THE IMPACT OF CRYOGENICS ON DEEP MINES

BY DANIEL L. CLUFF

Cryogenic Energy Storage is an emerging technology that, when installed at a mine site, provides the economies of scale to create the availability of cryogenic liquids which are also capable of delivering several ancillary services to the project. Mining projects are large energy consumers and are not often conveniently located near thriving metropolises with a high voltage grid connection. Energy supply and cost are a significant variable in the viability of a project. Projects are usually remote or as is often the case located in a geopolitical jurisdiction where they would consume upwards of 20% of the available energy produced for the grid; thus, a source of reliable energy is key to success of these projects and the comparability of the size of a mining project to a small community suggests that the scale of the energy project would be conducive to remote communities. The use of renewable energy has been embraced by two Canadian mining projects, Raglan Mine in Quebec and Diavik in the North West Territories have both installed wind turbine projects.

> *"Combined with an efficient storage system, renewable energy proved to significantly reduce operating costs, green house gas emissions, and dependence on diesel fuel, in mining operations and communities of the Canadian North. Furthermore, experience indicated that energy storage is a necessary enabler towards persistent penetration higher than 40% of diesel micro-grid capacity."*[1]

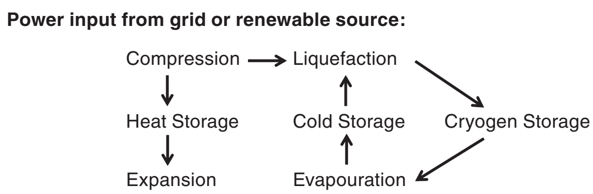
Diavik has no energy storage capacity, but the 9.2 MW turbines produced 17 GWh/yr in 2013 or 8.5 % of the total power produced for the mine, reducing the Diesel consumption by 3.8 million litres or $5 million for the year. This on-site renewable energy production cut back on the winter ice road fuel haulage by approximately 75 loads [2].

SUMMARY

Deep mining is a challenging undertaking. As the project gets deeper, the geotechnical and thermodynamic aspects are the two most difficult aspects to control. In this article, the innovative concepts of chilling deep mines via cryogenics and the added services that are potentially available are explored.

The use of storage at Raglan has demonstrated the import of an energy storage system for increased penetration.

Although cryogenic energy storage is an emerging technology, indications are that in comparison to other storage modalities of an appropriate size, it is cost competitive, nontoxic, has no barriers to location and is scalable to very large grid sized systems. The source of the cryogenic liquids is a surface liquefaction plant. The basics of the system are outlined in the following diagram.



DISCHARGE INFRASTRUCTURE FOR POWER OUTPUT

The hot and cold storage increase the round trip efficiency of the system, the heat rejected from the compression stage in the liquefaction process is used during the expansion stage to generate electricity and the cold created during the evapourative cooling is stored for use in the liquefaction process [3]. Using heat from industrial processes can significantly increase the efficiency of the power generation and similarly cold from the expansion of liquid natural gas will increase efficiency of the liquefaction, both of which increase the round trip overall efficiency of the system. The attainment of much higher round trip efficiencies is due to the purchase of the cold in the form of the LNG or the use of heat from industrial processes that has also been purchased, but would otherwise be lost to the environment. In the grid connected case, an opportunity for the mining project to perform energy arbitrage forms a substantial part of the argument for the larger plant size. When such an energy project is located at the site of a mining project the concept of global adjustment manipulation is a noteworthy possibility. The global adjustment factor is determined by the power utilities measurement of the project consumption during selected peak power periods over the course of the year. Companies often attempt to anticipate these peak power periods and reduce consumption by ramping down

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large power draws, but this is a statistically difficult endeavour. Having a behind the grid power storage and/or production facility provides the flexibility of being able to produce power during the peak periods, increasing the probability that the power draw is reduced during the peak, during which a measurement has can be taken by the power authority.

CHILLING THE MINE AT DEPTH

There are a few typical approaches to chilling mines: the first tactic is to introduce more air flow for removing excess heat; another approach is to pump cold water or an ice slurry to an underground holding facility with heat exchangers to interact with the ventilation flow, and finally the construction of an underground refrigeration plant to cool the air on a bulk basis. As the mines get deeper there are increasing drawbacks to these solutions. Firstly, the air heats up as it descends, commonly referred to as autocompression in the industry, but physicists would recognise the meteorological term “lapse rate”, in simple terms the dry air temperature increases by about 9.8 °C/km but, depending on the shaft conditions and relative humidity, the lapse rate is often about 6.5 °C/km; thus, the air arriving at 2500 m depth drawn from the surface at 25 °C will be about 35 °C to 50 °C, which is clearly an unacceptable working environment.

Cryogenic chilling is a remarkably straight forward concept. A liquid cryogen comprised of oxygen and nitrogen is pumped underground, where it absorbs a substantial amount of heat upon expansion. Of great interest to the mining project designers is that there is no return circuit required, because the liquid cryogen expands to air at ambient temperature and simply exits the mine via the normal ventilation raise. After more than a century of engineering, cryogenic technologies are safe, advanced, reliable and typically available off-the-shelf. The cryogenic liquid has certain advantages compared to the other chilling systems due to the basic physical properties of cryogenic liquids. For use in a mine, the cryogen will have to contain a certain oxygen fraction such that, upon expansion and mixing with the ambient air, the minimum oxygen content in the air is maintained at 19.5%; therefore, due to the variability of the O_2/N_2 ratio, these are approximate properties. The latent heat of vapourisation is about 205 kJ/kg and the specific heat capacity of air varies with temperature over the range from cryogenic temperatures from about 78 K to ambient temperature, say 300 K, but an average value of 1.05 kJ/kg-K can be used for convenience, so for 1 kg of cryogenic liquid the heat absorbed is:

$$1\ \text{kg}(205\ \text{kJ/kg} + 1.05\ \text{kJ/kg-K} \times (300 - 78)\text{K}) = 438\ \text{kJ}$$

The expansion factor depends on the ambient temperatures and density at a given depth, but a typical value is that about 720 litres of air is produced for each litre of liquid; additional heat added during the expansion phase causes increased final volume leading to more power extracted by the turbines and increased efficiency of power production. The elegance of cryogenic chilling for deep mines becomes immediately apparent due to the amount of heat absorbed per kilogram of liquid and the one-way trip that the liquid takes, but there are more implications that even strengthen the argument [4].

The placement of a power generation unit underground requires that the cryogenic liquid be piped to that depth to supply the evaporative cooling and expansion sections, see diagram 1, which allows for the simultaneous production of electricity and chilling. The heat from the mine is converted to electricity creating an electricity/chilling cogeneration system. Unlike any other underground chilling system where the heat is simply moved around consequently a hot discharge to the surface is required, which creates many complications such as a no-go area for mine personnel.

The availability of the cryogen underground leads to a concept of chilling on demand, which is achievable by additional strategically placed cryofans™ to provide consistent temperatures given varying heat loads. This is an exciting possibility given the introduction of electric vehicles to deep mining, which may allow for a reduction of the ventilation flow by up to 50% of that legislated when using Diesel equipment. The reduction in airflow increases the susceptibility to larger air temperature changes for lesser amounts of heat introduced. This can be problematic if the flow cannot be increased to carry the heat away the temperatures may increase beyond the allowable working limits rather quickly. A cryogenic system has the capability of delivering chilling on demand, able to respond rapidly by simply increasing the liquid flow. Not only does the liquid air provide chilling, it actually replaces some of the air that would be drawn from the surface, a 10% airflow reduction can translate to upwards of a 25% power saving.

A Computational Fluid Dynamics model was created to simulate Chilling by a Cryofan™ vapouriser [5]. The model is comprised of a concentric tube heat exchanger, to allow the latent heat of vapourisation to be absorbed by the liquid flow. Converting the liquid to a gas occurs at ultralow temperatures, which results in very cold gaseous air with a density of about 4.2 kg/m^3. The gaseous flow then continues to absorb heat causing increases in volume and pressure. The air is confined to increasing diameter pipes until it exits to the ventilation airflow through venting outlets. At the exit to the normal ventilation flow the air sourced by the cryogenic liquid is still very cold so expands somewhat upon exhausting to the airflow in the downcast shaft. The heat exchanger and gaseous flow tubing are all located in the normal ventilation air flow so all of the heat absorbed by the cryogen is taken from the ventilation air. This ensures that the temperature of the flow is reduced to reasonable values rather than introducing ultra cold flows at any point in the system, as this would present a hazard to workers in the immediate vicinity.

The model is used to study the interaction of a cryogenic chilling system given the assumed conditions in a shaft at various depths and initial conditions. The ambient inlet conditions for a given model considered as typical were a pressure of 125 kPa and temperature of about 46 °C, which were set to simulate the conditions of the air at a depth of 1900 m, after the effect of auto-compression, which are derived from the surface conditions of 28 °C dry bulb, 19 °C wet bulb at 43% relative humidity. The chilling power, 8.87 MWr is required to achieve 12 °C dry bulb, 12 °C wet bulb at 100% relative humidity at that depth, was selected to compare to the expected chilling delivered by a bulk air chiller installed at that depth. The liquid air mass flow is 19.8 kg/s, which introduces 13.9 m^3/s of air into the ventilation system. The impact on the ventilation system is chilling and replacement of some of the required ventilation flow at that depth. In order to provide the required 180 m^3/s flow at the 1900 level depth requires 211 m^3/s be drawn from the surface rather than the 228.25 m^3/s that would have been drawn from the surface had the cryogen not introduced 19.77 kg/s, or 13.59 m^3/s, keeping in mind that the differences between the required flow from the surface 16.43 m^3/s and that at depth are due to the air density at depth is 1.42 kg/m^3 whereas that at the surface is about 1.2 kg/m^3. The power saving due to the reduced flow from the surface to the 1900 m level is that the main fans are now operating at 78.5% of full power. Ventilation power costs can be upwards of 60% of the total required by the mine, so this power saving is significant and there is 19.77 kg/s less air that must be chilled. These details are significant because they add up to a substantial saving when calculated over the lifetime of the mine, in this case the expected life of mine was twenty years.

COMPRESSED AIR SOURCED FROM CRYOGENIC LIQUIDS

Should a scheme using cryogenic energy storage and an underground electricity generation/chilling cogeneration system be adopted by a mining project, then the existence of cryogenic liquids underground provides an opportunity to produce compressed air not only at the typical 120 psi required by a mining project, but also any elevated pressure as required for any special purposes. A typical compressed air system for underground use would be about 5000 cfm. The current method of providing this amount of compressed air to the mine is to use a surface plant with supplemental compressors and storage underground at strategic locations. This type of system requires about a 1300 hp compressor, storage tanks and piping from surface to the levels underground. The industry standard costs of such systems are modelled over a ten year expected life as follows 76% energy, 12% capitol costs and 12% maintenance on a yearly basis. The energy costs for this size system are about $1 million per year so the total cost of the system is about $1.24 million per year. The cost of piping for a 2500 m deep mine is estimated to be about $5 million at start up with ongoing maintenance. If the cryogenic systems are already installed, then it is a simple case of using some of the liquefied air to produce compressed air at underground storage tanks. The 5000 cfm compressed air requirement can be met by about 125 to 140 tpd of cryogenic liquid, this is somewhat less than the actual 5000 cfm, but it is quite typical and expected in the mining industry that compressed air suffers significant losses of 30% to 50% of the system capacity, so the estimated amount of compressed air delivered by a 5000 cfm system would be in the 2500 cfm range at about 90 psi. The cryogenically sourced compressed air would be created underground and proximal to the working area where it is needed so these losses incurred during delivery would not be expected. The additional benefit is that a 2500 cfm system would produce 600 kW of chilling so the compressed air production is also a cogeneration concept that provides compressed air and chilling simultaneously.

A comparison was created of the costs associated with installing the cryogenic liquefaction plant with storage and piping to a bulk air chiller installed underground at about 1900 m depth as the capitol expenditure and using the energy costs and yearly maintenance costs as the operating expenditures with a discount rate of 10% over a life of mine of 20 years, see Table 1. The options 1, 2 and 3 are a straight comparison of: the bulk air

TABLE 1

Cost comparison of cryogenic systems to typical mine systems.

	Option 1 Chiller only		Option 2 5 MWe generation		Option 3 5 MWe and compressed air	
($M)	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX
BAC	$31.4	$3.22/yr	$31.4	$3.22/yr	$37.5	$4.37/yr
CRYO	$31.9	$3.48/yr	$44.7	$1.74/yr	$45.9	$2.47/yr
20 year NPV Calculated at a discount rate of 10% ($M)						
BAC	$58.80		$58.80		$75.78	
CRYO	$61.60		$59.52		$66.90	
Percent of Plant Capacity Required for Mine Chilling						
Mine	31%		55%		61%	
Surplus	69%		45%		39%	

chiller and the cryogenic liquids, both creating 12 °C DB and 12 °C WB at the 1900′ level; 5 MW underground electricity generation with supplemental chilling and the former, plus compressed air supply respectively [6].

EXTRACTING CHILLING OR ENERGY FROM THE PRESSURE IN DEEP MINE DELIVERY SYSTEMS

Deep mining is generally considered to begin at about 2500 m depth, which can create pressures in the liquid delivery piping of 21,315 kPa (3091 psi), for a density of 870 kg/m^3. The pressure would not reach those levels because the piping system would include reservoirs and pressure reducer systems on the way down, but 1000 psi is required for the 5 MWe electricity generation system, which can be achieved by a head of about 800 m. This is advantageous as the design can incorporate the pressure head, which will allow for elimination of the compressors, required if the same system had been placed on the surface. This is a substantial price reduction of the electrical generation system. Another quite interesting aspect is the use of the pressure to create chilling via the Joule Thompson effect. Temperatures of gaseous flow of −150 °C are possible at the 1000 psi pressure needed by the electrical generation system. This has not been prototyped, but the same concept is applied to create the cryogen in the liquefier and is also the reason why more chilling is available from in the expansion turbines during the creation of the electricity.

CONCLUSIONS

Cryogenics offers the opportunity for cogeneration of electricity/chilling, compressed air/chilling and motive force/chilling. The ability to extract chilling simultaneously while providing another service has been shown to be possible and is attractive to mining projects as they descend beyond 2500 m. The use of cryogenics as an energy storage vector is an emerging technology, but is based on systems that have been engineered for over a century; thus, the safety aspects are well developed and the equipment is readily available and reliable.

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