Canada Mining Innovation Council (CMIC)  
Comminution Technology Appraisal Study  
Final Report
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Appendix A

CMIC – Hatch Questionnaire Template
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Executive Summary

The Canada Mining Innovation Council (CMIC) has identified energy in mineral comminution as a key area where emphasis on innovation needs to be focused and intends to allocate funding towards collaborative development of new technologies to reduce energy requirements in ore comminution. CMIC engaged Hatch to perform a comminution technology appraisal study to determine one or two key technologies on which the CMIC should focus their efforts.

During this study, Hatch, through its global network have assisted CMIC in determining the key innovative comminution technologies with potential for significant energy savings and possible application in full scale mining operations. In addition, Hatch facilitated and participated in the process of screening and selecting the best options for future development. The study followed a number of steps, as follows:

1. Research of potential technologies through a comprehensive literature review and through the consultation with experts in the field
2. Elaboration of an analysis matrix to gauge the possible benefits and shortcomings of the identified technologies.
3. Ranking and compilation of all potential technologies in a table format for easy visualization of all options and their classification based on several metrics such as the energy savings potential.
4. Sharing the findings with CMIC’s project team and suggesting the selection of the top 5 technologies.
5. Conducting reviews and discussions with the CMIC’s team which resulted in the refinement of the top 5 technologies list with the amalgamation of two similar technologies and one additional technology resulting in the following options:
   a. HPGR or VRM in closed-circuit with Air-Classifiers
   b. HPGR and Stirred-Mill combined circuits
   c. High Voltage Electric Pulse Treatment
   d. Conjugate Anvil Hammer Mill (CAHM)
   e. Super Fine IMPTEC Crusher
6. Follow up analysis and discussions for the selection of the best 2 cases for further investigation. As an outcome of these discussions it was decided that options a., b. and c. did not fulfill all the criteria for CMIC’s collaboration.

7. Participation in meetings with the leading developers of the CAHM and IMPTEC technologies where they presented the details of the technologies such as equipment information, stage of the technology development, size range for comminution, and estimation for energy consumption levels.

As outcome of this study, the CAHM was considered to be the technology for CMIC to concentrate on in the near future as it has great potential, there is the common desire to work cooperatively and the technology is at early stages of development which means it can greatly benefit from CMIC’s support. In addition, the inventor, while living in the USA, is in close proximity to Canada and has recently started to work with Canadian researchers and companies, e.g. the University of British Columbia as well as Teck.

Up to the date of the release of this report, the potential for significant energy savings of the CAHM has been demonstrated through the use of Discrete Element Method (DEM) modeling and simulation package called ROCKY that is used to simulate realistic comminution. The inventor of the technology is open to work in collaboration with CMIC and has already accepted CMIC suggestions for proceeding with the technology development in a systematic, small scale to larger scale equipment mode.

Additionally, CMIC will continue to investigate other comminution technologies that promise increased energy efficiency, especially development and application of the Super Fine IMPTEC Crusher. CMIC will closely monitor the development of this technology during the next months and maintain communications with the developers to understand the performance of the semi-commercial unit currently being tested and learn how and when to work together on further developments.

It is Hatch’s judgment that these plans are well-conceived. Hatch is interested in being involved further in the development of these promising approaches.
1. Introduction

The Canada Mining Innovation Council (CMIC) has identified energy in mineral comminution as a key area where emphasis on innovation needs to be focused due to comminution being a large, inefficient consumer of energy. The CMIC intends to allocate funding towards efforts to reduce energy requirements in ore comminution. To efficiently develop the technologies, selection and planning is required to move the program forward. The comminution technology appraisal study intends to determine one key technology that the CMIC should focus their efforts on and provide insight on future developments and other upcoming technologies.

Hatch through its global network and innovative nature assisted CMIC in determining the key innovative comminution technologies that have potential to be game-changers in the industry and also assisted CMIC in selection of one of them for future development. This report covers all phases of the project and the key items discussed here are as follows:

- **Approach:** The approach the authors have taken to researching and ranking the technologies for discussion and further investigation. This includes a global census of comminution experts and their insight on where the technologies are moving and a literature research to understand and compile technological advances in each area.

- **Technologies:** The technologies that have been investigated to understand the stage of the technology development, the potential for energy reduction relative to currently proven technologies and applications, the downstream benefits for which the technologies can be applied indirectly, the cost of the technology for practical application, and the inherent safety of the technology as applied on an industrial scale.

- **Preliminary recommendation:** The authors have identified the top five technologies, through careful ranking and selection, that were object of the analysis in the initial phase of the project.

- **Final recommendation:** In conjunction with CMIC processing group, one of the top options was selected for further investigation and support by CMIC, and a second option selected for continuous monitoring of its developments for possible future engagement.
2. Approach

This section describes the approach the authors have taken to perform this comminution technology appraisal; it lists the objective of study, the scope of work, the project execution milestones, and the background information review.

2.1 Objective

The objective of the study is to provide a well-rounded assessment of existing, emerging, typical, and non-conventional technologies in comminution. The study intends to define and discuss some aspects of the comminution technologies, as follows:

- **Limitations**: Discussion on the engineering limitations of existing technologies. The current limitations of well-established technologies need to be investigated to understand the potential for further improvement to their current level of energy efficiency. In contrast to this, some emerging technologies may not have well defined limitations due to nonexistent applications at the industrial scale.

- **Potential**: Many technologies have well established applications and knowledge surrounding how they perform in their usual or standard duty at an industrial scale. However, there may be potential value of these existing technologies in new applications that have not been tested as yet on an industrial scale.

- **Prospect**: There is a pool of emerging prospective, non-conventional technologies, that are not considered to be typical technology that may have significant upside potential in comminution innovation. This study intends to gather information around these prospective technologies and to gain a better understanding of them.

- **Alternative**: There are alternative technologies considered which have been overlooked by the comminution community, especially the ones that do not rely on traditional mechanical forces. These novel ideas need to be better understood to assess their potential.
2.2 Scope of Study
The study focuses on the process technologies directly related with comminution. The appraisal takes into account technology readiness, engineering and cost considerations. Where possible, the study focuses on industrial scale operational data as this is considered as proven concepts.

The study excludes technologies or applications that are not directly related to comminution, although they may have an impact on the overall comminution process. These excluded items are listed below:

- **Mining Methods**: Methods that reduce the size of feed delivered to the comminution plant, such as fine blasting in the mine.
- **Pre-sorting**: Methods that reduce the feed into the mill through dense-media separation and sensor ore-sorting.
- **Energy Recovery**: Methods that recover energy from inefficient process streams and/or unit operations in the mill.

2.3 Project Execution Milestones
The project was executed in two phases.

**Phase 1**
- **Literature review**: an investigation of conference proceedings and relevant technical publication to initially screen possible technology candidates (focused on material published since 2010).
- **Interview/contact**: academia, mining companies R&D, suppliers, consultants/experts around the globe. Utilize Hatch’s extensive network worldwide.
- **Technologies list**: a compilation containing all potential technologies, including details such as: the maturity level of development, the potential percentage reduction in energy requirement, and applicable size range, e.g. from 50mm to 1mm.
- **Analysis matrix**: development of the basis for ranking all listed technologies
- **Sharing the findings**: presenting the findings to CIMC processing group, including:
  - The complete matrix with resulting ranking
  - **Top 5 technologies**: detailed information on suggested technologies meriting the joint assessment with CMIC team
  - Request for review and possible adjustments to the suggested top 5 list of technologies

**Phase 2**
- **Selection of two technologies**: together with CIMC processing group, select the best two cases for further investigation
• **Detailed investigation of top two technologies**: presentations to CMIC and Hatch by the leading developers and Hatch project lead.

• **Selection of one technology for immediate action**: together with CIMC processing group select the best technology for future development plan and funding.

• **Decision to monitor the development of the second option**: together with CIMC processing group a decision was made to monitor the short term development steps that the other technology has planned to undertake and then evaluate the merits and opportunities for extra collaboration.

• **Final report**: delivery of the final report by Hatch.

### 2.4 Background Review

A comprehensive technology background review was completed for the study. The review was intended to identify and record the current status of technologies globally. To facilitate this process, an in-depth review of published literature was completed as well as conducting a census of various acknowledged comminution experts from around the world.

#### 2.4.1 Literature Review

A literature review on current published technical papers within the comminution area was completed. The papers follow the development of new, novel, and existing technologies in comminution. This review included an investigation of technical publications and patents in the comminution area.

The literature review papers were categorized according to the following criteria:

- Non-traditional Method of Rock Disintegration, e.g. Microwave Frequency Treatment, and High Voltage Electric Pulse Treatment (Selfrag).

- Conventional Methods of Rock Disintegration and subdivided in:
  - Existing Technologies (optimization opportunities/different applications),
  - Arising Technologies,
  - New Technologies / Technologies from other Industry (e.g. coal, cement, powder)

A complete list of the papers reviewed for this report is referenced in Section 4. All the papers are available upon request and will be sent to CMIC at the time of project completion.

#### 2.4.2 Global Census

A questionnaire was developed by the authors and sent to comminution experts around the world to determine their opinions and insight on upcoming trends, recently installed pilot plants, and other items of interest related to comminution. The comminution experts contacted by Hatch are listed in Table 2-1 and the questionnaire template is included in Appendix A. All the answered questionnaires received by the date of completion of this report have been sent to CMIC Processing Group.
<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aidan Giblett</td>
<td>Newmont</td>
</tr>
<tr>
<td>Barun Goran</td>
<td>Barrick</td>
</tr>
<tr>
<td>Jens Lichter</td>
<td>AngloAmerican</td>
</tr>
<tr>
<td>Richard Neu</td>
<td>Newmont</td>
</tr>
<tr>
<td>Thomas Logan</td>
<td>Golden Metallurgical Group</td>
</tr>
<tr>
<td>Hamid-Reza Manouchehri</td>
<td>Sandvik</td>
</tr>
<tr>
<td>Marko Hilden</td>
<td>JKMRC</td>
</tr>
<tr>
<td>Phil Thwaites</td>
<td>XPS Consulting &amp; Testing Services</td>
</tr>
<tr>
<td>Bern Klein</td>
<td>UBC</td>
</tr>
<tr>
<td>Edgard Wipt</td>
<td>Weir</td>
</tr>
<tr>
<td>Lawrence (Larry) Nordell</td>
<td>Conveyor Dynamics</td>
</tr>
<tr>
<td>Walter Valery</td>
<td>Hatch</td>
</tr>
<tr>
<td>Robert McIvor</td>
<td>Metcom</td>
</tr>
<tr>
<td>Stephen Morrell</td>
<td>SMC Testing PTY</td>
</tr>
<tr>
<td>Malcolm Powell</td>
<td>JKMRC</td>
</tr>
<tr>
<td>Chris Rule</td>
<td>Angloplatinum</td>
</tr>
<tr>
<td>Grant Ballantyne</td>
<td>JKMRC</td>
</tr>
<tr>
<td>Prof Mike Moys</td>
<td>University of the Witwatersrand</td>
</tr>
<tr>
<td>Prof Aubrey Mainza</td>
<td>University of Cape Town</td>
</tr>
<tr>
<td>Adrian Hinde</td>
<td>Independant/Mintek</td>
</tr>
<tr>
<td>Manqiu Xu</td>
<td>Vale</td>
</tr>
</tbody>
</table>
3. Technologies

3.1 Technology Classification

A multitude of comminution technologies have been investigated during the course of this study. The technologies evaluated are organized into four categories:

- **Existing Technologies**: Existing technologies are proven concepts/technologies that have been successfully applied in an industrial scale operation. These technologies are well established in proven applications. Currently, there may be opportunities for these technologies to be incorporated into new applications/circuit configurations. However, for the majority of them, any significant energy saving potentials has already been realized.

- **Arising Technologies**: Arising technologies are concepts that have been explored, studied, and are operational to some extent, or technologies from other industries that are already finding new applications in the mining industry. Some of these technologies are well proven in other applications and in other industries, and offer some benefit over existing comminution technologies. They are gaining interest within the mining community.

- **New Technologies**: New technologies are technologies currently in the development phase and that have not been applied on an industrial scale or in pilot scale applications. Most of the technology development has been bench or lab scale, but may have significant potential benefit in comminution applications. These technologies can either be a new industrial unit application, or an existing, proven application in a different industry and applied in a different duty or application, e.g., ultrafine grinding for the pigment industry.

- **Non-conventional Technologies**: These are technologies that are not conventional, utilizing electrons, magnetic pulse, accelerated electron beams, i.e. technologies that do not rely on mechanical methods of comminution.

3.2 Technology Ranking Methodology

A ranking methodology consisting of five key factors to assess all the different technology options was developed for this study. A list of the considerations for ranking the technologies is described below:

- **Potential Energy Reduction**: The overall potential for reduction in energy consumption, relative to what is commonly and currently achieved in existing mining operations. This rating also takes into account the application size range and the overall effect in energy savings for the total comminution energy requirement.

- **Safety**: Safe application and utilization of the technology is a critical factor for long term applications. The perceived, and hopefully the actual, safety risk associated with the technology is an important factor in the future success of its application and therefore has been taken into account in the ranking process.
• **Downstream Benefits**: There may be benefits in downstream processes that could be realized with new comminution techniques.

• **Stage of Technology**: The maturity of the technology provides an indication of how far the technology has progressed towards an industrial scale.

• **Cost (estimated/perceived)**: The actual or perceived capital cost and operating cost associated with the technology is an important factor that may assist or limit its introduction and acceptance.

A ranking level between 1 and 5, with 1 being poor and 5 being excellent, was applied to each of the considerations for each technology investigated in this study. See Ranking Matrix in Table 3-1. A sum of all the scores then provides an overall indication of which technologies should be considered in the next phase of study.

**Table 3-1: Ranking Matrix**

<table>
<thead>
<tr>
<th>Matrix of Rating</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy reduction</td>
<td>Very low</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Very high</td>
</tr>
<tr>
<td>Safety</td>
<td>Unsafe</td>
<td></td>
<td></td>
<td>Proven safe</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>Very high</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Very low</td>
</tr>
<tr>
<td>Stage of technology</td>
<td>Idea</td>
<td>Laboratory</td>
<td>Pilot</td>
<td>Demonstration unit</td>
<td>Operating Commercial unit</td>
</tr>
<tr>
<td>Downstream benefits</td>
<td>Very low</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Very high</td>
</tr>
</tbody>
</table>

### 3.3 Technology Ranking Summary

The technologies identified and assessed were classified, listed and ranked based on the methodology described in the previous sections and the result is summarized in Table 3-2.
<table>
<thead>
<tr>
<th>Table 3-2: Summary Ranking Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy reduction</td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>1. Microwave frequency treatment</td>
</tr>
<tr>
<td>2. High Voltage Electric Pulse treatment: Selfrag</td>
</tr>
<tr>
<td>3. Magnetic impulse treatment</td>
</tr>
<tr>
<td>4. Super powerful hyper-impact waves</td>
</tr>
<tr>
<td>5. Electric hydrodynamic effect</td>
</tr>
<tr>
<td>6. Accelerated electron beam</td>
</tr>
<tr>
<td>7. Nanosecond high-power electromagnetic pulses (HPEMP)</td>
</tr>
<tr>
<td>Non-traditional method of rock disintegration</td>
</tr>
<tr>
<td>1. HPGR</td>
</tr>
<tr>
<td>2. AG/SAG mill</td>
</tr>
<tr>
<td>3. Ball mill</td>
</tr>
<tr>
<td>4. Classification: Derrick® Multi-deck Stacking Screen</td>
</tr>
<tr>
<td>5. Vertimill™</td>
</tr>
<tr>
<td>6. Isamill™</td>
</tr>
<tr>
<td>Existing technologies (optimizations/ different applications)</td>
</tr>
<tr>
<td>Conventional method of rock disintegration</td>
</tr>
<tr>
<td>1. Horomill®</td>
</tr>
<tr>
<td>2. Vibrocone™</td>
</tr>
<tr>
<td>3. HIGmill™</td>
</tr>
<tr>
<td>4. Super-fine IMPTEC Crusher</td>
</tr>
<tr>
<td>Arising technologies</td>
</tr>
<tr>
<td>1. EDS Multishaft mill</td>
</tr>
<tr>
<td>2. Conjugate Anvil-Hammer Mill (CAHM)</td>
</tr>
<tr>
<td>3. HPGR - in close circuit with air classifiers</td>
</tr>
<tr>
<td>4. HPGR-Stirred Mill combined</td>
</tr>
<tr>
<td>5. Multi-Pass HPGR circuit</td>
</tr>
<tr>
<td>6. Jet microniser (air jet mills)</td>
</tr>
<tr>
<td>New technologies / technologies from other industry (coal, cement, powder...)</td>
</tr>
<tr>
<td>7. Rotary Collider Mill (RCM) - DevourX</td>
</tr>
<tr>
<td>8. Hicom Mill</td>
</tr>
<tr>
<td>9. Vertical Roller Mills</td>
</tr>
</tbody>
</table>
3.4 **Top 5 Technologies**

The selection of the top five technologies was made based not only on the results of the ranking table but also taking into account the responses from the various experts involved in the global census. These five most promising technologies are listed together with short descriptions.

- HPGR in Closed Circuit with Air Classifiers
- Vertical Roller Mill (VRM)
- Conjugate Hammer Anvil Mill (CHAM)
- HPGR – Stirred Media Circuits
- High Voltage Pulse Treatment – Selfrag

3.4.1 **HPGR – in closed-circuit with air classifiers**

The application of HPGR technology in comminution circuits is already well established for the processing of hard ores in precious and base metal operations. Of the many possible flowsheets that have been proposed for HPGRs, those using HPGRs as tertiary crushers, in closed-circuit with wet screens (apertures in the range of 6mm to 10mm), and feeding Ball mills seems to have become the standard for these applications.

Although these circuits provide reduced operating costs with a relative increase in energy efficiency and the elimination of steel grinding media when compared to SAG-based circuits, the overall energy reduction of the circuit is compromised by the requirement of complex material handling systems. In addition, the total capital cost is usually higher than for a traditional SABC circuit.

Several different circuits have been proposed to better utilize the HPGR by applying it for higher reduction ratio and therefore the elimination of the less efficient Ball mill, e.g. the multi-stage HPGR. However, the one circuit/application that seems to be the most promising in terms of energy reduction, allied with relatively low capital cost requirements, is one with a single stage HPGR in closed-circuit with air classification. This dry circuit has already been used in the cement industry for reliable pre-mill grind or final product grind, reducing power and steel consumption cost, and increasing throughput capacity, while operating to make a high quality product as fine as 25 µm.

Weir (KHD HPGR) is advocating this new circuit and has reported on recent project studies and a few operations (iron ore and limestone processing), with final product sizes of 75 µm or as low as 15 µm, are feasible and enable significant energy reduction (more than 50% overall if compared to traditional circuits with tumbling mills).

This dry HPGR circuit usually is designed with a combination of static and dynamic air classifiers and a schematic of its flowsheet is shown in Figure 3-1. It is also interest to note that “dry ground feed for flotation shows superior performance in pilot testing to wet milled product” (Aidan Giblett – Newmont TS Processing).
Figure 3-1: HPGR in closed-circuit with Air Classification (Van der Meer et al., 2012).

High Pressure Grinding Roll (HPGR) is recognized as an energy efficient comminution technology, and is in fact a dry process. A better understanding of this alternative circuit, the limitations, actual process benefits, and probably improved modelling is required to validate this technology to be more widely applied within the industry, and for scale-up and design purposes.

A pilot test program was recently conducted as a collaborative project between Metso® PTI and CSIRO (Jankovic et al., 2015) and demonstrated an additional 20 to 30% power reduction when comparing this dry circuit to a HPGR-Ball milling circuit for an application with a size reduction from 10mm F80 to 50 µm P80, and it is concluded that there is a possibility for a potentially higher reduction factor when comparing a non-HPGR circuit to this dry-processing flowsheet.

3.4.2 Vertical Roller Mills

Vertical Roller Mills (VRMs) are currently mainly used in the cement and coal industry as a 3-in-1 machine (grinding, separation and drying). However, VRMs are not currently common in the mining industry despite reports about successful production and pilot trial experiences for Iron Ore, Copper Shale, Copper Matte, Copper Slag, Titanium Slag, Tin Slag, Steel and Stainless Steel Slag with Loesche® VRM (Carsten et al., 2012).
VRM’s are well-established grinding equipment for various tasks in the coal and cement industry today. In terms of numbers of new installed units in the cement industry VRM’s have overtaken ball mills for a few years (Harder, 2010).

VRMs are considered an energy-efficient alternative to conventional grinding technology for similar reasons to the HPGR, i.e. inter-particle breakage in compressed bed. An extract of Reichert et al. 2015 publication about a research project for VRM model development is reproduced below as it gives a good description of the Loesche® Airflow-Mode (standard), which is installed in the majority of the VRM plants. Loesche® currently can also supply an alternative flowsheet and equipment design, for higher energy efficiency, the Overflow-Mode configuration.

“The grinding parts of a Loesche® mill (Figure 3-2) are a rotating table (1) with a horizontal grinding track and rollers (2), which are pressed onto the table by lever arms and a hydro pneumatic spring system. Between the working surfaces of track and rollers, particle bed comminution takes place. A dynamic air separator (3) is located above the grinding chamber, which classifies the ground particles. The transport of the particles from the grinding table to the air separator is done pneumatically. For this purpose air is sucked through the mill, entering the mill from below the grinding table, streaming upward through the louver ring (4), catching the particles at the edge of the grinding table and passing through the dynamic air separator. Air and fine fraction leave the mill into a bag house, whereas the coarse fraction is guided by the grid cone (5) back onto the grinding table for further comminution. In case of wet feed material it is possible to preheat the air flow with a hot gas generator. In summary, four separate processes take place in this compact machine: grinding, classifying, transport and drying.” (Reichert et al. 2015)
Figure 3-2: Schematic operation of a standard, Airflow, VRM (Reichert et al., 2015)

In the "Overflow-Mode" configuration the classification is external to the mill. "There is no suspension of solids within the VRM grinding chamber. The material is fed onto the grinding table and then allowed to drop off into the recirculating stream. This stream is transported mechanically through an external "2-stage" air classifier. The first stage consists of a static classifier that allows the coarse particles and some middlings to return to the mill immediately. The undersize from the static classifier is then drawn into the dynamic classifier for final classification, followed by de-dusting. The oversize from the dynamic classifier is combined with the oversize from the static classifier and returned to the mill. Alternatively, the middlings of the dynamic classifier, usually in the range of -1.5mm, could be treated separately. The external classification circuit allows the installation of a fan, which has a lower compression, thereby improving circuit energy efficiency. An illustration of the Overflow-Mode flow sheet is given in Figure 3-3." (Carsten et al., 2012)
Review of VRM technology suggests that it offers energy efficiency and process benefits that would be favourable for minerals applications, where it could potentially replace final stages of crushing and grinding in one process step. VRM technology is well applied and proven in the cement and power industries, and therefore a market exists and the technical risk is reasonably low. There are several suppliers of VRM and the leading supplier, Loesche®, is trying to break into the minerals industry.

VRM and HPGR can potentially operate in similar roles, from final stages of crushing through to grinding applications, but requires further evaluation for mineral applications. A test program to determine their limitations, impact on downstream processes, energy efficiency and a comparison with more conventional circuits and technologies would be a very good contribution to the industry. This test program could provide direction for further development of the VRM technology and also provide supporting evidence of how this technology could be applied in mineral applications to reduce energy consumption.

### 3.4.3 Conjugate-Anvil-Hammer Mill (CAHM)

The Conjugate-Anvil-Hammer Mill (CAHM) is an innovative and apparently revolutionary comminution machine invented and patented by Dr. Lawrence Nordell. Dr Nordell is a renowned comminution expert with great experience in SAG mill optimization, crushers and mill liner design, belt conveying advance design, and DEM modeling. He explains that the original idea for the development of the CAHM came from studying the SAG Mill comminution “Sweet Spot”. As can be seem in DEM illustration (Figure 3-4) explaining how a SAG mill comminutes rock, i.e., the shear work energy map of the mill during its comminution cycle.

![Figure 3-3: Flowsheet for a VRN, Overflow-Mode (Carsten et al., 2012)](image-url)
Dr. Nordell explains that to enhance the SAG performance it is desirable to pass as much ore as possible through the concentrated breakage zone ("Sweet Spot") and intensify the contact forces in this zone to meet the comminution objectives. The “Sweet Spot” location is independent of mill size, length, ore, balls, and fluids but its magnitude is highly dependent upon these respective properties. (Nordell and Potapov, 2011)

Figure 3-4: DEM for SAG mill comminution energy map (Nordell and Potapov, 2011)

As Dr. Nordell was investigating ways to intensify the "Sweet Spot", one idea was to apply an internal heavy roller assembly within the mill atop the toe charge surface. Exploring these concepts led to a machine that processes ore without grinding media and water by using two rotating circular surfaces. The two rolling surfaces rotate together in a conjugate pair as shown in Figure 3-5.
The CAHM description given by the authors: “The CAHM is made of two principle parts. First, a rotating outer ring with a horizontal axis of rotation, called the Anvil ring. It is supported by the ground on hydrostatic bearings or rollers to take the comminution reaction force. A second ring is placed inside the Anvil ring, called the Hammer. As the two rings rotate in unison, they produce impact on rock much like the blacksmith’s anvil and hammer produces impact on horseshoes.

Rocks inserted in a gap atop the Hammer ring and inside the Anvil ring will rotate, fall, or be carried into a diminishing gap. Comminution takes place in the closing gap within the synchronized concurrent rotations of the two rings. Pressure is applied to the ore by the Hammer via hydraulic pneumatic pistons, acting on the hammer shaft similar to how HPGR applies pressure to a bed of particles via the hydraulic-pneumatic system. Ore can be fed from one or both sides. Retainer shields are fitted at the open ends to contain the feed within the compression zone” (Nordell and Potapov, 2011).

Figure 3-6 to Figure 3-8 give more details of the simulation, breakage mechanism, and machine construction, respectively.
Figure 3-6: DEM Model of the CAHM Mill

Figure 3-7: CAHM Mill Breakage Mechanism
The inventor claims that the CAHM may be able to replace both primary crushing and SAG milling with their respective conveyors and stockpiles and thus may improve comminution circuit efficiency by 100%. CAHM compresses rock in a more efficient way, similar to 19\textsuperscript{th} century stamp mills, which follows the fundamental research of Schönert (1990 & 1996). The basis for the claims in that the CAHM efficiency was proved through the use of Discrete Element Method (DEM) modeling and simulation package called ROCKY that is used to simulate realistic comminution. CAHM is customizable with many geometries that are rock-property specific.

The main attributes of CAHM are:

- Rock is comminuted in a compressed bed of particles similar to HPGF, but with a lower wear rate (non-slip surface action)
- Extreme Range of Nip Angle (< 14 degrees to zero over 90 degree Anvil rotation)
- Mathematically Twice Efficiency of HPGF (\(\sim 0.5\) kW-hr/ton)
- Digest Larger Rock (1000 mm or larger with anvil diameter 6 m)
- Wear Rate Reduction with many times more life than Size Reduction Ration per pass (> 20:1) 2-Stage can replace gyratory, cone, and SAG mill.
- Coarse to Fine Crushing & Grinding (two stage machine \(\sim 1000\) to 2.5 mm)
• Control of ore plastic deformation eliminates the need for de-agglomeration

• Easy and fast replacement of wear surfaces using cartridges

Although the CAHM technology is still in the early stages of development with the main indication of its effectiveness being the mathematical model, though very promising, there may be an opportunity for the collaboration with the inventor and some HPGR equipment manufacturers to build a pilot unit with relatively low effort.

Dr. Nordell has informed that Outotec tentatively offered the use of their 1.2 m diameter x 600 mm wide refurbished HPGR machine located in Perth, Australia. Details are to be formalized with Outotec but they may even allow modest modifications to their machine (rotate 90 degrees to vertical) for fitting the Anvil Ring together with the feed and discharge chutes for rock feed trials. Outotec will not limit the participation of other parties.

The Anvil Ring and chutes will need to be fabricated, apparently not a large expense. Dr Nordell believes that if a mine does not show interest in testing the CAHM at their site, maybe a sand and gravel producer would be willing to test on their property. He estimates that such a pilot-trial would not take more than 6-8 months to engineer, fabricate and install. The largest cost is expected to be for the supply of energy to the testing facility as the unit has two 300hp motors.

It is also anticipated that the maximum feed size would be a rock size between 100-150 mm. The preliminary plan is for the processing of a 10-50 ton batch. The Anvil drum will need to be built and its surface lined with an abrasion resistant material. The inventor believes that such a pilot trial should be enough to show proof of principle for comminution efficiency of the CAHM.

3.4.4 HPGR – Stirred-Mill Combined

As mentioned in the sections above, High Pressure Grinding Rolls (HPGR) are recognized as an energy efficient comminution technology and a number of base and precious metal hard-ore operations have applied it as a tertiary crushing stage to feed Ball mill(s). The crushing mechanism of interparticle breakage in a compressed bed is considered one of the most efficient ways for ore comminution. Also, as proposed with the HPGR air classifier circuit technology, the HPGR- stirred media mill circuit has the HPGR with a greater duty to produce a relative finer product. This could be achieved with two HPGR in series for tertiary and quaternary crushing to produce a suitable feed for the downstream Stirred Media mill. An example of a study with this type of circuit was conducted with ore samples from Huckleberry copper-molybdenum mine (BC, Canada) and demonstrated a great potential for energy savings, approximately 34% power savings for the production of 75 µm P80 when compared to a conventional SAG circuit (Wang et al, 2013). Figure 3-9 shows the flowsheet utilized in the Huckleberry study.
Stirred media mills apply higher speed than ball mills and provide forces which are 65% higher than a conventional grinding device (Schonert, 1989). In addition, as the media size is smaller the effective number of collisions is much higher. It has been also observed reductions in energy requirements of 25% to 35% when comparing stirred mills such as IsaMill™ and the Vertimill™ to Ball mills at similar duties, i.e. being feed with 1mm P80 or coarser size distributions (e.g. SAG mill product) and producing similar product sizes at lower energy levels (Anderson et al., 2011; Davey, 2010).

Both technologies are quite mature and have been applied in the similar required reduction ratio ranges at mine sites independently, i.e. in different flowsheets receiving or feeding other types of equipment, but apparently never combined in a flowsheet (or a variation of it) as recommended by academic research and encountered in the literature produced by experts in the area.

Probably, to really prove the concept and get the mining industry more interested in this “technology” (more a flowsheet combining the two technologies together), a pilot plant testing program or a small scale demonstration plant at a mine site may be required.

### 3.4.5 High Voltage Electric Pulse Treatment

Russian researchers more than 60 years ago used high voltage pulse technology to decompose water into oxygen and hydrogen and then found that the water shock waves generated by the pulses were able to crush rocks. The technique uses the electrical breakdown of water to create shock waves. In this technique, known as electrohydraulic disintegration, the energy is transferred to the rock through the surrounding water in the form of the shock wave impact (Shi et al., 2013).

Another technique of rock breaking by high voltage pulses is called electrical disintegration, and differs from electrohydraulic disintegration because the energy of high voltage pulses is transferred to the rock by electrodes directly in contact with the surface of the rock immersed in the water.
in water. Another term for high voltage pulse breakage is electrodynamic disintegration (including the term electrical pulse disaggregation, EPD), in which the electrodes do not contact the rock surface directly, as a small water gap exists between the electrodes and rock particles (Shi et al., 2012).

The SelFrag equipment utilizes electrodynamic process of disintegration and a schematic of the machine is shown in Figure 3-10. The main components are the high voltage (HV) power supply, a HV pulse generator, and process area. Materials are immersed in a liquid in the process area, short termed electrical discharges are introduced into the materials which are surrounded by a media with higher breakdown field strength. Dielectric liquids, like water, have a high dielectric strength when voltage rise time is kept below 500 ns. As a result, discharges are forced through the immersed material.

![Schematic of a rock disintegration electrodynamic equipment (SelFrag)](image)

**Figure 3-10: Schematic of a rock disintegration electrodynamic equipment (SelFrag)**

The JKMRC has been conducting research on electrodynamic rock disintegration for several years. The main findings to date are linked to benefits such as:

- pre-weakening for more efficient downstream comminution (with significant reduction of Axb and BMWi),
- generation of microcracks (improved leaching),
• preferential breakage through grain boundaries, with corresponding enhanced mineral liberation and thus the possibility of higher recovery rates at coarser particles, and, more recently,

• the utilization of the technology for ore sorting. It seems that the selectively breakage can produce finer particles containing metalliferous minerals (high grade material) and produce larger particles that are barren or significantly low grade which enables a size-based screening procedure to split the ore by grade and thus sort it.

There is still a need to scale up the equipment for potential processing rates utilized in the mining industry but the opportunity for significant gains in the overall mineral process seems appealing. However it does not seem that a 50% direct energy saving in comminution will be easy to achieve, even if it is proved a practical technology, but the process may in fact benefit mineral processing in a more holistic way.

3.5 Selection of 2 technologies
Following the identification of the top five technologies and the release of an interim report (Phase I) to all members of CIMC Processing Group, the team members provided feedback by email to Hatch and discussions happened through meetings/telecons. Based on these discussions, an agreement was reached to discard four of the five top technologies and include an additional technology for further investigations. The meeting notes are presented in Appendix B and following a summary of the main findings and recommendations.

HPGR – in closed-circuit with air classifiers AND Vertical Roller Mills (discarded)
These two technologies have lot in common and their advantages and challenges were considered very similar, especially as both employed air classification. It was decided to not carry them for further studies and the main reasons for this decision were:

• Air classification needs to be used to close the HPGR or VRM circuits to the achievement of the desired product as these equipment operate dry and would not work if high moisture material is recirculated.

• The material needs to be relatively dry and, in most cases, mined ores have moisture levels above the minimum allowed value. If the downstream process is wet (e.g. flotation) and no heat is available in the overall flowsheet, the energy gains in comminution can be offset by the drying requirements.

• Transport of hard and abrasive material is quite a challenge due to wear and dusting of hazardous materials (silicates). The most common VRM has the dynamic classifier as an integral part of the mill but this system seems to reduce the efficiency gains in comminution energy and may also be subjected to wear problems when dealing with abrasive and relatively coarser fresh feed.

• HPGR with air classification will naturally develop or fade depending on the economics and suitability of the approach. Vertical Roller Mills are well developed in the cement and industry and will migrate to hard rock applications if the economics work.
HPGR – Stirred-Mill Combined (discarded)
It is well understood that both technologies can provide significant energy savings and if used together, in a feasible and simple circuit, the joined benefits can be substantial. However, HPGR combined with stirred mills is a natural extension of work for two of CMIC members, Metso® and Glencore, and the development of such a circuit will continue to advance through theirs, and other equipment suppliers, initiatives and cooperation with mining companies and their R&D departments - thus further engagement with CMIC is not considered essential.

High Voltage Electric Pulse Treatment (discarded)
The electrodynamic process applied by equipment such as the Selfrag has been object of research for a number of years and may become an interest option for rock disintegration in the future. However, at the current stage, there are still some doubts as to the broad applicability of the process for all different types of rocks encountered in base and precious mining as well as how the technology can be efficiently scaled up. CMIC is aware that Selfrag has been object of research in Australia for many years and assumes that a high level of expertise in this technology is already in place> It has been decided that that the best route of action for CMIC now is to just monitor the development of this technology and CMIC’s further involvement in the research and testing of high voltage electric pulse treatment for comminution is thus currently considered not essential.

Conjugate-Anvil-Hammer Mill - CAHM (maintained)
The CAHM technology seems to be the one that meets most of the criteria set for this project, i.e. possibly low energy consumption, larger size-reduction ratios (less grinding stages), and relatively simple material handling requirements. In addition, when compared to HPGR technology, it seems possible that the CAHM circuit will bring reduced capital expenditures, smaller circuit foot-print, and it may be possible to achieve lower wear rate of “rolls” and liners as this technology seems to rely on greater particle to particle interactions.

Super Fine IMPTEC Crusher (added)
Although not included in the top five technologies at the completion of phase I, during the discussions it was decided to add this technology for further investigation during phase II. It was perceived that the IMPTEC super-fine crusher can provide significant savings in comminution energy, the fundamentals of the technology seem strong, and the technology is already ready for pilot evaluation.

It is interesting to note that in fact this technology achieved a high rank with a total of 15 points as shown in the extract of the ranking table below (Table 3-3). In addition, if the stage of technology is updated and the down-stream benefits are somehow similar to the ones achieved with the HPGR, the adjusted ranking would be 17 or higher.
Table 3-3: Ranking summary for the IMPTEC Crushers

<table>
<thead>
<tr>
<th>Arising technologies</th>
<th>Energy reduction</th>
<th>Stage of technology</th>
<th>Safety/Risk</th>
<th>Cost</th>
<th>Downstream benefits</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional method of rock disintegration</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>IMPTEC Crushers</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>15</td>
</tr>
</tbody>
</table>

The Super-fine IMPTEC crusher comprises a rotating compression chamber with an internal gyrating mandrel. The axis of rotation of the chamber is displaced relative to the axis of the vertically mounted mandrel. The inner surface of the chamber is built to create double cone frustums at an angle equal to the displacement angle. The rotating compression chamber is also equipped with a product chamber. Figures Figure 3-11 to Figure 3-13 present schematics of the equipment.
Figure 3-12 - Schematic 2 of the IMPTEC Crusher

Figure 3-13 - Schematic 3 of the IMPTEC Crusher
During the operational of the Super-fine IMPTEC crusher, the feed is accelerated into a compressed particle bed, which forms a lining on the inside of the compression chamber. The depth of the bed progressively increases until the mandrel is engaged and is free to rotate with the compression chamber. Additional pressure on the mandrel increases the power draw and triggers the mandrels gyratory motion drive. The axial displacement of the compression chamber distributes compressive forces throughout the particle bed at “high intensity” power density. Product is transported to either a collection facility or a classification circuit.

The super fine IMPTEC crusher has been advanced to a pilot scale and has reported up to 5% in energy savings in downstream processes (C. Kelsey and J. Kelly, 2014).

3.6 Deeper investigation on top 2 technologies

Subsequently to the selection of the two most promising technologies, the main developers of the CAHM and the IMPTEC crusher were contacted and invited to present the technologies to CMIC process group and Hatch project leads.

On Feb, 3rd 2016, Dr. Larry Nordell and Prof. Bern Klein attended a teleconference and presented the main features, fundamentals, stage of the technology and ideas of future testing and developments for the Conjugate Anvil Hammer Mill (CAHM). A summary of the material presented and the main topics discussed follows and the meeting notes are reproduced in full at Appendix B.

- The CAHM employs a crushing mechanism similar to a gyratory crusher but operates on a horizontal axis and employs no eccentric motion. The dynamics of the apparatus have been extensively studied by ROCKY, a discrete element modelling software developed by Dr. Nordell and used extensively in commercial HPGR designs. A CAHM apparatus has not yet been built. Projected operating parameters described below are derived from the simulation model.

- In the CAHM breakage occurs under compression; the CAHM uses no water and no grinding media.

- A reduction ratio of 20:1 is projected which can reduce the number of comminution stages

- Energy consumption is expected to be half of an HPGR in the same service.

- A large machine could accept rock of 500 mm in size to produce 25 mm product in one stage. A second machine might produce a 5 mm feed.

- In one configuration of the CAHM, the outer anvil ring is equipped with liner plates similar to those used in SAG mills. As well, these plates can be equipped with ports to relieve stress during the crushing process reducing the energy required for crushing. The concept can also employ smooth surfaces, like those employed in HPGR.
• UBC has large expertise in modelling and simulating HPGR operation with piston presses. These can be employed to reasonably estimate the particle size/energy relationships and wear patterns. While the dynamics of the CAHM with the slotted rolls are different from HPGR, these differences could be studied effectively with the piston press equipment available at UBC.

• In the question and answer period, the following subjects were raised:
  - What if the material in the ports binds (moisture perhaps) and will not flow? The ports operate as a positive displacement pump, the material being forced through. Cohesive material can be simulated in the UBC tests.
  - How to relieve chokes? The hydraulic bearing mechanisms are similar to those on an HPGR and allow it to be opened and accessed from the side.
  - Will excessive wear of the ports be a problem? Piston tests can estimate the amount of force required for breakage under different configurations. These tests can also yield information useful for estimating wear. Additionally, there are new wear resistant materials available.

On February 11, 2016, Mr. Chris Kelsey and other representatives from IMPTEC attended a teleconference and presented the main features, fundamentals, stage of the technology and their planned development program for the Super-fine IMPTEC crusher. A summary of the material presented and the main topics discussed follows and the meeting notes are reproduced in full at Appendix B.

• In the IMPTEC equipment the crushing/grinding mechanism employs compound movements. Mandrel rotates with charge and is vibrated simultaneously. High tensile shears. Tensile breakage the major mechanism. Grinding parts of hardened. There is a small constrained (active) volume to attain maximum pressure and efficiency.

• The goal is to enable ultra-fine crushing of hard materials, e.g. zircon, black slag from Pb blast furnace.

• The process is dry and the reduction ratio and applicability corresponds to a feed size of about 15mm to a product of 10-25 microns and there is no use of grinding media. Although essentially a dry process the machine should be capable treating wet material.

• The development started in 2013 with device that was 100 mm internal diameter at the mantle and ran in closed circuit with a classifier being capable of a production rate 20-100 kg/h. The feed rate is regulated according to hardness. Open circuit operation may be viable.

• Machines have been scaled up and they are currently on third model, the SFC 350, a semi-commercial machine expected to produce 1 tph fresh feed (2 tph production at 200% circulating load).
• Apparent scaled up limit is equipment for 100 tph. The expected life for the mandrel is 8000 h.

• Commercial operations on black slag will commence in March 2016 and they expect to have reliable data in about 30 days after that.

• IMPTEC will provide drawing which will better define the grinding motions.

3.7 Conclusions regarding the technologies for cooperation

**The Conjugate Anvil Hammer Mill (CAHM)**

Together with CIMC processing group it was decided that the Conjugate Anvil Hammer Mill (CAHM) is the best technology for the cooperation for future development.

The inventor of the technology, Dr. Lawrence Nordell, is open to work in collaboration with CMIC and is currently continuing to work on mathematical simulations of the equipment. He is now also concentrating on the mechanical aspects of the material discharge ports and bearings supporting the inner "hammer" wheel. He accepted CMIC suggestions for proceeding with the technology development in a systematic, small scale to larger scale equipment mode.

The CAHM is considered to be the technology for CMIC to concentrate on in the near future as it has great potential, there is the common desire to work cooperatively and the technology is at early stages of development which means it can greatly benefit from CMIC’s support. In addition, the inventor, while living in the USA, is in close proximity to Canada and has recently started to work with Canadian researchers and companies, e.g. Bernd Klein at the University of British Columbia as well as Teck.

Hatch supports the decision and is looking forward to continuing collaboration for the successful development of the technology. In addition to Hatch’s Mining and Mineral Process Department, Hatch can also offer support through Hatch’s Machine Design group which can be engaged at any point in time.

**Super Fine IMPTEC Crusher**

Nonetheless of this conclusion and the decision to concentrate on the development of CAHM, CMIC will continue to investigate other comminution technologies promising increased energy efficiency.

The potential for energy efficiency in high reduction rate comminution apparently linked the application of the Super Fine IMPTEC Crusher is considered promising and CMIC will closely monitor the development of this technology during the next months. The stage of its development is in a more advanced stage than the CAHM, as the current development of a semi-commercial indicates, but CMIC will maintain communications with the developers to get a better understating on how and when to cooperate with them.
3.8 Other Appraised Technologies

3.8.1 Existing Technologies

3.8.1.1 High Pressure Grinding Roll (HPGR)

High Pressure Grinding Roll (HPGR) was first adopted by the cement industry in the 1980’s (E. Burchardt, R. Ojeda, 2010), but has been gaining steam in the mineral processing industry in the last two decades (G. Barrios, et al, 2014), with the first HPGR in industrial scale, mineral processing application at the Los Colorados plant in Chile in 1998 (A. Gruendken et al, 2009).

Gabriel Borrios et al writes the mechanism to which the HPGR works in their paper *High pressure grinding rolls simulation using the discrete element method dynamic coupling method* in 2014, and to quote, “The HPGR machines comprises a pair of counter-rotation rolls mounted in a sturdy frame. One roll is fixed in the frame, while the other is allowed to float on rails and is positioned using pneumohydraulic springs. The feed material is introduced in the gap between rolls and is crushed by the mechanism of interparticle breakage. Comminution performance is largely determined by the pressure exerted on the bed of particles by the floating roll mechanism. The operating bed pressure depends on the hydraulic system start-up parameters and the loading response of the feed material.” Figure 3-14 presents the HPGR breakage mechanism well.

![Figure 3-14: HPGR Operation](image)

HPGRs provide beneficial downstream effects as the compression mechanism creates microcracks within the resulting ore particles – unlike crushing - leading to weakening of the ore that can reduced the energy requirement for downstream comminution, can increase
susceptibility in leaching or other processes that benefit from liberation of particles (Y.X. Han et al, 2012). Figure 3-15 presents the microcracking on a microscopic level.

Figure 3-15- Microcracking Generated by HPGR

Numerous HPGR operations have been installed in the last decade including Cerro Verde in Peru and Grasberg in Indonesia, each proving that the technology is indeed established and worth reviewing for large tonnage, hard rock applications (E. Burchardt, R. Ojeda, 2010). However, in current economic conditions where owners are only looking at reducing upfront capital costs, the HPGR technology needs to streamline the high material handling costs and complex flowsheet requirements to ensure that capital effective operations are installed (P. Rosario, J. Drozdiak, 2015).

3.8.1.2 SAG/ AG Mill

SAG mills (or Semi-autogenous grinding mills) and AG mills (autogenous grinding mills) are well established technologies with many different mining operations utilizing it in their primary grinding applications.

The tumbling mill, like others of its kind, is hugely energy inefficient, especially in hard rock applications. At its current state, it is difficult to anticipate if there are many more methods in which new innovations or applications in SAG/ AG milling can be done to improve energy utilization. However, there may be applications where a combination of SAG or AG with other, newer and less proven applications can improve energy consumption (P. Rosario et al, 2010). Figure 3-16 presents the SAG mill mechanism.
3.8.1.3 **Ball Mill**

A ball mill is a tumbling grinding mill similar to the SAG/AG mill, but used for a different size classification, often in the secondary grinding circuit if paired with a SAG mill, or directly after two or three stage crushing. Similar to any tumbling mills, it is hugely energy inefficient and there is not much potential for decreasing energy utilization as the technology is well established and has matured. There is potential for ball mills to get better utilization in new applications or in new flowsheets, with new, less proven applications. Unlike the SAG mill, the ball mill does not rely on impact to break particles and instead relies on abrasion.

However, similar to the SAG / AG mill combination, the ball mill may use pebbles as grinding media. This can lead to energy reduction potential of up to 10%.

3.8.1.4 **Classification: Multi-deck Stacking Screens**

The mainstream classification method for large operations are hydrocyclones. There are inefficiencies in this method, as recovery of fines may end up back in the grinding circuit, regrinding particles that have already been ground, leading to wasted energy. It has been reported that the use of these multi-deck stacking screens can lead up to 5% less power consumption.
A more efficient classification system can also equates in the generation of a product with a narrower size distribution from the ball mill circuit and thus it can be speculated an increased recovery in downstream processing such as in flotation.

In smaller applications, such as the Round Mountain operation in Nevada -USA, multi-deck screens have been applied with success. The benefit to this is that only coarse particles are sent back to the ball mills, leading to better energy use. The reason large operations do not see this use is because screening flux is often quite high with small apertures (<300 um), leading to a requirement for large screening areas. The even distribution of feed to the screens is also difficult to achieve at a mechanical level.

3.8.1.5 Vertical Mills

Vertical Mills were first designed in the 1950s for applications in fine and ultra-fine grinding in Japan (D.B. Mazzinghy et al, 2014). Lately, the Vertical Mill is making progress towards primary grind application and shown promise in energy reduction relative to ball mills, typical to what is normally seen in regrinding applications (D.G. Mazzinghy, et al, 2014). This vertical mill would be in series with either an AG or a SAG mill grinding circuit.

The Vertical Mill, or Vertimill™ by Metso® Minerals, has since seen many installations worldwide in regrind applications, noting a significant decrease in energy consumption compared to typical tumbling mill like a ball mill (S. Palaniandy et al, 2014).
3.8.1.6 **IsaMill™**

The IsaMill™, as patented and distributed by Glencore technologies, is a high intensity, horizontally mounted stirred mill that uses fine (2-6mm) ceramic media for grinding in fine and ultra-fine applications (M. Larson et al, 2014). The utilization of ceramic media can have benefits downstream in flotation performance as steel as grinding media can lead to an alteration in surface properties of ground material whereas ceramic is generally inert (T. Khonthu et al, 2012). Hatch has completed a recent project where Red Dog operations owned by Teck Alaska replaced older vertical mills with the new IsaMill™ technology leading to lower energy consumption and an increase in recovery which has been speculated to the use of inert ceramic grinding media instead of steel media.

The IsaMill™, when compared to other regrinding mills, i.e. Vertimill™ and ball mill, have shown energy reduction potential of up to 2/3 at a laboratory scale (T Khonthu et al, 2012). The IsaMill™ has made huge progress in industrial scale applications in South Africa for the platinum industry and has shown promising results in other regrinding applications (G.S. Anderson et al, 2011).
The IsaMill™ does not require to be in closed circuit with hydrocyclones for classification. The natural mechanism of the IsaMill™ encourages classification within the body of the IsaMill™.

At this stage, the IsaMill™ is a well-established technology within the mining industry for regrinding applications. There has been interesting development suggesting the use of IsaMill™ for primary grinding of HPGR product for significant energy savings, as discussed in Section 3.4.4 (J. Drozdiak et al, 2011).

![Figure 3-19: IsaMill™ Schematic](image)

### 3.8.2 Arising Technologies

#### 3.8.2.1 Horomill®

The Horizontal roller mill, or Horomill®, is well accepted technology in the cement industry and can substitute dry ball milling (relative fine grinding) with higher energy efficiency (claimed to be 30% to 50% more efficient). The Horomill® design mechanically combine many elements of a ball mill such as cylindrical shell on hydrodynamic shoes, drive gear rim, and a HPGR (roller and bearings) but with much lower grinding pressure.

The Horomill® operates on the principle of a horizontal ring-roller mill. Similarly to a vertical roller mill, the Horomill® uses the centrifugal force principle for transporting the material, for which the material cylinder is driven above the critical rotational speed. Figure 3-20 shows a picture of a Horomill® in a cement plant and schematic drawings.
Figure 3-20: Horomill®: Picture and schematics

3.8.2.2 Vibrocone™

The Vibrocone™ is similar to the cone crusher in operation in that there is a mantle swinging within a chamber effectively crushing the ore. To quote its operation H. Manouchehri paper *Changing the game in comminution practices: Vibrocone™, a new crusher having grinding performance:* “From the outside, Vibrocone™ resembles a conventional cone crusher and under its hood, it still has a crushing chamber with a mantle and a concave/bowl liner. However, unlike the cone crusher, it is an energy efficient inertia machine that is driven by an unbalanced vibrating mass. The main shaft is supported by a spherical bearing and the crushing action originates from an unbalanced weight rotating around the main shaft, i.e. same principle used to generate vibration movements in screens. Accordingly, the mantel is allowed to swing unrestrained inside the crushing chamber.”

The paper reports that fines generation beyond what conventional crushing machines can produce and that the fines generated exhibit microcracks, which may provide similar benefits in downstream processes as recorded for HPGR (H. Manouchehri, 2014). The microcracking would lead to a decrease in ball mill power consumption, directly reducing energy by up to 5%. Similarly to the cone crusher, the Vibrocone™ can be used for secondary, tertiary, and pebble crushing duty. The equipment has not been tested fully at an industrial level.
3.8.2.3 **HIGmill™ (High Intensity Grinding Mill)**

The HIGmill™ works similarly to the IsaMill™, see Section 3.8.1.6., but is stood vertically as opposed to a horizontal configuration.

There has been reports from Outotec (the producer of the HIGmill™) that the HIGmill™ has similar energy savings as the IsaMill™. However, reports have shown that the HIGmill™ can further reduce energy savings by 10% relative to the IsaMill™.

3.8.3 **New Technologies**

3.8.3.1 **Multishaft Mill**

EDS, the manufacturer of the Multishaft Mill, describes the machine as a compact vertical mill suitable for processing a wide variety of materials and explains that the milling action combines a number of processes, crushing, milling, densifying, blending and attrition. The mill has a number of horizontal shafts with strengthened flinger attachments which are used to agitate the product as it passes through the mill.

The product is broken down due to impacts on flingers, the mill body as well as other particles of the product. The body of the mill is protected internally by removable liners. It has been applied with success in Africa in niche applications such Chromite and for the preparation of material for underground back filling. It is very energy intensive and can reduce ore from F80=25 mm to P80=300 microns (P80=150 microns for soft ore). First perception is that its efficacy may be ore dependent and not comparable to technologies such as HPGR or VRMs. Figure 3-22 shows an isometric drawing of the equipment.
3.8.3.2 Jet microniser (air jet mills)

The Sturtevant Micronizer® is a jet mill (fluid energy mill) employing compressed air or gas to produce particles less than one micron. Inside the machine, precisely aligned jets create a vortex. Material is fed into this vortex along an engineered tangent circle and accelerates. High-speed rotation subjects the material to particle-on-particle impact, creating increasingly smaller fines. While centrifugal force drives large particles toward the perimeter, fine particles move toward the center where they exit through the vortex finder.
Main applications are for pigments and chemicals. The Jet Micronizer® will usually generate particle size distributions ranging from 0.25 microns to 10 microns, depending on the incoming feed size, the friability of the material and the feed rate. The maximum capacity is in the order of 4 t/h achieved with the largest model which has a mill diameter of 42 inches.

### 3.8.3.3 Rotary Collider Mill (RCM)

The RCM utilize fracture mechanics for maximum reduction of ores and minerals, it applies the force of multiple air-flow vortices to enable the size reduction to occur without contact between the feed material and any internal portion of the mill (reduced wear).

The mill shaft rotates an impeller at a specific speed so that the feed material is crushed primary by contact with other pieces of the material. When the reduced material is small enough it is forced out of one of the outlet ports by the pressure distribution within the machine. Typically the feed is crushed material which achieves a high reduction ration and discharges at sufficient force to deliver it to the next step in the production process, e.g. material capture system of cyclone, baghouse and final dust filter. Figure 3-24 shows an schematic of the RCM basic circuit.

![Figure 3-24 - Schematic of the RCM circuit](image)

### 3.8.3.4 Hicom Mills

Hicom Mills are applied fine and ultra-fine grinding (typically below 20 microns) of particles in both wet and dry applications. The Hicom Mill is a high-intensity tumbling mill that uses a nutating motion to generate centrifugal accelerations up to 50 times stronger than gravity. The energy intensity generated within the mill can achieve 2,500 kW/m³.

The Hicom Mill is a cylindrically symmetric vessel that is smaller in diameter at the top, increasing to around 1/3 from the bottom and then decreasing on approach to the closed bottom, see Figure 3-25. There is a narrow cylindrical neck at the top through which feed material enters. The liner has eight vertical lifters running from the neck to the base. Ports in
the form of circular openings are located between the ribs of the mill liner in the lower section of the grinding chamber. These allow finely ground and/or large ore particles or media to discharge. Typically such a mill will be operated in closed circuit with media being separated from the discharge stream and returned to the mill.

Alternatively fine grates can be placed over the ports to retain media while permitting finer particles to exit. The grinding chamber is inclined at an angle of 4.75 degrees from the vertical, and moves with a nutating motion at a frequency of 380 rpm. In performing this motion, the nutation point remains stationary, while points on the chamber below describe circles around the vertical axis having diameters increasing with distance below the nutation point. The nutating mill was filled through the central feed opening with media particles to a specified fill level of 50% by volume. This was achieved for this mill by feeding in new material at the top at a rate that matches the discharge rate, so maintaining the weight of the particles in the charge constant at 2318 kg. An interesting fact about this mill is that there is no critical speed which means it can be tuned at high speeds in the order of 600 to 900 rpm.
3.8.4 Non-conventional Technologies

3.8.4.1 Microwave Frequency Treatment

Microwave frequency treatment is an interesting concept that enhances the grindability of ore, and largely, make it more susceptible to mechanical breakage forces (R.K. Amankwah and G. Ofori-Sarpong, 2011).

It is seen that microwave heating generates microcracks (Figure 3-26) which can enhance the grindability of ore in milling stages that occur downstream (A.Y. Shaw and S.M. Bradshaw, 2011).

![Figure 3-26: Microwave Induced Microcracks](image)

It was studied preliminarily and presented in the South African Journal of Science that there are a multitude of factors that could lead to the success or failure of this option, as presented in Figure 3-27.

![Figure 3-27: Factors for Success and Failure of Commercial Microwave Technology](image)
3.8.4.2 Magnetic Pulse Treatment
The process of magnetic impulse treatment applies for refractory gold ores in ferriferous quartzite and can provide higher recovery at low energy consumption. The process is conducted by transporting ore or pulp through a section of dielectric pipe where a series of electromagnetic coils is mounted and generates regularly impulses of an electromagnetic field with a frequency of 50 Hz. The ideal application is ahead of grinding and enhancing iron ore grinding and gold recovery.

3.8.4.3 Superpowerful Hyperimpact Waves
This process was demonstrated in 1996 by V.Yu. Veroman and utilizes micro-resonance disintegration of mineral complexes. Comminution is achieved but with high energy consumption and insufficient selectivity was observed at pilot scale testing.

3.8.4.4 Electric Hydrodynamic Effect
The Institute of Electrophysics, Ural Branch, Russian Academy of Sciences, Yekaterinburg, developed a machine for electric hydraulic treatment of materials by nanosecond impulses up to 250 kW in amplitude and 300 Hz in frequency. The apparatus, where the mechanism of nanosecond breakdown of water containing the suspended microparticles is implemented, had substantial imperfections and proved inefficient at low breakage capacity and high energy consumption.

3.8.4.5 Accelerated Electron Beam
Studies of employing the directed energy of accelerated electron beam to pre-condition ore ahead of conventional mineral processing circuits were conducted in Russia in 1983 (Bochkarev G. P., et al.). Although it demonstrated higher productivity of grinding circuit and enhance metal recoveries (Cu, Zn, Pb flotation and Au cyanidation) was proved high capital intense and presenting technical problems to the incorporation of mineral processing flowsheets.

3.8.4.6 Nano-second High-power Electromagnetic Pulses (HPEMP)
The nanosecond HPEMP treatment has been investigated Russia since 1997 (Chanturiya, V., and Bunin, I. Z., 2007). It has shown two important effects, first, the loosening of the mineral structure due to electrical breakdown mechanism and second, the development of thermomechanical stresses at the boundary between the dielectric and conductive mineral components.

The nanosecond HPEMP treatment showed promising results in the treatment of gold refractory ores due to high efficiency and selectivity in the disintegration of mineral complexes.
4. References


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Appendix A

CMIC – Hatch Questionnaire Template
HATCH & Canada Mining Innovation Council (CMIC)

QUESTIONNAIRE

Date: ______________ Participants: 

Q: __________________ 

A: __________________

Introduction

The main objective of this collaborative project is the performance of an assessment of the value of existing and emerging technologies to reduce the energy required for industrial ore comminution. The overall objective of this long-term program is to reduce the energy required for comminution by greater than 50%!

Boundaries: this study is about size-reduction possibilities and we are very open to hear about non-conventional methodologies or notable alternatives technologies originated outside mining. However, ore sorting and other ways to reduce feed volume are out of scope. (Being studied by other groups within CMIC).

1 – What first technology comes to your mind?

2 - Is it an efficiency increase (an extension) to a known technology (e.g. coarser application for stirred media mills) Type A Yes ( ) No ( )

3 - Or do we classify it as non-conventional approach towards a known technology (e.g. microwave to weaken SAG feed) Type B Yes ( ) No ( )

4 - Or is it an alternative comminution technology not yet applied to industrial comminution (e.g. Selfrag for primary grinding at industrial capacities) Type C Yes ( ) No ( )

5- Could you please rate this technology regarding the following requirements/specifcics?
Please use rating scale as per the table below

<table>
<thead>
<tr>
<th>Ranking</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology readiness (TR)</td>
<td>basic idea</td>
<td>being proved</td>
<td>mid way Dev.</td>
<td>almost Dev.</td>
<td>Developed</td>
</tr>
<tr>
<td>Engineering Efforts Req. (EE)</td>
<td>tremendous</td>
<td>significant</td>
<td>medium</td>
<td>minimum</td>
<td>none</td>
</tr>
<tr>
<td>Cost Considerations (CC)</td>
<td>extreme</td>
<td>possible higher</td>
<td>similar</td>
<td>probably lower</td>
<td>great savings</td>
</tr>
</tbody>
</table>

Notes
a) technology readiness (TR): ________________________________
b) engineering efforts required (EE): ________________________________
c) cost considerations (CC): ________________________________

6 - In your opinion, what are the inhibiting factors (challenges) for this technology to gain a broader application? Do you have ideas on the possible ways to mitigate these factors?

7 - In your view how could we assist in the development of this technology? (e.g. academic testing; building a pilot plant; enabling an industrial trial) – Please give as much detail as possible!

8 - Do you know about other technologies that may merit an investigation? Please list them, classify, and rate regarding technology readiness (TR), engineering efforts required (EE) and cost considerations (CC). Please use the same as scale as per question 5.

1-

TR ( ) - EE ( ) - CC ( )

2-

TR ( ) - EE ( ) - CC ( )

3-

TR ( ) - EE ( ) - CC ( )

Any other ideas?