Dearman.

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To: Rodney Hill
California Air Resources Board
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From: Michael Ayres
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Subject: **Dearman comments on CARB Draft Technology Assessment: Transport Refrigerators**

Introduction

Dearman appreciates the opportunity to comment on the technology assessment "Draft Technology Assessment: Transport Refrigerators, August 2015," by the California Air Resources Board. We appreciate the methodical approach to assess the technical readiness, feasibility, suitability and impacts of various technologies as a matter of responsible policy development and rulemaking process. Dearman recognizes that this is an extremely challenging and complex task, and we stand ready to assist.

Dearman is a technology company developing clean cold and power systems. Its technologies harness the unique properties of liquid air or liquid nitrogen to make zero-emission power and cooling available for use in a range of applications, including transportation, logistics and the built environment.

The most advanced application of Dearman technology is to provide high efficiency, zero-emission transport refrigeration units (TRUs). More efficient than previous generations of cryogenic TRUs and far less polluting than diesel systems, Dearman's transport refrigeration system could provide a commercially attractive zero emission alternative to existing technology.

1. GHG emissions
Chapter III – Assessment of potential transport refrigeration technologies

To inform the recommendations made in the assessment, each technology/fuel's characteristics have been described and analysed individually – in particular the anticipated GHG emission rate reductions associated with them. In estimating a TRU/TR's total GHG emissions, the assessment takes into account[1]:

- A system's Well-to-Tank (WTT) GHG emissions – consisting of GHG emissions from fuel production and distribution to refuelling stations (either public or private)
- A system's Tank-to-Wheels (TTW) GHG emissions – consisting of fuel use by the vehicle/technology while in operation

Dearman wishes to formulate the following comments regarding this methodology.

[1] See Chapter III and Appendices III.A-1 to III.E-2

1.1. High GWP HFC refrigerants

The assessment highlights[2] the fact that baseline mechanical vapour compression systems use high-GWP hydrofluorocarbon (HFC) refrigerants regulated by U.S. EPA, which CARB has previously proposed the prohibition of. While the assessment discusses this issue qualitatively, it does not do so quantitatively in its WTW GHG Emission rate comparisons.

The following outlines the reason why Dearman believes the HFC issue is significant and should be quantified in the assessment.

During normal operation, TRUs/TRs tend to leak part of the high-GWP refrigerants they are charged with to the atmosphere (20-25% every year[3]). In fact, a common annual maintenance operation for these systems consists in replacing the leaked refrigerant fluid to ensure most efficient system operation. The impact that high-GWP refrigerant leakage has on the environment can be quantified using its equivalent CO_2 emissions – since a substance's GWP is defined as the equivalent amount of CO_2 emitted to the atmosphere. For instance R404a, the refrigerant used in most mechanical vapour compression TRUs, has a GWP of 3,922 – meaning that every kg of R404a leaked is equivalent to releasing 3,922 kg of CO2 to the atmosphere[4]. The contribution of HFC leakage to a system's annual GHG emissions can therefore be calculated by:

$$TRU\ HFC\ charge\ (kg) * Annual\ leakage\ (\%) * HFC\ GWP = Annual\ GHG\ emissions\ from\ HFC\ leakage\ (kgCO_2e)$$

Applying this to a baseline truck TRU with a 3kg R404a charge would give:

$$3\ (kg) * 20\% * 3{,}922 = 2{,}350\ kgCO_2e/year$$

For a truck TRU used 2,000 hours per year[5], this represents an additional 1.17 $kgCO_2e$/hour – 12.5% of the system's total WTW GHG emissions[6]. Trailer TRUs typically carry higher refrigerant charges (6-8 kg), meaning that for a baseline trailer TRU the incremental GHG emissions would represent:

$$6\ (kg) * 20\% * 3{,}922 = 4{,}700\ kgCO_2e/year$$

Or an incremental 17.5% over the current WTW GHG estimate for trailer TRUs[7].

This realisation of the significance of HFC leakage has motivated the recent phase-down regulations on high-GWP refrigerants in Europe by the European Commission[8]. In the United States, the U.S. EPA is able to effectively ban the use of

[2] Chapter II Section G, p. II-13
[3] https://www.ipcc.ch/pdf/special-reports/sroc/sroc04.pdf#page=6
[4] Chapter II Section G, p. II-13
[5] CARB 2015 TRU assessment
[6] Table ES-1: Conventional 2015 truck TRU, 2015 fuel, emits 8.26 kg-GHG/hr
[7] Table ES-1: Conventional 2015 trailer TRU, 2015 fuel. emits 11.01 kg-GHG/hr
[8] http://ec.europa.eu/clima/policies/f-gas/index_en.htm

certain high GWP refrigerants through the Significant New Alternatives Policy (SNAP) program[9].

In the California Air Resources Board technology assessment, taking this fact into account will modify the WTW GHG emissions rate for baseline diesel TRUs, as well as the estimates for systems using mechanical vapour compression systems – all-electric plug-in/battery/solar trailer TRs, all-electric H2 fuel cell trailer TR, all-electric plug-in/battery/generator truck TRs, and CNG and LNG systems are all such systems. These transport refrigerators, despite using alternative fuels/power generation equipment, rely on the same mechanical vapour compression refrigeration machines for which HFC leakage will remain an issue.

Taking this into account in the calculation will impact the WTW GHG emission rates presented in table ES-1.

1.2. Technology manufacturing/disposal

Another significant contributor to a technology's total GHG emissions is known to be the technology's manufacturing and disposal processes. Recently, a number of studies have highlighted the fact that as powertrains and fuels' increasing efficiencies contribute to lower emissions during the driving phase of vehicles, the use of tailpipe CO_2e emissions will become "almost irrelevant in terms of true carbon profiles of future vehicles"[10]. For instance a Ricardo report on this issue indicated that production emissions of a battery electric vehicle could total more than 50% of the vehicle total life cycle emissions[11]. However unlike for HFC leakage, quantifying the equivalent CO_2 emissions resulting from these processes is a complex task and could require significantly more resources than available for this assessment.

Dearman recommends that the assessment recognises that as new technologies reduce emissions from fuel usage, emissions from product manufacturing and disposal become relatively more important and an effort to quantify them should be made. As demonstration projects are being developed, we believe resources should be allocated to investigating GHG emissions resulting from product manufacturing and disposal.

2. All-electric Plug-in/Generator/Battery TRs
Chapter III.A

The type of equipment that is being described in the CARB TRUs/TRs technology assessment as all-electric plug-in/generator/battery TR (p. III-1) is a technology that is well-established in Europe, and in fact commonly used on trucks – in particular trucks used for urban delivery-type missions[12]. Typically these transport refrigerators are operated in the following way:

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[9] http://www.epa.gov/ozone/snap/index.html
[10] http://www.worldautosteel.org/new-study-highlights-the-need-for-a-life-cycle-assessment-approach-to-vehicle-emissions-regulation/
[11] Preparing for a life cycle CO_2 measure, Ricardo, Low Carbon Vehicle Partnership, 2011
[12] Food transport refrigeration, S. A. Tassou, G. De-Lille, J. Lewis, Brunel University

- When stationary, the TR is plugged into shore power and runs from grid electricity
- When on the road, the system is either powered from:
    - an alternator mounted on the vehicle's main engine
    - batteries if no power is available from the vehicle's main engine

Because small non-road engines are submitted to less stringent efficiency and performance standards than larger road vehicle engines, the vehicle engine is generally more energy efficient that non-road engines. While this is widely accepted in the industry, it is not the only factor having an impact on the fuel efficiency of transport refrigerators.

Because the batteries for these TRs are sized to only provide emergency power provision, they are not capable of sustaining high loads for continuous periods of time. This in turn means that the refrigeration machine is highly dependent on the vehicle engine's operating conditions. When the vehicle engine's load factor is low/medium (vehicle cruising on the highway for instance) the added load from the refrigeration machine (through the alternator) will bring the engine to operate at a more efficient point therefore having an overall positive impact on fuel efficiency. However if the truck engine is idling when stopped in traffic the refrigerator load will be very low for an engine designed to power a heavy duty truck (over 10 times lower than the maximum power output). The result is that estimating whether the overall impact on fuel consumption from replacing the non-road engine by a vehicle engine driven alternator is positive or negative is a complex task. This, combined with the fact that these systems still use diesel as the primary source of energy while on the road, means that in Europe these systems aren't considered a route towards truly clean transport refrigeration.

In an attempt to illustrate the difficulty of estimating fuel consumption impact from these units, we propose to apply the method used in Appendix III.A-1 (to estimate an all-electric truck TR's fuel consumption).

In Appendix III.A-1 (p. Appendices-1), the calculation provided is as follows:

i. Average power output of the vehicle engine driven generator is 3.225 KW[13]
ii. Taking the inefficiencies of the belt, engine, and generator into account gives the power requirement from the vehicle engine:
    - Engine – 45%
    - Generator – 70%
    - Belt – 96%

$$\frac{3.225\ kW}{0.45 * 0.70 * 0.96} = 10.7\ kW$$

[13] Aura Systems, Inc. "White Paper for All-Electric Transport Refrigeration: Intra-City Mid-Size Refrigeration Trucks." 2012.

iii. To determine fuel use rate, the Lower Heating Value for ULSD, which is equal to 127,464 BTU/gal[14], is converted to:

$$\left(127{,}464\frac{BTU}{gal}\right) * \frac{1{,}055J}{BTU} * \frac{1W}{\left(\frac{J}{s}\right)} * \frac{1kW}{1{,}000W} * \frac{1hr}{3{,}600s} = 37.3\ \frac{kW-hr}{gal}$$

iv. Vehicle engine fuel use rate due to the refrigeration system load is then:

$$Diesel\ fuel\ use\ rate = 10.7\ kW * \frac{1\ gal}{37.3\ kW-hr} = 0.287\ gal/hr$$

Given that the baseline fuel use rate for a standard non-road engine is assumed to be 0.6 gal/hr, the baseline truck TRU engine efficiency can be derived from reversing the steps above:

i. In order to compare both systems "like for like", the average power output of the non-road auxiliary diesel engine is taken as 3.225 KW[15]

ii. To determine the energy input rate to the non-road engine, we must account for the inefficiencies of the non-road engine (no belts or alternators needed in this configuration):
   - Engine – X%

$$\frac{3.225\ kW}{X\%} = P\ kW$$

iii. The fuel use rate as it was calculated before does not vary so[16]

$$\left(127{,}464\frac{BTU}{gal}\right) * \frac{1{,}055J}{BTU} * \frac{1W}{\left(\frac{J}{s}\right)} * \frac{1kW}{1{,}000W} * \frac{1hr}{3{,}600s} = 37.3\ \frac{kW-hr}{gal}$$

iv. The fuel use rate equation can be written as:

$$Diesel\ fuel\ use\ rate = P\ kW * \frac{1\ gal}{37.3\ kW-hr} = \frac{3.225\ kW}{X\%} * \frac{1\ gal}{37.3\ kW-hr} = 0.6\ gal/hr$$

Therefore the non-road engine efficiency is given by:

$$X\% = \frac{3.225\ kW}{0.6\ gal/hr} * \frac{1\ gal}{37.3\ kW-hr} = 14.4\%$$

Applying the fuel use rate calculation to baseline truck TRU non-road engines with the inputs used in Appendix III.A-1 indicates that non-road engines used in diesel

[14] "Detailed California Modified GREET Pathway for Ultra Low Sulfur Diesel (ULSD) from Average Crude Refined in California," February 2009, Section 5: Carbon Emissions from ULSD Combustion, Table 5.01.
[15] To provide a similar amount of cooling, both the non-road engine and the vehicle engine driven units require the same power output
[16] "Detailed California Modified GREET Pathway for Ultra Low Sulfur Diesel (ULSD) from Average Crude Refined in California," February 2009, Section 5: Carbon Emissions from ULSD Combustion, Table 5.01.

TRUs would only be on average 14.4% efficient, while the engines powering trucks and trailers are on average over 3 times as efficient (45%). While it is recognised that there is a performance gap between road and non-road engines[17], the results from this calculation indicate a difference which appears unrealistic. Manufacturers of truck TRU engines typically claim efficiencies of ~30% (see Kubota[18]) while the industry generally agrees that real-life efficiency is closer to 20-25%. One likely explanation for the large difference observed in the calculation is that baseline truck TRUs provide higher cooling capacity than the Auragen system – in order for both systems to be compared on a like for like basis, the all-electric generator driven system diesel fuel rate should be adjusted to reflect its lower cooling capacity, therefore lower fuel efficiency than the one claimed in Appendix III.A.

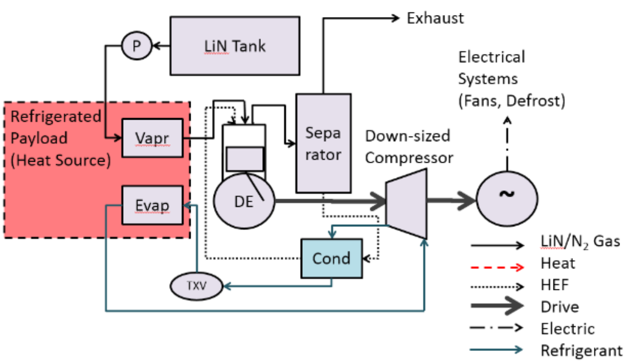
3. Cryogenic TRs

3.1. Technology description

Chapter III Section E, p. III-39

The discussion in this section addresses all TRs making use of cryogenic liquids, and distinguishes these systems between direct and indirect TRs. While most cryogenic TRs fall in either of these categories, Dearman's view is that its TR system falls in a 3rd sub-category which should be explicitly distinguished – the cold and power systems (which would include the Reflect Scientific system).

In the Dearman system, refrigeration is provided in two ways in order to improve both efficiency and operational performance.



Dearman transport refrigeration system

First, latent heat from vaporization of the liquid nitrogen is extracted from the refrigerated compartment. This is similar to an indirect TR and uses comparable technology. Unlike indirect systems, instead of releasing the warmed nitrogen to the atmosphere, the warmed nitrogen then drives the Dearman engine.

The Dearman engine performs two functions: firstly, it operates a generator so that the TR powers its own electrical systems, and secondly, it powers a down-sized conventional mechanical vapour compression cycle. This cycle must reject heat through a condenser, and this heat is used to warm the heat exchange fluid for the engine – a synergy that raises the efficiency of the engine and vapour cycles simultaneously. The system therefore is an efficient, self-contained, zero-emission refrigeration device, with downsized vapour compression cycle (only 1/3 of the baseline system size due to the cooling available from liquid nitrogen).

[17] Food transport refrigeration, S. A. Tassou, G. De-Lille, J. Lewis, Brunel university

[18] http://www.kubota.co.uk/product-range/engines-uk/product-range/super-mini-series/d722/

The two key benefits of this architecture are:

a. Direct and indirect cryogenic TRs that are not equipped with a means to recover power (like the Dearman engine) require electrical power to operate their electrical systems (e.g. air circulation fans, control and safety systems …). Power consumption from air circulation fans is deceptively high, therefore these systems typically draw electrical energy from the main vehicle engine – having an impact on the vehicle fuel consumption and therefore the overall GHG/criteria pollutant emissions.
   Dearman's TR eliminates the need for this by generating its own power.
b. While indirect cryogenic TRs treat the warmed cryogenic "fuel" as waste and release it to the atmosphere after it has passed through a heat exchanger, the Dearman TR recovers the useful mechanical energy in the gas to generate both electrical power and more cooling from the vapour cycle.
   This significantly reduces the amount of cryogenic fuel required to produce a given amount of cooling – in other words it greatly increases the vehicle range, increases operational efficiency and reduces the environmental impact of the system's use.

3.2. Technology readiness
Chapter III Section E, p. III-42

"In Europe, the cost of cryogenic fuel is comparable to the cost of diesel"

Dearman's experience is that the economics of liquid nitrogen distribution depend primarily on end-users' scale of consumption. As an example a fleet of 1-2 vehicles would be unlikely to have attractive economics because the liquid nitrogen would have to be delivered by smaller vehicles stopping frequently to supply numerous end-users – which increases transport costs to the liquid nitrogen supplier. Optimum economics can be achieved when deliveries of 15 to 20 tonnes of liquid nitrogen take place in a single drop – given the refrigerated vehicles' usage patterns this requires a minimum of around 10 vehicles on a single site. Clustering vehicles also helps reducing refilling infrastructure costs to end-users as a single bulk tank and refilling system can be used to supply tens of vehicles. A detailed discussion of the cost of producing liquid nitrogen can be found in the *Liquid Air on the Highway*[19] report.

In light of these comments, Dearman's view is that demonstration of multiple vehicles on a single end-user site should be incentivised in order to create favourable economic conditions.

3.3. Economics and emission reductions
Chapter III Section E, p. III-46

In light of previous comments regarding both GHG emission rate calculations and the different nature of the Dearman refrigeration system (in particular its reduced fuel consumption) compared to other cryogenic systems, Dearman's view is that its cold and power cryogenic technology will in practice achieve higher WTW GHG emission

[19] http://www.liquidair.org.uk/files/highway-guide.pdf

reductions and better economics than the ones calculated in the technology assessment. Dearman recognizes that quantifying these benefits is a challenging and complex task, and we stand ready to assist.

3.4. Key performance parameter issues and deployment challenges *Chapter III Section E, p. III-49*

"Key performance parameters include […] capital costs and operating costs".

In light of the previous comment regarding capital costs and the fact that cryogenic trailer TRs are shown (p. III-47) to have lower annual operating costs than the baseline diesel TRUs, Dearman's view is that capital and operating costs for cryogenic TRs should be not considered as issues/challenges but rather as advantages.

"Key performance parameters include […] safety issues around potentially oxygen deficient atmospheres".

Approximately 235,000 tons of liquid nitrogen are produced every day in the United States, therefore adequate safety procedures are well known and routinely followed. Cryogenic equipment, including storage tanks and piping are manufactured to American Society of Mechanical Engineers (ASME) specifications and Department of Transportation (DOT) codes for temperatures and pressures involved.

Dearman's view is that – at least for indirect systems where nitrogen is never directly sprayed inside a closed compartment – these safety concerns, despite being realistic, should not be regarded as deployment challenges. Given the size of the industrial gas industry, there is considerable experience in handling such liquids therefore following standard training and safety procedures will ensure safe system operation.

"Rate of release for the cryogenic fuel is affected by temperature differential between atmospheric and product temperature, door openings, and thermal efficiency of the cargo van. Minimizing door opening frequency and duration will minimize need for temperature recovery."

While this statement is true, Dearman's view is that this applies to any transport refrigeration technology – door opening frequency as well as temperature differential between atmospheric and product temperature will affect the energy consumption of all transport refrigeration technologies. For this reason, Dearman's view is that it should not feature in the performance issues and deployment challenges for cryogenic TRs, but rather in section J – Efficiency.

"In addition, fuel storage and dispensing infrastructure adds to the cost due to lack of availability of public cryogenic dispensing facilities"

While this is true, infrastructure cost for cryogenic fuel storage can be shared between a large number of vehicles which is not the case for electric charging infrastructure for example. A cryogenic fuel refilling station is operated very similarly to a diesel refilling station, therefore a unique bulk storage tank and refilling point can be used for a large fleet of vehicles and the infrastructure cost for an appropriately sized refilling station will typically be a fraction of the TR's annual operating cost.

"In the U.S., the cost of diesel fuel is generally much less expensive than the cost of the cryogenic fuel, but in Europe the cost of diesel is comparable to the cost of cryogenic fuel"

This follows from our previous comments regarding the economics and technology readiness of cryogenic TRs. Dearman has developed, in collaboration with UK academics, simulation tools showing that the Dearman cold and power technology's reduced fuel consumption improves the economic case vs. baseline diesel TRUs significantly. In fact it shows that despite the less favourable situation (for cryogenic systems) in the U.S. the performance improvements are sufficient to close the cost gap with baseline TRUs.