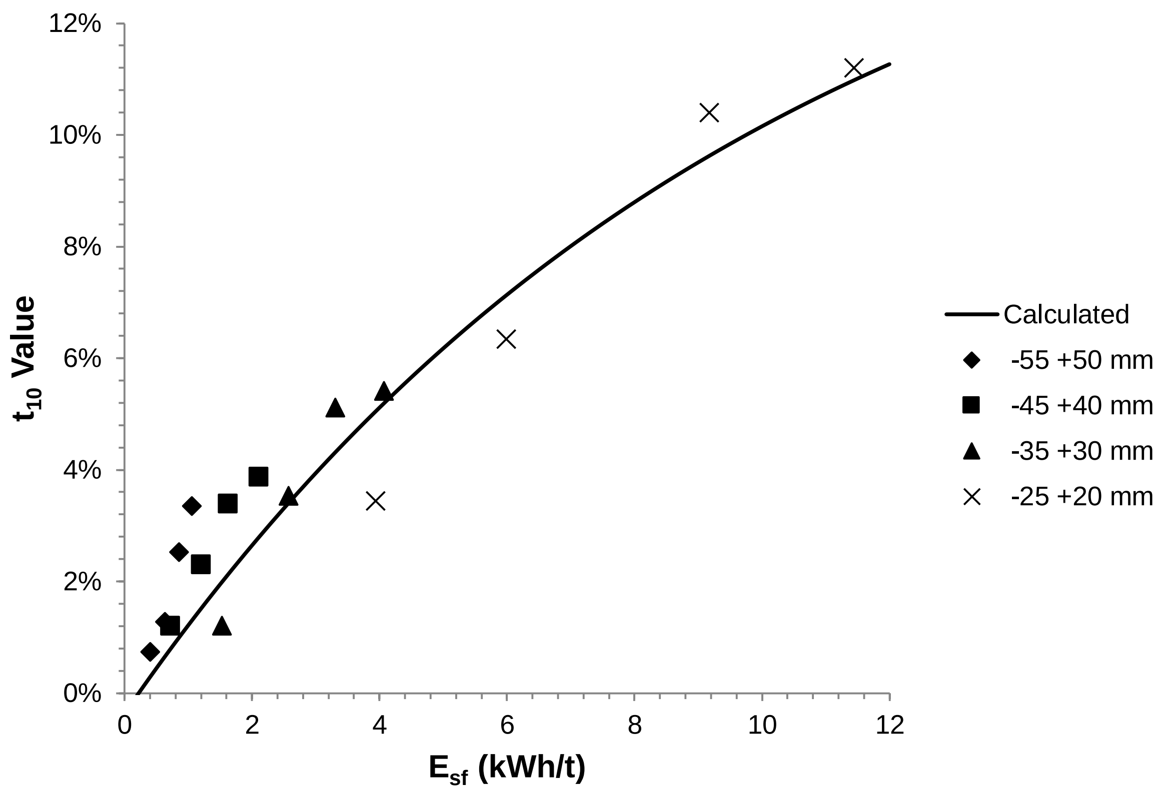

Figure 9 – t10 Value as a function of SELFRAG energy input for four different feed sizes.

Table 4 – High voltage fragmentation parameters for Schwarzwald Granite.

A_{Hv}	16.3%
b_{Hv}	0.10
E_{min}	0.23 kWh/t
t_{10} @ 2 kWh/t	2.64%
r^2	0.92

Discharge Ratio

Figure 10 shows the discharge ratios obtained for each feed size treated at the pulse energies listed in Table 2, including the Weibull fit, and table 5 lists the shape and scale parameters. A discharge ratio of 1 was achieved for every test on the -55 +50mm fraction, meaning it was only possible to constrain the lower and upper limit of the scale and shape parameter respectively for the Weibull distribution. As mentioned in the test outline, HVB machines are likely to treat a material bed with a thickness approximately equal to the size of the largest particles in the feed, which would be 55 mm for the dataset presented in Figure 10. Because the discharge ratio for the -55 +50 mm fractions was always one and for the -45 +40 mm fraction only one data point gave a discharge ratio below 1, it was not possible to use these data sets to accurately constrain the minimum field strength required. Consequently, it was decided to base the calculation on data for the -35 +30 mm size fraction. Using equation 13 and the recommended pulse energy of 400 J/pulse determined above, a minimum required field strength of 5.45 kV/mm is calculated for the -35 +30 mm fraction. Further work would be required to accurately constrain the actual minimum field strength required as the value quoted above is likely an overestimate.

Table 5 – Parameters for the Weibull fits of discharge ratio to electrical strength per size fraction.

	-55 +50 mm	-45 +40 mm	-35 +30 mm	-25 +20 mm
z_{Hv}	0.053	0.033	0.024	0.019
ES'	38.0	54.5	70.8	78.22
β_{ES}	4.29	4.62	5.15	5.42
E_{mat} required for r_{dp}=0.95 (kV/mm)	~5.6	~5.8	5.5	7.3

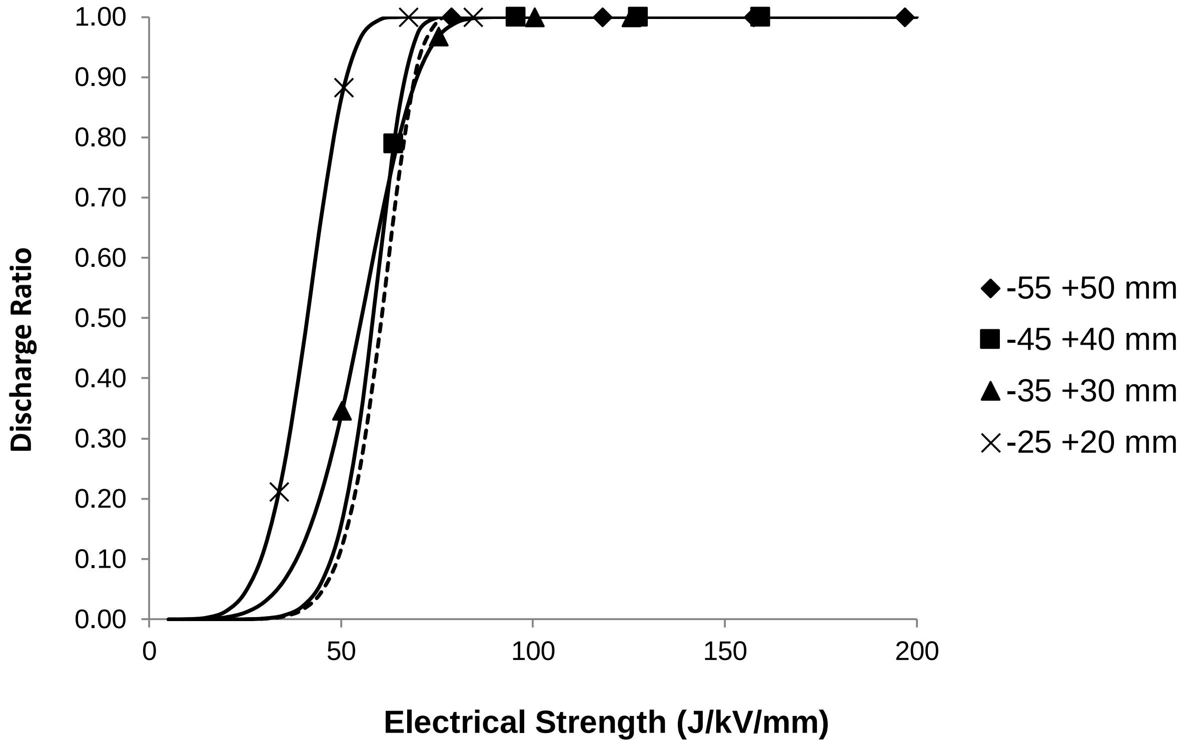

Figure 10 – Weibull fits for discharge ratio – pulse energy/field strength relationships for the four tested materials.

Scale-up to Continuous Processing

Based on the results presented above the most suitable generator setup for the PWTS was estimated and used for semi-continuous treatment of a 10 and 100 kg sample. The feed size for these tests was -45 +25 mm and PWTS was set to apply 2 kWh/t at 400 J/pulse twice, giving a total E_{sf} of 4 kWh/t. A screening step was included between the two runs to remove -25 mm material. This locked cycle-style approach was chosen to reduce the amount of energy spent on the -20 mm size fraction, thereby effectively preventing the high voltage equivalent of overgrinding. Because selection of the largest particle from each pulse is not feasible, the drop weight test was done on the estimated size range of the single particle test progeny used for weakening analysis (-45 +25mm).

Table 6 lists the weakening values achieved for the three samples. The variation between the samples was larger than expected, and surprisingly the batch and continuous test sample both outperformed the single particle test sample. There are several factors which may have contributed to this. Firstly, the size fraction for weakening analysis from the batch/continuous test may not be representative of the same fraction in the single particle test sample. Secondly, two passes at 2 kWh/t gave the oversize particle a larger chance to be affected by a discharge. This gave larger particles the chance to receive more energy and accumulate a larger degree of damage, which may be measured as a larger degree of weakening. Lastly, single particle tests rely on a single discharge being applied to a single particle. During batch/continuous processing on the other hand, multiple particles may be affected during a single discharge, meaning a larger portion of pulse energy may be utilised for fragmentation rather than for streamer propagation in water. Further research is required to increase in the scale-up factor from single particle tests to batch and continuous test results.

Table 6 – Comparison of single particle, batch and continuous test results

	Single particle tests	**10 kg batch sample**	**100 kg continuous sample**
E_{sf} (kWh/t)	3.98	3.23	3.84
Measured pre-weakening	93.2%	100.3%	119.2%
Calculated pre-weakening	98.8%	91.2%	98.1%
Difference	-5.6%	+9.1%	+21.1%
PWi	23.8%	31.1%	31.0%

Conclusions and Recommendations

This paper considered the high voltage and fracture mechanics of high voltage breakage, and the fundamental physical relationships underlying them. Based on these principles a methodology was outlined for the exploratory assessment of high voltage breakage. This holistic methodology allows for description of weakening and size reduction induced by high voltage breakage and also enables definition of the optimum treatment conditions in terms of pulse energy and effective electrical field strength. The outlined test procedure can be used as a first step towards high voltage treatment optimisation for further batch/continuous testing and generator design. The key conclusions from data and considerations presented in this paper can be summarised as follows:

- It was shown a minimum high voltage treatment energy input exists below which no weakening occurs. This minimum energy is followed by a strong increase of weakening towards a plateau at higher specific energy inputs. This relationship can be described using an adapted version of the general breakage probability curve by Vogel and Peukert (2007). The proposed weakening-energy equation can be used to calculate the HVB equivalent of the $A\times b$ values, the $H\times v$ ore parameters. These parameters can be used to ascertain expected weakening at any high voltage energy input within the range tested to determine these values.
- The pre-weakening index as a function of pulse energy was shown to follow a relationship for which a maximum can be determined. This maximum represents the pulse energy at which the highest pre-weakening index can be attained. Averaging of the *PWi* values obtained at identical pulse energies for different feed sizes allows determination of an average pulse energy that will most effectively weaken the entire feed size range.
- Size reduction of particles subjected to high voltage breakage through single particle tests was shown to follow a
- Based on high voltage physics it was demonstrated that the probability of electrical breakdown occurring (the discharge ratio) is proportional to the electrical strength of a material. The relationship between discharge ratio and electrical strength can be described using a Weibull distribution.
- Following the proposed test procedure, a $H\times v$ value of 57.6 was measured for a granite, which equates to 69% weakening at 2 kWh/t. Treatment of this rock type at 2 kWh/t yielded a t_{10} value of 2.6%. Lastly, it was determined this ore requires a pulse energy of approximately 385 Joule/pulse and an electrical field strength of at least 5.5 kV/mm to exceed an discharge ratio of 0.95.

- Scale-up from single particle tests to continuous tests showed continuous treatment results to produce superior results. The weakening percentages are in a similar range, showing the single particle test approach is a good starting point for more detailed weakening assessments. However, a larger data-set is required to establish a clear correlation between single particle and continuous test results.

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