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Reintroduction of Cryogenic Refrigeration for Cold Transport

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ABSTRACT

The refrigerated product transport industry is actively looking for alternative approaches to present day diesel fueled, electro-mechanical refrigeration systems. Alternative systems look to reduce CO₂ emissions to meet operational criteria of minimal use of fossil fuels and for compliance with Kyoto Protocol criteria for elimination of HCFCs and their derivatives. Ideally the approaches should also minimize noise generation and be cost competitive.

Forty years ago there was a significant attempt to move to on-board cryogenic refrigeration alternatives. At the time the driver was not environmental sustainability issues as it is today, rather that cryogenic systems offered simpler more reliable functionality. The movement failed for several reasons, namely: (1) Cost of cryogenic fluids compared to cost of fossil fuels (fossil fuels were less than $1.00 /gal in the U.S.), (2) Limited reliable availability to cryogenic fluids in the U.S. (3) Limited operational capability. (single temperature control or operation) (4) Limited capacity. (8-hour operation without refill maximum) (5) Safety. No preclusion to inadvertent or premature entry to an O₂ depleted trailer atmosphere. Presently there is a new move back to cryogenic refrigeration. Today, designs for cryogenic refrigerated systems are significantly safer, more user-friendly, completely adaptable to operational requirements and are fully capable of long haul demand. Cryogenic refrigeration designs incorporate both direct and indirect injection of nitrogen, the later offering significant safety advantages over direct nitrogen injection.

The cryogenic manufacturing industry has expanded its production and distribution capability, with reliable, cost effective nitrogen supply in the 50 U.S. states and virtually every country in the developed world. The cost of cryogenic fluids has proven to be extremely stable in a global economy which has seen the cost of fossil fuels increase and vary significantly. Domestic supply of liquid nitrogen minimizes dependence on foreign suppliers of fossil fuels. Cryogenic production costs are based predominately on the cost of electricity.

Most importantly, the use of cryogenic fluids has a significantly lower effect on the environment from both global warming and ozone depletion standpoints. This includes the total effects resulting from the production of the fluids. There is data which provides a comparison of carbon footprints for a diesel driven vs. nitrogen refrigerated trailer cooling system on an annualized basis.

Annual consumptions of diesel, refrigerant and liquid nitrogen and CO₂ emissions: Total CO₂ emissions 31.8 tons eqCO₂/an for mechanical diesel systems and 13.9 tons eqCO₂/an for LIN a savings of 56% based on US EPA estimate. (http://www.epa.gov/oms/climate/420f05001.htm#carbon). This data is based on a refrigerated trailer at 37°F, 8 hours/d, 300 days/y. Assumed diesel consumption at 4 liters/hr; nitrogen consumption at 30 liters/hr.

Both ‘Direct’ and ‘Indirect’ nitrogen refrigeration systems quietly vent spent nitrogen vapor back to the atmosphere after cooling the trailer. Since the source for cryogenic fluids is our atmosphere, and nitrogen is totally recycled, 100% of the fluid used to cool the trailer is returned to the atmosphere with zero greenhouse effect.
This paper will illustrate the technical, economical and environmental reasons why the cryogenic systems will be successful.

1. INTRODUCTION

Cryogenic refrigeration is experiencing a re-birth as a viable alternative to mechanical systems for refrigerating transported product. There are many circumstances which have resulted in the transport industry searching for alternative refrigeration methods. These methods must not only minimize environmental impact but must also prove commercially viable. Alternative refrigeration methods must have minimal impact on transportation logistics.

The transport industry has looked at new developments with new technology. Coming to the fore are variations of a technology which was developed over 40 years ago. Circumstances and innovative improvements in the applied cryogenic technology have resulted in the reintroduction of cryogenic refrigeration.

2. HISTORY OF CRYOGENIC REFRIGERATION FOR TRANSPORT

Forty years ago there was a significant attempt to move to on-board cryogenic refrigeration alternatives. At the time the driver was not the environmental sustainability issues as it is today, rather that cryogenic systems offered simpler and more reliable functionality.

Three organizations spread over three continents developed direct injection cryogenic systems in this time frame. Strangely each was very similar in practice and each was patented in its home country. One was developed in Germany, the Messer Polar Stream system, one in Ukraine, The Verkin Institute LIN system and one in the U.S., the Liquid Carbonic CO₂ system. Each system utilized one or more channels which moved the liquid through the length of the trailer and released liquid cryogenic fluid through a series of orifices in the channel. Figures 1 and 2 are of the Ukraine system. Figure 3 is the Liquid Carbonic System.

![Figure 1](Ukraine Original Truck System)

![Figure 2](Ukraine Original Trailer System)
2.1 Reasons for interest in cryogenic systems

Cryogenic refrigeration performance significantly has always exceeded that of mechanical systems both for the rate of temperature pull-down and the ability to accurately maintain temperature set points. Independent measurement recently has indicated cryogenic systems have output power in excess of 3 times mechanical systems.

Temperature distribution throughout the trailer was superior to that of mechanical systems because of the lack of sensitivity to wall roof and floor blockages.

Cryogenic systems operated clean and with minimal noise since there are minimal to virtually no moving parts required for operation which can generate noise and no fossil fuels are required.

2.2 Reasons why earlier cryogenic systems failed

- The cost of cryogenic fluids compared poorly to cost of fossil fuels. Fossil fuels were less than $1.00 /gal in the U.S. ($0.26/ltr), liquid nitrogen (LIN) cost approximately $0.08 per kg. For +4°C operations it used approximately 40 kg per hr or $3.20 / hr. Mechanical systems used approximately 2 liters diesel / hr at a cost of $2.00 / hr. Even with the significant reduction in maintenance and repair the operational cost of LIN far exceeded the cost of diesel. Liquid carbon dioxide was even more costly. Diesel cost was relatively stable during the period of introduction of LIN systems.

- Limited availability of cryogenic fluids in the U.S. Air separation plants that manufacture nitrogen were not present in all of the 48 continental states. In the states where it did exist, auxiliary supply depots were limited. The supply and distribution of LIN was considered limited and inefficient.

CO₂ was even less readily available, since its production was dependent on close proximity to industrial manufacturing processing.

- Delivery of cryogenic fluids proved to be unreliable and costly. Delivery of LIN was dependent on users monitoring their inventory. Transport of LIN was not logistically managed as it is today.

- There was limited operational capability. (single temperature control or operation) The method used for dispensing the liquid nitrogen precluded compartmentalized transport. Temperature balance between bulkheads was poor. Snow effect caused top freeze. No method in place for monitoring.
the temperature inside; only temperature entering the chamber. This was improved in recent years for the systems remaining in operation.

On-board nitrogen capacity limitations restricted delivery tours to maximum 8-hour operation without refill. Cryogenic tanks were extremely expensive. Unit capacity was very limited; 400 liter tanks were the maximum capacity tanks manufactured in sufficient quantities. Cryogenic tanks should never be completely emptied (keeping them cold). Therefore, only 350 liters of liquid nitrogen were available for use from a 400 liter tank. At best, this capacity provided 9 hours of run-time for +4°C operation and 7 hours for -10°C operation if food products were pre-cooled to trailer set point temperatures. If significant differential existed between food products and trailer set temperatures, nitrogen consumption increased at least 20% and operational time was reduced accordingly.

- Safety issues were a problem.
  There was no preclusion to inadvertent or premature entry to an O2 depleted trailer. No interlocked, fail safe entrance barricades were in place to warn against unsafe entrance. Remote oxygen sensing technology was not yet developed to monitor O2 content in the refrigerated chamber. There was no method in place to monitor the O2 content in the refrigerated chamber during the operational phase. Battery operated O2 sensors were not reliable in temperature environments below -10°C. Only direct injection systems were in place during this time. Indirect systems were studied but operational, performance and design limitations precluded any incentive to bring indirect or hybrid systems to a production phase.

The above factors ultimately led to the rejection of cryogenic transport refrigeration in two of the three countries. Germany continued to maintain about 1,000 units in operation, but no significant growth for direct or indirect nitrogen refrigeration systems occurred. It must be noted that the refrigeration performance of cryogenic nitrogen refrigeration systems always outperformed the existing mechanical systems under comparable conditions.

3.0 WHY CRYO-TRANS TECHNOLOGY WILL BE ACCEPTED TODAY

Market conditions different today vs. 40 years ago present a unique environment for the successful re-introduction of Cryogenic-Transportation (Cryo-Trans) refrigeration systems. Today’s fluctuation in the price of diesel fuel is one obvious change, but noise and emission issues with mechanical refrigeration are equally significant reasons driving the development of alternative refrigeration methods. Market resistance to cryo-trans systems may be easier to overcome today than previously encountered. Today’s market needs are strong enough to drive a successful re-birth of the Cryogenic Transportation application.

3.1 Economic and Fuel Independence Reasons

When diesel fuel prices spiked above $4.50 /gal in the US, liquid nitrogen as an expendable refrigerant became a viable economic alternative to diesel driven mechanical refrigeration. In fact, diesel prices in the $2.50-$3.00 /gal range can provide favorable economics for Cryo-Trans refrigeration in certain operating modes.

Factors such as trailer temperature, outside temperature, number of stops, and trailer insulation are needed to accurately determine economic viability. There is no rule of thumb that applies, but a database of operating costs from over 1,200 Cryo-Trans trailers in service in Europe documents nitrogen based refrigeration can cost less to operate and maintain than diesel powered mechanical units.

The electricity used for nitrogen production in the US is predominately generated from power plants using domestic fuel sources such as natural gas and coal. By powering Trailer Refrigeration Units (TRU’s) with nitrogen that was
produced with domestic electricity, we can lower transport refrigeration operating costs while reducing our dependence on foreign generated oil.

3.2 Technological
Initial Polarstream Cryo-Trans systems introduced in the 1960’s were thermally less efficient and significantly less safe than the current designs of Cryo-Trans systems. DOT certified nitrogen trailer tanks manufactured today have better insulation and improved durability than comparable tanks from the 1960’s. Nitrogen trailer tanks today have larger capacities offering greater distribution operating ranges. In addition, today’s nitrogen injection systems transfer refrigeration energy more efficiently from trailer tank to trailer enclosure thereby providing lower operating costs.

Matching this improved injection efficiency with today’s new, super-insulated trailers provides an attractive argument for an economic alternative to diesel fueled mechanical refrigeration.

3.3 Niche Market Situations
Operating restrictions in certain markets has mandated changes in the distribution of refrigerated and frozen goods. Metropolitan and suburban markets impose noise restrictions on delivery vehicles both for day and night time deliveries. One example is a creamery in Northern California, Clover Stornetta, Petaluma, CA, that converted to a hybrid CO2 based refrigeration system 15 years ago solely for noise reduction reasons. A twenty trailer fleet of mechanical refrigeration units, loaded for delivery throughout the night, vibrated neighboring residential windows. The problem grew to the point where the city council imposed a “fix-it or relocate” ultimatum if the noise problem was not corrected. The CO2 system is no longer in operation, but at the time eliminated the noise problem, and the Creamery did not have to relocate operations.

Underground delivery to hotels or other institutions is another market that can benefit from Cryo-Trans systems. The operation of mechanical refrigeration is restricted when making these deliveries and can lead to non-recoverable loss of refrigeration, the warming up of refrigerated products and obvious quality control problems. Cryo-Trans systems can operate noise and emission free in this delivery mode, providing a solution for this niche market. The ability of Cryo-Trans systems to rapidly restore refrigeration provides additional operating flexibility.

3.4 Cryogenic Fluid Availability
Liquid Nitrogen is manufactured by compressing and cooling air to liquefaction temperatures, then distilling it to its liquid oxygen, liquid nitrogen and liquid argon component parts. Eighty per-cent of the production costs are electrical energy related. Delivery costs are based on distribution expenses determined by mileage between production plants and use points. Reliable U.S. domestic nitrogen production is available in virtually every commercial market. This is a dramatic change from when cryo-trans technology was first introduced.

3.5 Environmental Drivers
The California Air Resources Board’s (CARB) regulation change effective December 31, 2009 requires Trailer Refrigeration Units (TRU’s) older than 7 years to reduce particulate matter (PM) emissions by 50%. Those same units must reduce PM emissions by 85% by year 2015. This continues until year 2013 when TRU’s with CARB compliant engines become available. (www.arb.ca.gov/diesel/tru.htm)

California transport company options for compliance this year include replacing the entire TRU with a new 2010 unit, replacing the TRU engine with a new one, or installing a Diesel Particulate Filter (DPM) on each TRU 7 years old, each of which extends compliance only 7 years. Alternative technologies such as Cryo-Trans TRU systems provide a 2013 CARB compliant solution today.

Carbon footprints of nitrogen based Cryo-Trans systems provide an immediate reduction in carbon emissions on top of achieving a CARB compliant solution in California. Nitrogen consumed in Cryo-Trans systems has significantly
lower carbon emissions than diesel fuel powered TRU’s. The exact amount depends specifically on the production source for diesel fuel and nitrogen, and TRU point of use to take into account specific production and distribution component emissions for diesel and liquid nitrogen. An example of a CO₂ emission comparison for a US location in California is illustrated in the table below.

<table>
<thead>
<tr>
<th>Per vehicle</th>
<th>Mechanical cooling</th>
<th>Liquid Nitrogen Cooling</th>
<th>( \text{USA} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>9600 l diesel/y</td>
<td>72,000 liters LIN/y = 46,541 m³ LIN/y</td>
<td></td>
</tr>
<tr>
<td>Emission factor(^1)</td>
<td>734 gram / ltr of diesel</td>
<td>274g eqCO₂/Nm³</td>
<td></td>
</tr>
<tr>
<td>CO₂ emissions</td>
<td>26.7 metric-tons eqCO₂/y</td>
<td>13.9 metric-tons eqCO₂/y</td>
<td></td>
</tr>
<tr>
<td>Refrigerants</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Losses(^3)</td>
<td>1.35 kg/y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission factor(^2)</td>
<td>3743.4 kg eqCO₂/kg of fluid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ emissions</td>
<td>5.1 tons eqCO₂/y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>31.8 metric-tons eqCO₂/an</td>
<td>13.9 metric-tons eqCO₂/an</td>
<td></td>
</tr>
<tr>
<td>Savings</td>
<td></td>
<td>56.3% reduction</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1 Emission Comparison of a Diesel vs. Nitrogen TRU System for a California Location**

### 3.6 Technology Variations now in Place

Present day Cryo-Trans systems are offered in 3 generic designs, namely:

1. Cryo-Trans Direct (CTD) Direct nitrogen injection into trailer
2. Cryo-Trans Indirect (CTI) Indirect nitrogen injection through a heat exchanger
3. Cryo-Trans Hybrid (CTH) Combination direct or indirect + mechanical

**Cryo-Trans Direct** (CTD) involves the direct injection of cold nitrogen liquid/vapor into the insulated trailer body. CTD is the method first introduced in the 1960’s under the Polarstream trade name. Direct injection of nitrogen is said to be the most efficient utilization of nitrogen’s refrigeration energy (BTU’s), but carries the risk of low oxygen levels within the trailer. Figure 4 depicts the CTD system.

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\(^1\) Data based on operating a refrigerated trailer at 37°F, 8 hours/day, 300 days/year. Assumed diesel consumption at 4 liters/hour; nitrogen consumption at 30 liters/hour.

\(^2\) [http://www.epa.gov/oms/climate/420f05001.htm#carbon](http://www.epa.gov/oms/climate/420f05001.htm#carbon)

\(^3\) Assumed 15% of the refrigerant is lost each year per vehicle

\(^4\) Emission factor of R404a fluid in kg eqCO₂ per kg of fluid; ADEME, Bilan Carbone®, Calculation of emission factors, version 5
Several overlapping safety controls are incorporated in today’s CTD systems that were not in place on former Polarstream trailers. Continuous oxygen monitoring within the trailer is tied to trailer entry barrier systems that prevent trailer entry until fresh air has replenished trailer atmosphere to above 19.5% O2. Applications where fewer deliveries and door openings occur offer higher efficiencies for CTD systems. Applications where full trailers completely unload at their destination offer attractive economics for CTD systems.

Cryo-Trans Indirect (CTI) represents the system where nitrogen chills a heat exchanger mounted inside the trailer that cools air circulated across this exchanger. Spent nitrogen vapors from the heat exchanger are safely vented outdoors, hence indirect cooling. CTI systems can be designed as single or multiple temperature zone trailers. CTI offers the safety advantage of being able to enter the trailer at any time without risk of low oxygen levels. Figure 5 depicts the functionality of the CTI system.

CTI has the potential to be energy competitive with comparable CTD systems, and are potential to be economically competitive where many trailer stops and trailer door openings occur. Door openings for CTD systems require fresh air purging of trailer air space, which in warm weather conditions increases nitrogen consumption. Conversely, CTI systems allow personnel to enter trailers immediately after door openings without disturbing air space. This helps reduce refrigeration demand, and in turn nitrogen consumption.

Cryo-Trans Hybrid (closed system): incorporates both mechanical and CTI. Figure 6 depicts a hybrid system concept. A heat exchanger, an insulated vessel and a monitoring system are installed in addition to a mechanical cooling unit in order to boost refrigeration capacity. The main advantages are a quicker pull-down after door openings and a reduction or elimination of noise and emissions depending on if the mechanical unit is working at lower speed or is completely turned off.
Regardless of the style of system, Cryo-Trans refrigerated trailers are designed with greater sophistication, reliability and efficiency than the initial Polarstream nitrogen trailer systems. Each system has its own advantages based on mode of operation it serves offering cost effective solutions to refrigerated transportation.

### 3.7 Operating Cost Differential

The CTD system has virtually no moving parts. There are no engines or refrigerant compressors, only small fan motors used for exhausting nitrogen from the trailer to reach safe oxygen levels prior to entry. The CTI systems utilize circulation fan motors for distribution of cooled air. The elimination of engine driven refrigerant compressors drastically reduces maintenance and associated downtime. This minimizes TRU maintenance labor and replacement parts while increasing the trailer’s available operating time. This can make the overall operating cost of Cryo-Trans systems more attractive than mechanical refrigeration systems.

### 4.0 SUMMARY

Modern Cryogenic-Transport refrigeration systems provide a reliable and cost effective alternative to diesel driven mechanical refrigeration for the distribution of refrigerated foods. Cryo-Trans systems provide an immediate 2013 CARB compliant solution to California based Transport Refrigeration Units. Nitrogen based Cryo-Trans systems reduce TRU carbon footprints, TRU maintenance and eliminate noise and diesel particulate pollution.

Liquid nitrogen (LIN) appears to be the most viable cryogenic operating fluid for the reintroduction of this alternative technology. The price stability and domestic availability of liquid nitrogen reduces dependence on foreign oil for fueling TRU’s.

Cryo-Trans entry into the Refrigerated Transport marketplace has been difficult because of a history of negative experiences. However, new Cryo-Trans technology development along with changing environmental and energy policies have helped re-introduce Cryo-Trans systems as a viable alternative solution for the transport of refrigerated and frozen goods.