Deep Mine Cooling

ADMIRA DHES INC.

GUPEX

CanMIND
Cryogenic-based Chilling for Mines
Patent Pending Hybrid Cryogenic Technology

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President AdmiraDHES

www.admiradhes.com
Big Picture of Underground Cryogenics

Large UG Equipment
Powered by Dearman Engines

Cryogenic Chilling
CFD Modelling

Compressed Air System Design

Power/chilling co-generation
8 MWr + 5 MW_e

Rapid Response Chilling on Demand

27/04/2021

2021 DR DANIEL CLUFF
Why Liquid Air Energy Storage (LAES) 
A Zero Carbon Green Energy Technology
EVERY TIME YOU DO SOMETHING WITH LiqAir IT ABSORBS HEAT !!

• The cryogenic liquids are produced on the surface in a standard cryogenic liquefaction plant or underground.
  • Heat rejected on or to surface

• Surface LAES System provides economy of scale, marketable byproducts, Ar, O₂, N₂

• Cryogenic liquid is delivered to the depth required
  • Depends on mine design decision
    • Sent to a central location and chill air in downcast shaft
    • Sent to individual levels to chill on demand
LAES Process

- A Liquid Air Energy Storage (LAES) system is comprised of a **charging system**, an **energy storage section** and a **discharging system**.
- Standard industrial air liquefaction plant; the electrical grid or a renewable energy project supply the electrical energy.
- Air drawn from the ambient environment. The process creates liquid air a cryogenic liquid at temperatures near -196°C (78 K).
- The liquid air is stored in a low pressure insulated tank.
  - Easily accessed energy storage repository
  - Low risk to the environment
  - We create a mix of O₂ and N₂ appropriate to the conditions and use
- When power is required liquid air is pumped to a high pressure and evaporated through a turbine system.
- Capable of providing the pressure necessary to power a piston engine or turbine resulting in useful work to generate electricity or drive a cryogenically powered vehicle.
Simplified LAES Schematic

Power Input
Charging Infrastructure

Compression ➔ Liquifaction

Hot Storage ➔ Heat air in winter

Cold Storage ➔ Evaporation Cooling

Liquid Air Storage ➔ LA to Underground Storage
Chilling on demand

Discharging Infrastructure
Power Output

Power/chilling placed Underground
5 MWe + 8 MWr
700+ ℓ Gaseous Air Per 1 ℓ Liquid Air

Expansion of liquid air to gaseous air as a function of temperature

Change of State

Expansion from 78 K to 300 K

Expansion liquid to gaseous state at 78 K

Volume liters

Temperature Kelvin
Cold Storage in a Liquid

1) **Latent Heat** = $\Delta Q_L = \text{mass} \times L_v$

   $L_v = 205 \text{ kJ/kg}$

2) **Expansion Heat** = $\Delta Q_a = \text{mass} \times C_p \Delta T_g$

   The specific heat capacity of air $C_p = 1.007 \text{ J/kg-K}$

   $$\Delta Q_T = \Delta Q_L + \Delta Q_a$$

   $$\Delta Q_T = m(L_v + C_p \Delta T_g)$$

   and for a mass = 1 kg, \(1\text{kg}(205 \text{ kJ/kg} + 226.13 \text{ kJ/kg})\)

   \(\approx 430 \text{ kJ/kg}\)

The total heat absorbed by 1 kg due to change of state and expansion is 430 kJ/kg so 1 kg/s of liquid flow provides 430 kWr of cooling.
Mine Cooling Via Cryogenics

So for 1 MW of cooling

The mass flow of liquid air required = 2.2 kg/s

The density of liquid air is about 870 kg/m³

The liquid flow of liquid air required = 2.6 l/s

The final gaseous volume is 1.9 m³ of air
Cooling, Electricity and Compressed Air
Three Incremental Cases for Glencore OPD

• **Stand Alone Simple chilling**
  • Liquid air released directly to airflow
    • 2.6 l/s (liq) → 1.9 m³/s (air) → 1 MWr

• **Chilling plus Electrical Power**
  • Liquid air exhaust directed through turbine
    • 1043 tpd → 5 MWe plus 8 MWr 24 hrs/dy

• **Chilling, Electricity and Compressed Air**
  • 5000 cfm (2.4 m³/s) → 1.2 MWr
Bulk Air Chilling vs Cryogenics
Comparison for Glencore Onaping Depth

- The CAPEX of both the LA and BAC are similar
- Significant OPEX reductions are possible based on selected LA option
- LA is a fast response “Chilling on Demand”™ (COD™) system
  - able to offset an abrupt heat influx in a lower air flow i.e. all electric mine.
- Optimal surface plant size is 2000 tpd with a 600 t storage facility allowing multiple options for Glencore OPD:
  - Energy storage
  - Electricity/chilling cogeneration production of 5 MWe with 8 MWr
  - Compressed air/chilling cogeneration of 2500 cfm with 600 kWr
  - Off-sales of surplus oxygen and argon
  - Powering vehicles
Key Concepts in Glencore OPD Study

- LA demand was correlated to 30 year environmental data.
- Cryogenic liquid is a form of stored energy.
- 2000 m Level bulk release chills sublevels (approximates BAC).
- Design condition: 12°/12° (DB/WB) at 2000 m from 28°/19° (DB/WB), provided by HATCH
- LA COD™ allows for daily cooling cost calculations.
- Underground cryogenic chilling system produces Electricity
- Compressed air/chilling cogeneration eliminates the compressed air plant and piping from the surface.
- Economic statements are accurate to +/- 25%.
- The 20 year NPV is calculated at a discount rate of 10% including both CAPEX and OPEX.
Glencore Onaping Depth Schematic Plan

Planned location of BAC

Source HATCH, with permission from Glencore.
CFD Model for Chilling the Entire Airflow, Similar to a BAC

Inlet Air
235 kg/s
124.97 kPa
319 K

Granite
Shear Modulus  318.9 MN/m²
Mass Density   2700 kg/m³
Tensile Strength 30 MN/m²
Compressive Strength 200 MN/m²
Thermal Conductivity 3.5 W/(m-K)
Specific Heat 1 J/(kg·K)

5 m
15 m Diameter
CFD Model for Chilling the Entire Airflow, Similar to a BAC

Inlet Air
235 kg/s
124.97 kPa
319 K

Granite
15 m diameter, 325 K

Heat Exchanger
Tubes in plate
Cryogenic liquid
\( T_{\text{cryo,liq}} = 78 \text{ K} \)
s.g. = 0.87
Flow = 24 kg/s

Cryogen Sourced Air
Perpendicular to Shaft Air Flow
\( T_{\text{cryo,gas}} \) 78 to 85 K on Exit
Density about 4 kg/m
Close up View of Heat Exchanger 1.67 sec
Close up View of Heat Exchanger 8.2 sec
Average Temperature of Air in Shaft

500 m deep cyl assemb 3.SLDASM [500 m deep [500 m]]
NPV Comparison 2000 tpd Plant to BAC

Option 1: Base Configuration (Vaporiser Only)

<table>
<thead>
<tr>
<th></th>
<th>CRYO ($M) CanMIND</th>
<th>BAC ($M) HATCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPEX</td>
<td>$31.9</td>
<td>$31.4</td>
</tr>
<tr>
<td>OPEX/yr</td>
<td>$3.48</td>
<td>$3.22</td>
</tr>
<tr>
<td>NPV (10%)</td>
<td>-$61.60</td>
<td>-$58.80</td>
</tr>
</tbody>
</table>

Cryogenic OPEX = maintenance 0.38M plus energy cost 3.1M

BAC OPEX = maintenance 0.82M plus energy cost 2.4M

Maintenance for cryo is low because it is tried and true started in 1900’s.
Option 1: Chilling/Surplus Estimate

Mine uses 31% of plant capacity (Potential extra production 69%)

- Monthly LA demand for chilling
- 2000 tpd Plant Monthly surplus estimate
Option 2: Cogeneration
Simultaneous Production of Electricity and Chilling

• Cogeneration Chiller:
  – 5 MWe operating for 24 hrs/day
  – 8 MWmin. to 14 MWmax. chilling
  – Consumes 1043 tpd
  – 2000 tpd Plant operates for 12.5 hrs/day drawing 16.7 MWe
  – Electricity generator operates for 24 hrs/day producing 5 MWe

• Requires hourly energy consumption/generation to calculate overall energy cost.
  – Mid-day is high cost recovery
  – Evening is low cost production

Peak Power Cost Shifting
Cogeneration of 5 MWe Electricity/chilling

Production Profile for 2000 tpd Plant for July 01, 2010 a Typical Summer Day

DEMAND for CHILLING

Tonnes per Hour

Hour of Day

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Cogeneration of 5 MWe Electricity/chilling

Production Profile for 2000 tpd Plant for July 01, 2010 a Typical Summer Day

- DEMAND for CHILLING
- PRODUCTION

Hour of Day

Tonnes per Hour

27/04/2021

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Cogeneration of 5 MWe Electricity/chilling

Production Profile for 2000 tpd Plant for July 01, 2010 a Typical Summer Day

- **DEMAND for CHILLING**
- **SURPLUS**
- **PRODUCTION**

Liquid air consumption (minimum) for a Cogeneration plant 5 MWe + 8 MWr operating continuously.

Storage capacity is indicated for the surplus production.
## Option 2: Energy Cost Comparison
### Cogeneration Electricity/Chilling vs BAC

<table>
<thead>
<tr>
<th></th>
<th>Energy Profile (MWH/yr)</th>
<th>Estimated Cost ($ M/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CRYO</td>
<td>BAC</td>
</tr>
<tr>
<td>Purchased</td>
<td>76193</td>
<td>20000</td>
</tr>
<tr>
<td>Recovered</td>
<td>-43800</td>
<td>0</td>
</tr>
<tr>
<td>Supplemental chilling</td>
<td>4300</td>
<td>NONE</td>
</tr>
<tr>
<td>Fan Energy Savings</td>
<td>-4000</td>
<td>0</td>
</tr>
<tr>
<td>Total energy</td>
<td>32693</td>
<td>20000</td>
</tr>
<tr>
<td>Maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total OPEX</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It takes approximately 76000 MWH/yr to produce enough cryogen to operate a 5 MWe (24/7). The 5 MWe cogeneration system produces 43800 MWH/yr. The cost of the production of LA (during off-peak energy rates) versus that of the energy production (during peak electricity rates), results in an overall savings.

** needed to add $.13M for PRU re: CRYO maintenance option
## Option 2: NPV Comparison
Cogeneration Electricity/Chilling vs BAC

<table>
<thead>
<tr>
<th>$ millions</th>
<th>CRYO 5 MWe (24/7)</th>
<th>BAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPEX</td>
<td>$44.7</td>
<td>$31.4</td>
</tr>
<tr>
<td>OPEX/yr</td>
<td>$1.74</td>
<td>$3.22</td>
</tr>
<tr>
<td>NPV (10%)</td>
<td>-$59.52</td>
<td>-$58.8</td>
</tr>
</tbody>
</table>

OPEX includes Electricity & maintenance costs
Option 3

5 MWe + 8 MWr Power/electricity Cogeneration

+ Add 5000 cfm (2.4 m³/s) compressed air to the existing system
Cost Estimate: Typical 5000 cfm (2.4 m³/s) System

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>$M/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opex</td>
<td></td>
</tr>
<tr>
<td>Energy cost from industry standard formula</td>
<td>$0.9</td>
</tr>
<tr>
<td>Energy cost from Atlas Copco Calculator</td>
<td>$1.02</td>
</tr>
<tr>
<td>Maintenance = 12% of energy cost</td>
<td>$0.12</td>
</tr>
<tr>
<td>Equipment = 12% of energy cost</td>
<td>$0.12</td>
</tr>
<tr>
<td>Capex</td>
<td></td>
</tr>
<tr>
<td>Piping installed one time cost (maintenance?)</td>
<td>$5.00</td>
</tr>
</tbody>
</table>

Compressed air costs/yr Over ten year horizon

- Energy 76%
- Capital 12%
- Maintenance 12%

Total: $1 M
### Option 3: Cost Comparison. Lair vs BAC
Cogeneration + Compressed Air 5000 cfm (2.4 m\(^3\)/s)

<table>
<thead>
<tr>
<th></th>
<th>Estimated Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CRYO</td>
</tr>
<tr>
<td>Total OPEX Cogeneration</td>
<td>$1.74</td>
</tr>
<tr>
<td>($M/yr)</td>
<td></td>
</tr>
<tr>
<td>Supplemental chilling</td>
<td>-$0.12</td>
</tr>
<tr>
<td>reduced</td>
<td></td>
</tr>
<tr>
<td>Additional OPEX</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>$0.70</td>
</tr>
<tr>
<td>Maintenance</td>
<td>$0.15</td>
</tr>
<tr>
<td>Total OPEX</td>
<td>$2.47</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>CAPEX Cogeneration</td>
<td></td>
</tr>
<tr>
<td>($M)</td>
<td></td>
</tr>
<tr>
<td>Equipment (compressors</td>
<td>$44.7</td>
</tr>
<tr>
<td>etc.)</td>
<td></td>
</tr>
<tr>
<td>Piping + installation</td>
<td>$0.50</td>
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<tr>
<td>Total CAPEX</td>
<td>$45.9</td>
</tr>
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</table>

<table>
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<tr>
<td>Energy</td>
<td>$1.00</td>
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<tr>
<td>Maintenance</td>
<td>$0.24</td>
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<tr>
<td>Total OPEX</td>
<td>$4.46</td>
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<td>($M)</td>
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<td>Equipment (compressors</td>
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<td>$5.00</td>
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<td>Total CAPEX</td>
<td>$37.50</td>
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### Option 3: NPV Comparison

Option 2 plus 5000 cfm (2.4 m³/s) Compressed Air

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<tr>
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<th>CRYO 5 MWe (24/7)</th>
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<tr>
<td>CAPEX</td>
<td>$45.9</td>
<td>$37.5</td>
</tr>
<tr>
<td>OPEX/yr</td>
<td>$2.47</td>
<td>$4.46</td>
</tr>
<tr>
<td>NPV (10%)</td>
<td>-$66.91</td>
<td>-$75.48</td>
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OPEX includes Electricity & maintenance costs
# Financial Estimates

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20 year NPV Calculated at a discount rate of 10% ($M)

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<th>Compressed Air</th>
</tr>
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<tbody>
<tr>
<td>BAC</td>
<td>-$58.80</td>
<td>-$58.80</td>
<td>-$75.48</td>
</tr>
<tr>
<td>CRYO</td>
<td>-$61.60</td>
<td>-$59.52</td>
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20 year NPV Calculated at a discount rate of 10% ($M)

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<th></th>
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<td></td>
<td>-$59.52</td>
<td></td>
<td>-$66.90</td>
</tr>
</tbody>
</table>

Percent of Plant Capacity Required for Mine Chilling

<table>
<thead>
<tr>
<th></th>
<th>Mine</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mine</strong></td>
<td>31%</td>
<td></td>
<td>55%</td>
<td></td>
<td>61%</td>
</tr>
<tr>
<td><strong>Surplus</strong></td>
<td>69%</td>
<td></td>
<td>45%</td>
<td></td>
<td>39%</td>
</tr>
</tbody>
</table>
Effect of adding heat to airflow and the impact of Chilling on Demand on the 3300 m level for a flow of 50 m$^3$/s at an initial temperature of 12/12 DB/WB$^\circ$C

<table>
<thead>
<tr>
<th>Heat added</th>
<th>kW</th>
<th>Temperature DB/WB$^\circ$C</th>
<th>WBGT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base amount</td>
<td>1100</td>
<td>25.9/25.2</td>
<td>25.5</td>
</tr>
<tr>
<td>+ 1 LHD</td>
<td>180</td>
<td>28.2/27.4</td>
<td>27.7</td>
</tr>
<tr>
<td>+ 2 LHD</td>
<td>360</td>
<td>30.5/29.6</td>
<td>29.8</td>
</tr>
<tr>
<td>+ 3 LHD</td>
<td>540</td>
<td>32.7/31.8</td>
<td>32.1</td>
</tr>
</tbody>
</table>

Increasing the cryogenic liquid air flow from 8.1 kg/s to 8.7 kg/s raises the chilling power from 3.73 MW$_r$ to 4.0 MW$_r$.

| Total heat | 1640 | 28.7/27.7 | 28 |

3300 level: the mass flow is 78.7 kg/s and density is 1.574 kg/m$^3$. 
Mine Cooling Via Cryogenics

Prototype Testing Results

Cooling test cryogenic liquid flow through heat exchanger with air flow from ventilation fan being cooled and airflow from liquid providing force for turbine

- Ambient room temperature
- Heat exchanger exit temperature
- Airchange entire room

Temperature °C

Time (minutes)
1 - The average chilling demand over this day is 3 about MWr
2 - The capability of the cryogenic system to respond to variations in chilling demand is a significant difference between the existing systems
3 - Power can also be produced from the expanding gas – a cogeneration system
Conceptual Design for Coleman

Details of the mixing chamber where the ultra cold cryogenic liquid expands and mixes with ambient air to cool the mine
Flow trajectories of a simulation for incoming air temperature of 20 °C at 90 m³/s and 10 m³/s of air created from the expansion of the cryogenic liquid to illustrate the mixing.
CFD Modelling for Coleman Design

- 35°C

![CFD Simulation Image](image-url)
CFD of Flow vs Time 0 s to 10 s

cryogenic flow initiation 0 s

0.095 s from start of flow

0.18 s from start of flow

0.27 s from start of flow

0.4 s from start of flow

10.7 s from start of flow
Boliden

Easy assembly
Prefabricated components “building block system”

Inspection doors
Conceptual Integration of Cryogenic Chilling with Guupex Heat Capture System
Mine Cooling Solution for Coleman

Simple Base Case Demonstration for Client Mine

1. Install a small liquid air plant
2. Liquid -196 °C enters vapouriser/heat exchanger
3. Air at ambient temperature exits vapouriser/heat exchanger
4. Heat is absorbed from airflow over vapouriser/heat exchanger
5. Cool air delivered to subsurface operations

Ventilation flow

Storage Tank on Surface

Cryogenic liquid flow in 7.5 l/s

Liquid IN
-196 °C

Vapouriser

Heat exchanger

Air OUT is at Ambient °C

Air flow out 6 m³/s

Air OUT Can be used to generate power
Dearman Engine CanMIND Study

• Engine uses liquid air instead of Diesel
• Larger fuel storage tank
• 1/3 power --- 2/3 cooling
  • 500 kW engine provides 1 MW (670 hp)
• Liquid fuel
• Cold pure air as exhaust
• Competitive with Diesel and Battery TCO
TCO for Various LHD at 2000 m

Study does not include load shifting for production, economies of scale or chilling created by the vehicle.
Advantages of Liquid Air Systems
Applied to mining, cryogenic technology offers

- Reduced ventilation requirements
- Underground cooling on demand
- Reduced power requirements for ventilation and cooling
- Underground compressed air
- Energy storage and load shifting
- Non-diesel underground motor power providing breathable air
- Exploitation of free geothermal power
- Commercialization of a suite of marketable technologies enabling mines to use cryogenics
- Green house gas emission reductions
- A model for remote projects/communities to have reliable renewable power and water supply
Thank You

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