Pre-weakening and Selective Liberation of Rocks using High Voltage Breakage Technology

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Mineral Processing Engineer, SELFRAG

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   - SELFRAG technology
   - Physics of high voltage breakage
   - Fragmentation principles
   - Improved liberation
   - Weakening

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   - Mining case study
   - Conclusions
SELFRAG in a nutshell

Technology company focused on high voltage pulse power

At SELFRAG, we develop and commercialize fragmentation systems for multiple industries using patented high voltage pulse power technologies that increase the value of material extracted or recycled.
What can we fragment?

SELFRAG systems fragment every composite or pure material starting at fist-size down to micron-size.
A revolutionary fragmentation technology
Focus on targeted applications in three segments

- **Manufacturing**
  - Add-on to existing product line
  - Solar grade silicon & quartz glass

- **Mining**
  - New extraction approach
  - Base & precious metals, industrial minerals

- **Recycling**
  - New recycling applications
  - High purity / value material

Recovery increase + energy savings + ecological process

Global and wide reach of SELFRAG’s technology
# History of high voltage breakage

**Old technology, new application**

<table>
<thead>
<tr>
<th>Technical advances</th>
<th>SELFRAG milestones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erwin Otto Marx invents the Marx generator</td>
<td>1924</td>
</tr>
<tr>
<td>Prof. Yutkin describes electrohydraulic crushing</td>
<td>1955</td>
</tr>
<tr>
<td>Tomsk Polytechnical University discovers electrodynamic fragmentation</td>
<td>1960</td>
</tr>
<tr>
<td>Prof. Andres publishes first paper on HVB</td>
<td>1977</td>
</tr>
<tr>
<td>Karlsruhe Institute of Technology (KIT) purchases Russian HVB unit</td>
<td>1995</td>
</tr>
<tr>
<td>Research at KIT was the first stop towards the foundation of SELFRAG</td>
<td></td>
</tr>
<tr>
<td>Ammann Group (Switzerland) enter license agreement with KIT</td>
<td>2003</td>
</tr>
<tr>
<td>First SELFRAG LAB machine sold</td>
<td>2007</td>
</tr>
<tr>
<td>First research into HV-induced weakening of rocks</td>
<td>2010</td>
</tr>
<tr>
<td>Commissioning of Pre-weakening Test Station</td>
<td></td>
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<tr>
<td>10 tph pilot plant unit ready for construction</td>
<td>2014</td>
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SELFGRAM technology:
How does high voltage (HV) pulse fragmentation work?

- Based on a HV physical selectivity
- At short pulse rise time water is more isolating than solids
- Discharge occurs through solid, causing strong internal shockwaves resulting in selective breakage
Our product portfolio addresses different applications

Technology has been mastered in a lab and continuous system

<table>
<thead>
<tr>
<th>Capacity</th>
<th>Lab system (batch)</th>
<th>Low-throughput continuous system</th>
<th>Container based system</th>
<th>Scalable high-throughput system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch</td>
<td>100kg – 1tph</td>
<td>10tph</td>
<td>100 – 2’000tph</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Value proposition</th>
<th>Purity</th>
<th>Selectivity</th>
<th>Recovery increase</th>
<th>Energy saving</th>
<th>Selectivity</th>
<th>High throughput</th>
</tr>
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<tbody>
<tr>
<td>Batch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous process</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Applications</th>
<th>Sample preparation</th>
<th>High purity glass recycling</th>
<th>Recycling</th>
</tr>
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<tr>
<td></td>
<td></td>
<td>Silicon crushing</td>
<td>Mining</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pilot planting</td>
<td>E-scrap</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mining exploration</td>
<td>recycling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Available 2014</td>
</tr>
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<td></td>
<td></td>
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<td>Available 2016</td>
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</tbody>
</table>
SELFRAG’s USP for the laboratories

Enables unmatched quality in sample preparation for laboratories

**Industry status**

- Fragmentation done by hand, old crusher or sometimes impossible
- Quality of the sample is limited and cross-contamination is an issue
- Time consuming and dirty process

**Value proposition SELFRAG**

- Fragmentation along grain boundary
- No cross-contamination
- Fragmentation of all materials
- Fast and clean process

Our clients today: 22 top tier universities around the globe
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Electrical Breakdown

Water acts as an insulator

Electrical breakdown occurs when a material is not conductive enough to fully accommodate electricity flow, yet not resistive enough to completely inhibit it either.

Differences in polarization mechanisms make breakdown more likely in rocks than water at the right conditions.
**High Voltage Breakage**

**Discharge/fragmentation process**

Electrical breakdown causes extensive plasma and shockwave damage

<table>
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<tr>
<th>Discharge process</th>
<th>Fragmentation process</th>
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<tr>
<td>Common analogue - lightning</td>
<td>Common analogue - blasting</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Formation of the electrical field</td>
<td></td>
</tr>
<tr>
<td>Plasma streamer creation and growth</td>
<td>Streamers get attracted to areas of strong field distortion (i.e. sulphides, oxides)</td>
</tr>
<tr>
<td>Plasma streamer(s) bridge the gap between electrodes and create a discharge</td>
<td>Localised crushing near plasma channel, circumferential/radial fracturing and spalling in periphery</td>
</tr>
<tr>
<td>Very rapid plasma channel expansion due to Ohmic heating</td>
<td>Shockwave emission causes tensile fracturing enhanced by plasma percolation into fractures</td>
</tr>
<tr>
<td>Plasma channel collapse</td>
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Plasma Streamers

Lightning as a natural analogue
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Fragmentation

Extensive experience with a range of rock types

- Exponential decrease of the amount of feed-sized particles remaining after SELFRAG treatment
- Fragmentation can be predicted based on bulk permittivity and tensile strength

\[
\% \text{ Feed size remaining} = \frac{-18.64}{13.98 + \tau \varepsilon_b}
\]
Fragmentation

Extensive experience with a range of rock types (cont.)

- Fractal law describes product $P_{80}$ increase with SELFRAG energy input
- Product $P_{80}$ is related to acoustic impedance and porosity

\[ \text{Product } P_{80} = -2.7 + 1.07 \times 10^{-7} \cdot z - 14.5 \Phi \]
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</tbody>
</table>
Selectivity of SELFRAG process arises from two sources:

1. Field enhancements are strongly dependent on electrical properties of minerals.
2. Shockwave interaction with acoustic properties of minerals.

SELFRAG processing causes two types of selective fracturing:

1. Inter-granular selective fragmentation, i.e. preferential fracturing along grain boundaries.
2. Intra-granular selective fragmentation, i.e. preferential fragmentation of certain mineral phases (most notably quartz).
Fragmentation
Selectivity (cont.)

Electrical selectivity

- Weak field distortion along grain boundary
- Limited electrostrictional tension

Shockwave selectivity

- Strong wave interactions in particle
- Considerable fracturing along grain boundaries

- Low contrast in acoustic impedance between inclusion and matrix
- High contrast in acoustic impedance between inclusion and matrix
Plasma channel effects

Very localised melting

- Melting effects are observed but volumetrically negligible
- Volumetrically negligible, no negative effects on flotation/dating/other mineralogical attributes
Fragmentation
Improved liberation

- 1.8% Chalcopyrite in feed upgraded to >10% at SELFFRAG energies in 0 – 5 kWh/t range
- Liberation/modal abundance advantages coincide with weakening energy range
Fragmentation

Weakening and liberation

Sample P1-2
0.6 kWh t⁻¹

Mineral Name
- Background
- Pyrite
- Ti Phases
- Quartz
- Plagioclase
- K-Feldspar
- Muscovite
- Ankerite
- Dolomite
- Apatite
- Fractures
Fragmentation

Weakening and liberation
Liberation for Geological Research

Improved geochronology results

- Vastly superior zircon/apatite liberation combined with quicker, dust-free sample preparation
- No negative effects on fission track, $^{40}\text{Ar}/^{39}\text{Ar}$, $^{40}\text{Ar}$ degassing curves, other thermochronology methods\(^1,\)\(^2\)

\(^1\) Sperner, B., Jonckheere, R., Pfänder, J.A., Testing the influence of high-voltage mineral liberation on grain size, shape and yield, and on fission track and 40Ar/39Ar dating, *Chemical Geology* (2014)

\(^2\)
Weakening

Definition of weakening

- Discharge-induced fracture network inside a particle that is:
  1. Sufficiently pervasive to cause a measurable strength reduction
  2. Not pervasive enough to cause full fragmentation of the particle

<table>
<thead>
<tr>
<th>% Weakening for grindability indicators that increase with softness(^1)</th>
<th>% Weakening for grindability indicators that decrease with softness</th>
</tr>
</thead>
</table>
| - i.e. A*b values  
  - No maximum weakening | - i.e. Bond work index  
  - Maximum weakening of 100% |

\[
\% PW = \frac{A*b_{\text{weakened}} - A*b_{\text{untreated}}}{A*b_{\text{untreated}}}
\]

\[
\% PW = \frac{BW_{i\text{untreated}} - BW_{i\text{weakened}}}{BW_{i\text{untreated}}}
\]

**References:**
Weakening – Energy Relationship

Similarities to drop weight test analysis (1)

- Electrical pulses contain a well-defined amount of energy deposited in a single high strain rate event

- Well-defined and widely recognised models for impact breakage analysis:
  - JKMRC Prior art model
    \[ t_{10} = A [1 - e^{-bE_{cs}}] \]
  - Vogel and Peukert
    \[ S = 1 - e^{-f_{mat}\times k(E_{cs} - E_{min})} \]
  - Shi and Kojovic
    \[ t_{10} = M [1 - e^{(-f_{mat}\times k(E_{cs} - E_{min}))}] \]

Substitutions: \( t_{10} \rightarrow \% \text{Pre-weakening} \)

- \( A \rightarrow H \)
- \( b \rightarrow v \)
- \( E_{cs} \rightarrow E_{sf} \) as the high voltage equivalent of \( A \times b \) values
Weakening – Energy Relationship

Similarities to drop weight test analysis (2)

‘Simple’ weakening model

\[ \%PW = H \left[ 1 - e^{-v(E_{sf}-E_{min})} \right] \]

‘Extended’ weakening model

\[ \%PW = H \left[ 1 - e^{-f_{mat.sf} x (E_{sf}-E_{min})} \right] \]
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Why care about weakening/selective liberation?

1. Comminution is often the biggest single cost factor in a processing circuit, consumes approx. 3 – 5% of global electricity production
2. 95 – 99% of comminution energy is wasted as heat/noise
3. The 1 – 5% remaining energy is used for largely a-selective grinding, significant amounts of energy are consumed grinding finer than strictly necessary

OPEX reduction due to weakening of rocks

- Brownfield site with escalating production costs
- Investigate potential for cost reduction and revenue increase using SELFRAQ technology
Case study

Existing circuit with 19.6 kWh/t input

Target: OPEX reduction at maintained throughput
- Extensive weakening study
- JKSimMet simulations were used to quantify benefits
- Close cooperation with mine owner (brownfield site)
- Simulation assumed 72% weakening at 2.6 kWh/t SELFrag energy

Commodity	Cu/Au
Specific energy input	19.6 kWh/t
Throughput	2000 tph
Grindability	A*b = 33.3
	BWi = 22.4 kWh/t
Case study

Shutdown of 2 pebble crushers and 1 ball mill is possible\(^1\)

- 25% Specific Energy Saving\(^1\)
- Incidental throughput increase of 6.7%\(^1\)
- Further potential for recovery improvements\(^2\)

\(^1\) Confirmed by JKSimMet modelling
\(^2\) JKSimMet suggest grind size decrease from 210 to 148 µm; Circuit originally designed for 150 µm
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7. **Conclusions**
Summary

High voltage physics

• Electrical breakdown occurs in rocks before water in SELFRAG units, and causes formation of plasma channels

• Shockwaves emanating from plasma channel, together with plasma percolation and limited direct plasma damage cause extensive weakening and highly selective liberation of SELFRAG technology

• Acoustic impedance and porosity correlate to product size after SELFRAG treatment, tensile strength and permittivity correlate to % remaining oversize after SELFRAG
Summary

Weakening, liberation and case study

- SELFRAG causes extensive micro-fracturing that leads to significant weakening of rocks
- SELFRAG liberates selectively and coarser than conventional comminution technologies
- Case study: OPEX reduction due to weakening of rocks
  - Shut down of one ball mill and two pebble crushers
  - Lower ore strength and reduced milling capacity mean lower grinding media and liner consumption
  - 4.9 kWh/t specific energy reduction at increased throughput
  - Potential for recovery improvements from decreased grind size