Cryogenics based chilling, energy supply and services for deeper or hotter mines.

Daniel L. Cluff  
CEO CanMIND Associates  
Fellow Camborne School of Mines  
www.deepmining.ca
Glencore
- Funding
- Engineering Critique
- Real Mine Design

CanMIND Associates
- Principle Investigator
- Physics Engineering
- Concept Development

Highview Power
- Liquid Air Energy Storage
- Pilot plant
- 5 MW plant

CEMI
- Project Management
- Business Acumen

Dearman Engine Co.
- Engine Development
- Techno-economic Analysis
- In Kind Contribution

UDMN
- Funding
- Industry Network
- Commercialisation
Project Elements

Large UG Equipment
Powered by Dearman Engines

Cryogenic Chilling
CFD Modelling

Compressed Air System Design

UG Cryogenic Piping and Storage

Receiver size
Piping
Modularity design

Rapid Response Chilling on Demand

PRU Design
5 to 10 MW_e

Heat Exchanger

31/05/2017
Dr. Daniel L Cluff CAP 2017 Cryogenics
Why LAES

- LAES technology provides plant size economy of scale
- Energy storage is an emerging technological niche
- The cryogenic liquids are produced on the surface in a standard cryogenic liquefaction plant.
- Cryogenic liquid is piped 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 Simplified Schematic

Power Input
Charging Infrastructure

Compression → Liquifaction

Hot Storage
Heat air in winter

Expansion

Cold Storage

Evapouration Cooling

Liquid Air Storage

LA to Underground Storage
Chilling on demand

On Surface

PRU can be placed Underground
5 to 10 MW_e
+ Chilling

Discharging Infrastructure
Power Output
350 kW 2.5 MWH Pilot Plant

Highview Power Slough UK
Six 3600 tpd $O_2$ plants in China
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

• 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.
Ancillary Economics Includes

Argon, Oxygen Markets Both Continue to Grow
700+ l Gaseous Air Per 1 l Liquid Air

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

Volume liters

Expansion from 78 K to 300 K

Expansion liquid to gaseous state at 78 K

Change of State

Temperature Kelvin

31/05/2017 Dr. Daniel L. Cluff CAP 2017 Cryogenics
A Basic Calculation to Illustrate the Heat Absorbed on Change of State

The heat absorbed per kg of liquid air:
Ambient $T_a = 29.85^\circ C \ (273.15 + 29.85 = 303 K)$
Cryogenic $T_c = 78 K$

Latent Heat of vaporisation $L_v = 205 \text{ kJ/kg}$

**Step 1:** The mass “m kg” absorbs $\Delta Q_L$,

Becomes a gas at or near $T_c$

$\Delta Q_L = m L_v = (m \text{ kg})(205 \text{ kJ/kg}) = (m \text{ kg})205 \text{ kJ/kg}$

Change of state is approximately $180 \ell \text{ (gaseous) / 1\ell \text{ (liquid)}}
A Basic Calculation to Illustrate the Heat Absorbed on Expansion

**Step 2:** Very cold air ($\approx 80$ K) warms up to $T_a$
Expansion with heat absorbed $\Delta Q_a$.

$$\Delta T_g = T_a - T_c = 303 - 78 = 225 \text{ K}$$  
change in gas temperature

$$\Delta Q_a = mC_p\Delta T_g = (m \text{ kg})(1.005 \text{ kJ/kg-K})(225 \text{ K}) = 226.13 \text{ kJ/kg}$$
Heat absorbed due to change in gas temperature

$$\Delta Q_T = \Delta Q_L + \Delta Q_a = mL_v + mC_p\Delta T_g = (m \text{ kg})(451.13) \text{ kJ/kg}$$
Total heat absorbed due to change of state and expansion
For 1 \text{ MW}_r \text{ Chilling}

So let $\Delta Q_T = 1 \text{ MJ}$

The total heat absorbed by the ambient air

The mass of liquid air required is $2.217 \text{ kg}$

So a liquid flow $2.217 \text{ kg/s}$ will provide $1 \text{ MW}_r$ chilling.

The density of liquid air is about $870 \text{ kg/m}^3$

So a flow of about $2.55 \text{ l (liquid)}$ provides $1 \text{ MW}_r$

Final gaseous volume $1899.42 \text{ l (gaseous)}$ or $1.9 \text{ m}^3$
Percent Fan Power Reduction on Surface due to Introducing Liquid Air at Depth

Percent power required due to inclusion of liquid air source on the level

WBGT°C

1915
2500
3000
3500
Chilling required for 12 DB 12 WB at Depth for Variations in Surface Temperatures
# Psychrometrics to Liquid Air

<table>
<thead>
<tr>
<th>Surface</th>
<th>Temperature</th>
<th>Celsius</th>
<th>Farenheit</th>
<th>AC effect</th>
<th>Target</th>
<th>Duty Factor Cooling</th>
<th>Depth (m)</th>
<th>Air Flow required at depth</th>
<th>Resulting mass Flow</th>
<th>Surface demand</th>
<th>Auto-compression Heat</th>
<th>Power</th>
<th>Liq Air Mass flow</th>
<th>Plant impact</th>
<th>Liq Air Plant Demand</th>
<th>Total Chilling</th>
<th>Liq Air Mass flow</th>
<th>Liq Air Volflow</th>
<th>Total Air Volflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>DB</td>
<td>28</td>
<td>82.4</td>
<td>46.5983</td>
<td>12</td>
<td></td>
<td>1</td>
<td>-1915</td>
<td>166 m³/s</td>
<td>254.936 kg/s</td>
<td>211.823 m³/s</td>
<td></td>
<td></td>
<td>19.7743 kg/s</td>
<td>0</td>
<td>1708.5 tpd</td>
<td>8.86582 MW</td>
<td>19.7743 kg/s</td>
<td>13.9586 m³/s</td>
<td>179.959 m³/s</td>
</tr>
<tr>
<td>WB</td>
<td>19</td>
<td>66.2</td>
<td>33.71</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WBGT</td>
<td>21.7</td>
<td>71.06</td>
<td>37.5765</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humidity Ratio</td>
<td>kg-w/kg-a</td>
<td>0.01072</td>
<td>0.02130</td>
<td>0.00697</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>%</td>
<td>43.3007</td>
<td>40.255</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface elevation (m)</td>
<td></td>
<td>402</td>
<td>124970</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PSI</td>
<td></td>
<td>14.009</td>
<td>18.3539</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Enthalpy</td>
<td>BTU/lb</td>
<td>31.5508</td>
<td>51.5084</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Volume</td>
<td>cu-ft/lb</td>
<td>14.5827</td>
<td>12.0154</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta H</td>
<td></td>
<td>0.91036</td>
<td>0.7501</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Surface Density:** 1.11018

**Density at Depth:** 1.41664

**Revised Main Fan Duty:** 0.78488

**Revised:**
- 152.041 m³/s
- 215.387 kg/s

**Other Heat:** 0
Chilling on Demand

Yearly Atmospheric Conditions Sudbury Ontario

Average Relative Humidity - 0600LST (%)
Average Relative Humidity - 1500LST (%)
Daily Maximum (°C)
Daily Average (°C)
Daily Minimum (°C)
Minimum Shaft Air Temperature 2 °C

Corresponds to Legend RH (%) or Temperature (°C)

Month of Year

31/05/2017

Dr. Daniel L Cluff CAP 2017 Cryogenics
Demand for Liquid Air (tpd) to Create a 12/12 DB/WB °C Environment at 1915 Depth

allows for offsetting of LA production during cheaper electricity rates.

Gap between daily MAX and MIN

Month of Year

tpd at minimum daily temperature

tpd at maximum daily temp

tpd difference MAX - MIN

31/05/2017

Dr. Daniel L Cluff CAP 2017 Cryogenics
Cryogenic Chilling for Actual Temperature Fluctuations
07/07/2010 One of the hottest days in 2010

Units correspond to Legend

DB °C
WB °C
kg/s
MWm

Time of Day (hrs)
A 2400 tpd plant production frontier when the surplus produced over the least expensive energy cost is redistributed to the peak time cost.
Summary of the cryogen production and power production

Power Arbitrage for a 3000 tpd Plant and a 10 MW PRU

- MWH Required for production of cryogen
- MWH Produced by PRU

Time of day

MWH produced or purchased

0.00
5.00
10.00
15.00
20.00
25.00

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Summary of the cryogen production and power production implications for a 10 MW PRU

<table>
<thead>
<tr>
<th>Plant Size tonnes</th>
<th>1600</th>
<th>1800</th>
<th>2000</th>
<th>2200</th>
<th>2400</th>
<th>2500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Cost</td>
<td>$3,170</td>
<td>$2,345</td>
<td>$1,520</td>
<td>$775</td>
<td>$787</td>
<td>$781</td>
</tr>
<tr>
<td>Final Cost</td>
<td>$1,899</td>
<td>$1,074</td>
<td>$248</td>
<td>-$496</td>
<td>-$484</td>
<td>-$490</td>
</tr>
<tr>
<td>YEAR at this rate</td>
<td>$693,071</td>
<td>$391,886</td>
<td>$90,701</td>
<td>-$180,987</td>
<td>-$176,752</td>
<td>-$178,869</td>
</tr>
<tr>
<td>MWH paid</td>
<td>218.84</td>
<td>218.84</td>
<td>218.84</td>
<td>218.91</td>
<td>219.04</td>
<td>218.98</td>
</tr>
<tr>
<td>10 MWH PRU</td>
<td>-120.00</td>
<td>-120.00</td>
<td>-120.00</td>
<td>-120.00</td>
<td>-120.00</td>
<td>-120.00</td>
</tr>
<tr>
<td>recovered</td>
<td>-10.20</td>
<td>-10.20</td>
<td>-10.20</td>
<td>-10.20</td>
<td>-10.20</td>
<td>-10.20</td>
</tr>
<tr>
<td>TOTAL</td>
<td>88.64</td>
<td>88.64</td>
<td>88.64</td>
<td>88.71</td>
<td>88.84</td>
<td>88.77</td>
</tr>
<tr>
<td>Tonnes produced</td>
<td>1094.00</td>
<td>1094.00</td>
<td>1094.00</td>
<td>1094.33</td>
<td>1095.00</td>
<td>1094.67</td>
</tr>
<tr>
<td>Tonnes required</td>
<td>1094.12</td>
<td>1094.12</td>
<td>1094.12</td>
<td>1094.12</td>
<td>1094.12</td>
<td>1094.12</td>
</tr>
<tr>
<td>Power Generation</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Operating Period</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>MWH Produced</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Efficiency</td>
<td>54.83%</td>
<td>54.83%</td>
<td>54.83%</td>
<td>54.82%</td>
<td>54.78%</td>
<td>54.80%</td>
</tr>
</tbody>
</table>
Cost of Chilling When Time shifting and Using a Power Recovery Unit

Comparison of 10, 8 and 5 MW Power Recovery Units Operating in Arbitrage Mode, While Providing Chilling at the 1915 m Level for a 1094 tpd Chilling Requirement
# Plant Configuration Costing

<table>
<thead>
<tr>
<th>Plant Configuration</th>
<th>Waste heat</th>
<th>Standalone</th>
<th>Standalone</th>
<th>Waste heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquefaction capacity (tonnes/day)</td>
<td>2500</td>
<td>3000</td>
<td>2000</td>
<td>1700</td>
</tr>
<tr>
<td>Power input (MW @ charge time)</td>
<td>21.4</td>
<td>25</td>
<td>16.6</td>
<td>14.3</td>
</tr>
<tr>
<td>Charge time hrs</td>
<td>6</td>
<td>6</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Consumed energy MWH</td>
<td>128.4</td>
<td>150</td>
<td>132.8</td>
<td>114.4</td>
</tr>
<tr>
<td>Discharge time hrs @ 5 MW</td>
<td>18</td>
<td>18</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Energy output (MWH)</td>
<td>90</td>
<td>90</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Liquid air store capacity (tonnes)</td>
<td>570</td>
<td>570</td>
<td>510</td>
<td>510</td>
</tr>
<tr>
<td>Round trip efficiency</td>
<td>70%</td>
<td>60%</td>
<td>60%</td>
<td>70%</td>
</tr>
<tr>
<td>CAPEX (million $)</td>
<td>46</td>
<td>40</td>
<td>33</td>
<td>38</td>
</tr>
<tr>
<td>PRU (turbines/generators/grid)</td>
<td>8.15</td>
<td>8.15</td>
<td>8.15</td>
<td>8.15</td>
</tr>
<tr>
<td>Storage cost</td>
<td>3</td>
<td>3</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Cost per kilowatt ($)</td>
<td>9285</td>
<td>8098</td>
<td>6569</td>
<td>7545</td>
</tr>
<tr>
<td>Cost per kilowatt-hour ($)</td>
<td>516</td>
<td>450</td>
<td>411</td>
<td>472</td>
</tr>
</tbody>
</table>
Ancillary Systems

- Chilling accounts for a major share of consumption
- There are a number of other services that can be implemented that provide a service while also simultaneously chilling as a side benefit.
  - Compressed air
  - Electricity production
  - Vehicles, pumps or fans that can be driven by liquid air
Compressed Air

• The production of compressed air exploits the liquid nature of the cryogen, which is simply squirted into a receiver tank and allowed to reach ambient temperature – quickly!
## Compressed Air Supply With Chilling Power

<table>
<thead>
<tr>
<th>Compressed Air Consumption</th>
<th>Receiver Size</th>
<th>Chilling Power</th>
<th>kW ft³/min</th>
<th>Mass flow</th>
<th>Liq flow</th>
<th>Plant impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>ft³/min</td>
<td>m³/hr</td>
<td>m³</td>
<td>kW</td>
<td>kg/s</td>
<td>l/s</td>
<td>tpd</td>
</tr>
<tr>
<td>500</td>
<td>850</td>
<td>1.79</td>
<td>124</td>
<td>0.248</td>
<td>0.29</td>
<td>0.33</td>
</tr>
<tr>
<td>1000</td>
<td>1699</td>
<td>3.6</td>
<td>248</td>
<td>0.248</td>
<td>0.58</td>
<td>0.67</td>
</tr>
<tr>
<td>2000</td>
<td>3398</td>
<td>7.28</td>
<td>496</td>
<td>0.248</td>
<td>1.16</td>
<td>1.33</td>
</tr>
<tr>
<td>3000</td>
<td>5097</td>
<td>11.06</td>
<td>744</td>
<td>0.248</td>
<td>1.74</td>
<td>2.00</td>
</tr>
<tr>
<td>5000</td>
<td>8495</td>
<td>18.54</td>
<td>1240</td>
<td>0.248</td>
<td>2.9</td>
<td>3.33</td>
</tr>
</tbody>
</table>

31/05/2017
Dr. Daniel L Cluff CAP 2017 Cryogenics
Assuming continuous demand the liquid air can be configured to provide a modular compressed air system which will simultaneously chill at the location the receiver tank is located akin to spot chilling.

**Chilling Power as a function of the Compressed Air Supply**

\[ y = 0.248x \]
Recall the earlier LAES Simplified Schematic

- In the schematic it was indicated that the PRU could be placed underground.
- Part of the PRU process is to pump the liquid air to a pressure of about 1000 psi before evaporating and expanding through the turbomachinery.
- At 2000 m the pressure is about 2500 psi
- Sufficient pressure to eliminate the pumps
Recall the earlier discussion regarding the gap between the MAX and MIN daily temperature was about 500 tpd, Below for a 5 MW<sub>e</sub> PRU

<table>
<thead>
<tr>
<th></th>
<th>Waste heat</th>
<th>Standalone</th>
<th>Standalone</th>
<th>Waste heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquefaction capacity (tonnes/day)</td>
<td>2500</td>
<td>3000</td>
<td>2000</td>
<td>1700</td>
</tr>
<tr>
<td>Power input (MW @ charge time)</td>
<td>21.4</td>
<td>25</td>
<td>16.6</td>
<td>14.3</td>
</tr>
<tr>
<td>Charge time hrs</td>
<td>6</td>
<td>6</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Consumed energy MWH</td>
<td>128.4</td>
<td>150</td>
<td>132.8</td>
<td>114.4</td>
</tr>
<tr>
<td>Discharge time hrs @ 5 MW</td>
<td>18</td>
<td>18</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Energy output (MWH)</td>
<td>90</td>
<td>90</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Liquid air store capacity (tonnes)</td>
<td>570</td>
<td>570</td>
<td>510</td>
<td>510</td>
</tr>
<tr>
<td>Round trip efficiency (waste heat)</td>
<td>70%</td>
<td>60%</td>
<td>60%</td>
<td>70%</td>
</tr>
<tr>
<td>CAPEX (million $)</td>
<td>46</td>
<td>40</td>
<td>33</td>
<td>38</td>
</tr>
<tr>
<td>PRU (turbines/generators/grid)</td>
<td>8.15</td>
<td>8.15</td>
<td>8.15</td>
<td>8.15</td>
</tr>
<tr>
<td>Storage cost</td>
<td>3</td>
<td>3</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Cost per kilowatt ($)</td>
<td>9285</td>
<td>8098</td>
<td>6569</td>
<td>7545</td>
</tr>
<tr>
<td>Cost per kilowatt-hour ($)</td>
<td>516</td>
<td>450</td>
<td>411</td>
<td>472</td>
</tr>
</tbody>
</table>

Typically the cold would be recycled to cold storage, but here it is absorbed by the air at depth
Exploitation of the Joule Thompson Effect

• With 2500 psi available as a forcing pressure the Joule Thompson Effect, which is part of the liquefaction process, can be exploited to provide further chilling commonly referred to as free expansion or a throttling process.

• \[ T_2 = T_1 - U_j(P_1 - P_2), \quad P_2 = 14.5 \, \text{psi}, \quad T_1 = 25^\circ \text{C} \]

• where \( U_j \) is the JT coefficient - ambient \( T_1 \) - contained \( P_1 \)

• For a contained pressure of 880 psi, \( U_j = 0.1815 \)

• \[ T_2 = 298 - 0.1815(880 - 14.5) = 140.9 \, \text{K} = -132.05^\circ \text{C} \]
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
- Flow: 235 kg/s
- Pressure: 124.97 kPa
- Temperature: 319 K

Granite
- Diameter: 15 m
- Temperature: 325 K

Heat Exchanger
- Tubes in plate
- Cryogenic liquid
- Temperature: $T_{\text{cryoliq}} = 78$ K
- Specific gravity: $s.g. = 0.87$
- Flow: 24 kg/s

Cryogen Sourced Air
- Perpendicular to Shaft Air Flow
- Temperature: $T_{\text{cryogas}} = 78$ to 85 K on Exit
- Density: about 4 kg/m
Close up View of Heat Exchanger 1.67 sec

Temperature [K]

Min: 58.8319 K  Max: 325.003 K
Time: 1.67701435 s
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]]
Cryogenics based chilling, energy supply and services for deeper or hotter mines.

Thank you to:

Glencore for Financial Support and Engineering Excellence.

UDMN for financial support.

CEMI for business expertise and project management

Dearman Engine Company for Cryogenics expertise and technoeconomic analysis.

Highview Power Storage for LAES expertise and technical support.

Camborne School of Mines for academic support

Dr. Daniel L. Cluff
CanMIND Associates
www.deepmining.ca