Conceptual overview and preliminary risk assessment of cryogen use in deep underground mine production

J. Sivret\textsuperscript{1,2}, D.L. Millar\textsuperscript{1,2}, G. Lyle\textsuperscript{2}

\textsuperscript{1}Laurentian University/Bharti School of Engineering, Sudbury, ON, P3E 2C6, Canada
\textsuperscript{2}MIRARCO, Sudbury, ON, P3E 2C6, Canada

E-mail: jsivret@mirarco.org

Abstract. This research conducts a formal risk assessment for cryogenic fueled equipment in underground environments. These include fans, load haul dump units, and trucks. The motivating advantage is zero-emissions production in the subsurface and simultaneous provision of cooling for ultra deep mine workings. The driving force of the engine is the expansion of the reboiled cryogen following flash evaporation using ambient temperature heat. The cold exhaust mixes with warm mine air and cools the latter further. The use of cryogens as 'fuel' leads to much increased fuel transport volumes and motivates special considerations for distribution infrastructure and process including: cryogenic storage, distribution, handling, and transfer systems. Detailed specification of parts and equipment, numerical modelling and preparation of design drawings are used to articulate the concept. The conceptual design process reveals new hazards and risks that the mining industry has not yet encountered, which may yet stymie execution. The major unwanted events include the potential for asphyxiation due to oxygen deficient atmospheres, or physical damage to workers due to exposure to sub-cooled liquids and cryogenic gases. The Global Minerals Industry Risk Management (GMIRM) framework incorporates WRAC and Bow-Tie techniques and is used to identify, assess and mitigate risks. These processes operate upon the competing conceptual designs to identify and eliminate high risk options and improve the safety of the lower risk designs.

1. Introduction
Reclassification of diesel engine exhaust as a carcinogen \cite{1}, has led to the Canadian mining industry exploring zero-emission alternatives to power underground mining equipment. Most interest lies with electric driven mining machines \cite{2,3}, however a new possibility is vehicle prime movers ‘fueled’ with cryogens. This new cryogenic technology has been developed by The Dearman Engine Company and is delivering clean and cold power in the food transportation sector \cite{4}. An implementation of such cryogenic technology in underground environments may lead to solutions for eliminating carcinogens from the underground working environment and have the added benefit of simultaneously providing cooling. However, as some experience of use of electric vehicles underground has already been established, in comparison to deployment of electrically driven mining machines and technology, execution of a plan for cryogen driven mine production may not be as straightforward, and a risk management \cite{5} approach to such an undertaking is required. Aside from consideration of the vehicles themselves, mine infrastructure requirements to support the technology are currently alien. Any approach to use of cryogenic technology in underground mines from a risk assessment point of view, must first establish a proper conceptual design. In this paper, research, scoping calculations and
estimates aim to provide insight on some of the necessary parameters and details that will be required to execute plans for supply, storage, distribution and handling of the cryogenic fuel in an underground environment to inform risk assessment process.

2. The Dearman engine
The Dearman engine is a cryogenic reciprocating piston engine that takes advantage of the large expansion ratio of compressed gases to drive the piston. This engine can produce mechanical energy with cryogenic fuels such as liquid air or liquid nitrogen. Any cryogen is not combusted, as a fuel, rather cryogen is injected into an engine’s cylinder and flashes to vapor while drawing heat from a concurrently injected heat transfer fluid comprising water and glycol at ambient temperature. As the space above the piston head is confined, the cryogen flashes under pressure and this pressure drives the piston head downward. The precise nature of the heat transfer fluid is not disclosed by Dearman but in our simulations of the engine cycle we needed to adopt a 50/50 (m/m) mixture of water and glycol to prevent the water freezing in the cylinder as the gas expanded.

The piston cycle of the engine can be seen in Figure 1. Starting with the return stroke the piston drops down the cylinder providing volume for a heat transfer fluid to enter. The piston then proceeds to the top dead center position where the cryogen can be injected and mixed with the heat transfer fluid. As the piston enters the power stroke the heat transfer fluid provides enough ambient heat for the cryogenic liquid to expand and evaporate almost instantaneously. This flash evaporation of the cryogen is what provides the mechanical power of the engine. In the power stroke, the vapor expands further and cools. The return stroke then pushes the cold vapor and heat transfer fluid to a low-pressure separator. From this point the heat transfer fluid is reheated to ambient temperature, forming a cycle similar to an automotive radiator circuit, and the cold vapor is exhausted to atmosphere providing cooling for the ambient mine working environment.

![Figure 1. Dearman engine piston cycle interaction with the cryogenic fuel and cylinder. [6]](image)

If developed at appropriate ratings, these engines can be paired with underground mining equipment such as so-called Load-Haul-Dumper (LHD’s) or haulage trucks eliminating diesel exhaust in underground environments while providing clean and cold air directly to the workers. An alternate application for these engines is pairing them with a fan to provide auxiliary cooling in deep underground mines. It is important to consider the mass flow rate, fuel cost, and rated power of the Dearman engine compared to conventional diesel engines to establish a proper comparison. Cryogenic engines should present direct competition to diesel alternatives and battery electric mine production vehicles which are still in a state of development. Albeit these possible benefits this technology comes with its own unique challenges.
3. Fuel consumption

Most modern mines are still relying heavily on diesel fuelled mining equipment. Only recently have large mining companies such as Goldcorp’s Borden mine near Chapleau, Ontario, begun investing in diesel alternatives that will become one of the first fully electric and battery powered underground mines [7]. Large fleets of diesel equipment lead diesel consumption in the range of 1.5 million liters consumed per annum [8]. It is important to establish early on the amount of cryogenic fuel that would be required to sustain a fleet of cryogenic mining equipment as this informs the scale of infrastructural requirements in conceptual design.

Through the construction of a Dearman engine model calculations have been made using initial parameters such as mass of fuel per piston cycle, engine cylinder dimensions, and thermodynamic properties to estimate the rated power and fuel consumption of a cryogenic engine. Our findings have shown a cryogenic engine rated at 112kW consumes 0.765kg/s of liquid nitrogen or 682.8g/s per 100kW of motive power. Comparing these values to those of a conventional diesel engine which consumes fuel at a rate nearly 100 times less at 6.47g/s of fuel per 100kW of power delivered, it can be readily appreciated that the mass flow infrastructure scaling required is two orders of magnitude higher for the cryogen option. These rates can then be applied to real diesel consumption data for a typical underground mine fleet to estimate the yearly cryogenic consumption if a mine were to adopt this technology. Inspection of Table 1 for a mine with a fleet of 93 units of diesel fuelled mine equipment can have a total rated power of 11,497kW consuming 4,108L of diesel per day [8]. The corresponding amount of cryogen that would need to be supplied amounts to nearly 400,000L per day. Consequently, the next question that immediately arises is: how costly would such a high-volume consumption rate be?

|                | Diesel | Cryogen (LN₂) |
|----------------|--------|---------------|
| Fleet total power (93 units) | 11,497kW | 11,497kW |
| Fleet daily power average (12 units*) | 544kW | 544kW |
| Liters per annum | 1,449,502L | 145,091,805L  |
| Liters per day | 4,108L | 397,512L  |

* Average number of active unit’s considering engine load factors, shift load factors and availability.

b Values are based on data from numerical models and industry sources.

For this research it was important to establish large scale conditions to properly inform the concept. For example, installing a few auxiliary fans paired with cryogenic engines would have a much smaller daily consumption of cryogen and would lead to far different infrastructural concepts.

4. Cost analysis

The price of diesel fluctuates substantially due to market conditions. For the purposes of this conceptual study a diesel price of $1200/tonne is assumed (all $ amounts are assumed CAD). This is approximately double the diesel price available at the time of writing [9] but reflects peak prices prevalent in 2014 when the study commenced. The cost of cryogens has been estimated assuming liquid nitrogen is the desired cryogen. Due to a lack of data available on industry standards for the cost of liquid nitrogen purchased in bulk, liquid oxygen was used as a foundation for the following cost estimate. Analysis of an air liquefaction plant process flow sheet relative to power consumption leads to liquefied oxygen costs of $60/tonne including annuitized costs of capital expenditure at a production rate of 1,500tonne/day. This plant produces oxygen by liquefying air and separating the oxygen from the remaining components, primarily nitrogen. Air consists of 78% nitrogen with a much smaller fraction of 21% oxygen. For every tonne of oxygen produced an equivalent 4 tonnes of nitrogen are produced for the same total operating cost. Operating costs for the plant are the same since the nitrogen and oxygen
both need to be separated from each other and the other minor components before sale and consumption regardless of if they’re needed or not. With a discount rate of 10%, 25MW of gross power, spares 5% of CAPEX per annum, labour of $1,000,000 per annum, and electricity price of $85/MWhr, this leads to a production cost of liquified nitrogen of 12$/tonne, exploiting this economy of scale. This is approximately 100 times less than diesel fuel which compensates for the cryogen being consumed at a rate ~100 times higher and supports the allocation of further effort to examine the infrastructural requirements in more detail.

Another beneficial factor considered was ventilation cost savings arising from elimination of contaminants. For mining operations in Ontario, Canada, as stated under regulation 183.1(3) of the Occupational Health and Safety Act “The flow of air must be at least 0.06 cubic meters per second for each kilowatt of power of the diesel-powered equipment operating in the workplace” [10]. The benefits are twofold. Firstly, flexibility to adjust the volume flow rate of mine ventilation air supplied. The cost of ventilating air varies with the cube of the volume flow rate. Doubling the volume flow rate increases ventilation costs by a factor of 8; reducing air flow to 79% of prior value halves the ventilation cost [11]. Secondly, reduced heat entering the mine ventilation air flow from diesel combustion as well as reduced volumes of required air flow also leads to cost savings. Ratings of refrigeration plants and total refrigeration effect requirements are both reduced. Mine ventilation air refrigeration loads exist at depths of 2,500m or greater in mines of Northern Ontario.

5. Supply
Depending on the location and demand of the mine a variety of options would need to be considered for the supply of liquid nitrogen to the site. Due to the large volume of liquid nitrogen required in this analysis one option is to purchase liquid nitrogen off site and have it delivered daily. This would require approximately 10 x 40 tonne trucks per day. This is not a universal solution because some mines in Northern Canada do not have year-round road access. An alternative scenario would be the construction of a surface pipeline providing enough liquid nitrogen to meet demand, provided there is already a surface plant within proximity of the mine location. A third possibility is construction of a liquid nitrogen plant on surface around the mine. An electrical grid connection of >20MW_e would be required for this option. Kunwar and Millar [12] articulated a concept using wind turbine work to drive compressors in liquefaction cycles with close to nil marginal energy input cost, but development of such a concept still requires further work.

Figure 2. Air separation plant at a pyrometallurgical facility [13].
Liquid air is a strong oxidant and consequently a potential hazard for mining at depth. This leads to the consideration of nitrogen only as a ‘cryofuel’ due to its inert nature. Assuming a liquefaction plant, as seen in Figure 2, is not readily available or located near the mine site, a plant would need to be constructed. For comparison, the air separation plant referred to earlier can produce 5,600tonne/day of liquid nitrogen equivalent to nearly 7,000,000L of per day. The capital cost of such a plant in 2017 is estimated at $50million and could be constructed in 20 months on a minerals industry site. In surface pyrometallurgical facilities supporting metal production there is a track record and experience in cryogen production at this sort of scale. For a single mine, a plant 1/17th of this size would provide enough cryogen to power an entire fleet of cryogenic mining equipment on average.

6. Distribution
At a daily consumption rate of 400,000L per day across 12-15 pieces of equipment per day it is important to establish a viable distribution arrangement. Mass and floor area in the mine cage, which is used to transport supplies underground, is restricted so that the largest volume of cryogen that could be transported in single track mounted Dewar vessel that could fit in the cage would be around 5,000L. The corresponding number of cage transits to supply 400,000L (80 @ ~10 minutes per transit @ 3,000m) is thus too high to be a practical option. Shaft and ramp time is the most prized resource required to support mine production processes. An alternative is a cryogenic pipeline going down the shaft/ramp or down a dedicated borehole. Cryogens can be piped long distances either horizontally or vertically. The challenge with the latter is dealing with 2-3km variations in head as the cryogen is piped underground. Special considerations also need to be given to the pipeline cooldown process, given the huge variation in head.

Shaft or dedicated borehole scenarios will adopt near identical materials for the cryogenic pipeline. There are slight differences in heat transfer rates but significant differences in infrastructure and cost. However, one of the serious issues with transporting liquid nitrogen down such a large vertical conduit is heat gain. It does not take much more than ambient heat to warm the cryogen to a temperature where it can freely evaporate. Provided the cryogenic pipeline is cooled down sufficiently, the pressure gained by the liquid head will increase its boiling point, impeding evaporation. This will require the cryogenic pipeline to be pressure rated upwards of 24MPa for a 3,000m extent. Although pipelines can withstand such pressures, storage and transfer infrastructure will quickly become expensive. Pressure reduction stations possibly incorporating energy recovery turbines will be necessary. This is common practice for the transportation of water in deep mines [14]. Passing the cryogen through a turbine could generate electricity for use elsewhere in the mine. The lower pressure will greatly reduce the cost of any equipment that would otherwise have highly pressurized liquid nitrogen within it.

Even with the cryogenic pipeline cooled down, an increase of temperature of 10-15°C will still be experienced by the liquid nitrogen which, with pressure maintained in the range of 1MPa, will still not evaporate. Provided the liquid nitrogen remains a liquid and is not near evaporation, cryogenic equipment will still operate as intended. It will be important to find a balance between operating pressure and operating temperature of the pipeline. It may be beneficial to sub cool the liquid nitrogen for its journey underground to allow for a larger pressure drop.

7. Pipeline heat transfer analysis and cooldown
One of the most complex design features of this study would be to properly conceptualize the temperature change of the liquid nitrogen travelling down the 3,000m pipeline. For this study, the temperature change from top to bottom can be estimated using the following relationship between temperature and enthalpy,

$$T_{LN2} = \frac{h}{c_p} + T_{LN1}$$  \hspace{1cm} (1)

where

$$h = \frac{Q_{avg}}{\dot{m}}$$  \hspace{1cm} (2)

and the average heat transferred to the fluid can be defined as,
$Q_{avg} = \Delta T_{air} / \sum R$

where each layer of material separating the liquid nitrogen from the ambient air has its own convective or conductive resistance relative to its thickness and thermal conductivity or heat transfer coefficient [15],

$$R_{conv} = \frac{1}{n_h(2\pi n_b)}$$

$$R_{cond} = \ln\left(\frac{r_n}{r_{n-1}}\right) / (2\pi k_h L)$$

Inspection of various pipe materials and insulation media comparing thicknesses and thermal conductivity values as well as fluid pipeline velocities, the temperature difference from top to bottom can vary greatly. Assuming a maximum fluid velocity of 2m/s [16] down the pipeline, a pipe nominal diameter of 6.35cm (2.5”), pipe thickness of 7mm, polyurethane insulation thickness of 5cm (0.0213W/mK) the temperature of the liquid nitrogen will increase by 10°C. The use of INVAR steel or expansion joints also needs to be considered to deal with the thermal contraction of the 3,000m vertical pipeline. Although vacuum insulated transfer lines would provide the greatest thermal insulation for the pipeline, this concept for mines assumes non-vacuum insulated transfer lines because maintaining vacuum in such a long pipeline in a mining environment is considered challenging and potentially costly. Practically, non-vacuum insulated transfer lines should have reduced maintenance and higher availability in this environment, and the consequences of loss of vacuum are eliminated.

Further work has established calculations to determine an appropriate cooldown procedure for the cryogenic pipeline. Detailed two phased flow fluid mechanics would be required to fully characterize such a procedure but for this study single phase calculations and empirical data has been used to estimate cooldown times [17]. Firstly, it is quickly evident that the liquid flow rate will have to be greatly reduced at the start of the chill down process to prevent air locking down the vertical pipeline due to friction losses. Once a sufficient section of the pipeline has been cooled down the liquid can be introduced at a reduced flow rate. Then once a sufficient pressure head of liquid has been established the flow rate of the liquid can be increased without worrying about air locking since friction losses will not exceed pressure head.

8. Storage

Large volumes of liquid nitrogen warrant large storage containers. The mainstream cryogenic industry has a large variety of viable cylindrical containers to store cryogens. Many of these options are eliminated when the restricted access route of mine supply shafts is considered. Larger storage vessels will have to be fabricated and commissioned in the subsurface increasing the cost in comparison to surface storage systems. In this conceptual study, cryogenic storage will be required above ground to provide a buffer between production and consumption of the liquid nitrogen. Underground storage options will require much more careful considerations. In terms of storage efficiency when dealing with substantial amounts of cryogens the front runner in storage containers is the LNG-type container used on surface. This container is a vertical cylinder with a flat bottom and a curved top allowing for the adjustments in the diameter and height of the cylinder to match the desired storage capacity. This option is favored when compared to the bullet-type cylindrical containers that are typically seen on surface at liquefaction plants and storage bays for multiple reasons. Vertical bullet-type containers may be installed on surface without having to worry about any overhead interference making them efficient due to the small footprint. Maximum diameters of raise bored excavations underground are in the range of 5-7m and so could be specially excavated to accommodate storage of this type and dimension. When vertical tanks are not viable, horizontal tanks can simply extend their length to match the desired storage capacity at the cost of additional surface area. Both options and their respective advantages quickly dissolve when considering an underground environment as surface area and volume don’t come cheap. Assuming an underground storage facility for a mine consuming 400,000L per day would need to store 2,000,000L, the storage options can be assessed. Appraising bullet-type tanks first, the largest containers on the market can store up to 1,000,000L in a 48.8m long with a 5.8m diameter cylinder. A LNG-Type [18] container could provide twice the capacity in a cylinder that’s 7.5m high and 18.5m in diameter and is,
by far, the much more volume efficient option. Infrastructure and excavation costs can be greatly reduced by opting for a LNG-type flat bottom underground storage room.

Another important consideration when conceptualizing storage infrastructure underground is the passive evaporation rate of liquid nitrogen that is kept in storage over time [17]. The rate at which heat leaks into the storage system is directly related to the surface area of the storage tank and can be mitigated further by designing a storage tank with a high volume to surface area ratio which further supports adoption for an LNG-type storage tank. By our estimates in a typical underground mine environment at 3,000m of depth, the ambient heat load experienced by a 7.5m high by 18.5m in diameter cylindrical tank filled with 2,000,000L of liquid nitrogen would be near 10kW. This heat load would evaporate 4500kg of liquid nitrogen per day if the tank was full, equivalent to a 0.3% evaporation rate which by all accounts is a very good rate considering the large volume of liquid stored. Oxygen Deficiency Hazard (ODH) analysis reveals that this is unlikely to pose a risk to worker health even in the confines of the underground workplace. A further trade off study can be done to evaluate the prospects of a condensation station to recapture any evaporated cryogen.

9. Preliminary risk assessment

Along with the conceptual design of the cryogenic infrastructure comes new hazards and risks that the mining industry has not yet explored. The major unwanted events associated with this research would be the potential for asphyxiation due to an oxygen deficient atmosphere, or physical damage to workers due to exposure to sub-cooled liquids and cryogenic gases. The Global Minerals Industry Risk Management framework incorporates Workplace Risk Assessment and Control (WRAC) and Bow-Tie [5] techniques to identify, assess and mitigate perceived risk.

| Step in operation | Unwanted event | Current controls | Likelihood | Consequence | Risk rating | Possible improvements |
|-------------------|---------------|------------------|------------|-------------|-------------|----------------------|
| Transportation of LN through pipeline | Leakage in pipe | Coupled pipes, inspected for leaks... | 1-2 | 2 | 1-4 | Welded pipes instead of coupling |
| Transportation of LN through pipeline | Ruptured pipe section | Pressure monitoring... | 1-2 | 2 | 1-4 | Pressure relief valves along the pipeline to prevent P > MAWP |
| Transportation of LN through pipeline | Workers come into direct contact with LN | Standard operating procedure... | 2-3 | 4 | 8-12 | Training and improvement of SOP’s |
| Transportation of LN down the borehole | Reboiling of LN into the rock mass | Borehole is cased and cemented | 1-2 | 1 | 1-2 | Different type of cement or grout, more thermal resistant |
| Depressurization | Failure of turbine or valves leading to P > MAWP | Regular inspection and... | 1 | 3 | 1-2 | Centralized monitoring system |
| Any step involving LN | Asphyxiation | Ventilation... | 1-2 | 5 | 5-10 | Emergency shut off, oxygen detection as PPE... |

Table 2 sets out a few of the highest risks identified (from 200+ considered) as a result of applying WRAC to the competing concepts and issues laid out earlier. The results of this analysis informed more detailed assessments of these risks and ongoing techno-economic assessment of the proposed use of cryogens in deep mining.
10. Notation

\( C_p \) = mean specific heat of liquid nitrogen; \( h \) = enthalpy; \( h_n \) = heat transfer coefficient of \( n^{th} \) layer; \( k \) = thermal conductivity; \( L \) = length of pipeline; \( m \dot{} \) = mass flow rate; \( Q \) = heat inflow; \( R \) = heat resistance; \( r \) = radius

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Acknowledgments

We wish to acknowledge the assistance of The Dearman Engine Company along with Air Products Ltd for their ongoing assistance in this research along with MITACS and the Northern Ontario Heritage Fund Corporation (NOHFC) for their financial assistance.