**ABSTRACT**

This paper deals with the advantages, disadvantages, promise and system design implications of CO₂ refrigerant in the industrial food processing and cold storage industries such as industrial air conditioning, dairy, chilled and frozen food, meat, ice cream, freeze drying and so on. Examples are given of possible applications.

CO₂ advantages are zero ODP and GWP potential, very low cost, universal availability, non toxicity, non-flammability, relatively high continuous exposure levels of 5,000 ppm, very small compressor swept volume, small piping sizes and so on.

Specific characteristics of CO₂ are relatively high working pressures, low critical point (+31°C), relatively high triple point (-56.6°C) and high density compared to air. The latter may represent a certain danger to human health if CO₂ should leak uncontrolled into confined spaces.

The system design implications are many for industrial applications of CO₂ such as:

1. A volatile secondary refrigerant by condensing CO₂ vapour in a PHX using a conventional two stage, single stage or economized ammonia system.
2. As a CO₂ to NH₃ cascade system with CO₂ at say -55 to -8°C and NH₃ at say -10°C/ +35°C.
3. As a two stage CO₂ system in future where the supercritical discharge pressures can provide the temperature glide for reasonable quality heat recovery and so on. This requires development of high pressure compressors and suitable lubricants.

Issues such as OH&S, CO₂ and oil miscibility, design and test pressures, defrosting and fade-out vessels, COPs and so on are discussed.

The relatively high allowable suction line pressure drop per degree C at low evaporating temperatures (compared to NH₃) has favourable implications for efficient evaporator design as high circuit mass velocities would be permissible without generating high pressure drops. The same applies to wet suction system risers.

In conclusion, the writer contends that CO₂ used in the first stage of CO₂/NH₃ cascade systems offers the industrial refrigeration industry a gifted opportunity to build safe, environmentally friendly and efficient industrial refrigeration systems well into the future.

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2. INTRODUCTION

The rediscovery of R744 (CO₂) as a natural refrigerant is mainly due to the efforts of Professor Dr Techn Gustav Lorentzen from about the mid 1980’s until his death in early August 1995. His widely published and voluminous work includes the development of a Trans-Critical CO₂ Vehicle Air Conditioning System. /1/

Rediscovery of CO₂ as a natural refrigerant is a true statement as it is claimed that Mr T.S.C. Lowe, an American, built the first CO₂ system in 1866. /2/

After the last world war, the general use of CO₂ in both land and marine applications rapidly declined. Ammonia and later R22, became popular for large land installations, whilst R12, and later R22 and R502, became popular for both marine and small to large land based systems. /2/

R12 was originally launched as a safety refrigerant /2/ and it
is ironic to observe now how much damage has been done (and is still being done) by the CFCs and HCFCs due to their liberated chlorines in the upper atmosphere breaking down the ozone layer.

Over the past 60 years or so, many other chemicals such as DDT, PCB, Pb etc have been found to be environmentally unacceptable, even in small quantities, although they were originally introduced for the benefit of mankind. /3/

Given this disastrous record, some have questioned the logic of the introduction of HFCs whose chemical compounds do not occur in nature. /3/ Several authors (Banks and Rosin) /3/ have suggested that HFC 134a may be decomposed by sunlight in the atmosphere and form acid and poisonous substances. This would be disastrous.

Some have predicted that the current crop of HFCs will need to be replaced in the next 10 to 20 years /2/ because of potential environmental problems.

Having regard to the above, it appears to me that the time of CO₂ used in conjunction with the already commonly used natural R717 i.e. Ammonia (NH₃), has come.

3. ADVANTAGES AND DISADVANTAGES OF R744 (CO₂)

3.1 Advantages of CO₂ /2/, /3/, /4/, /5/, /6/, /7/, /10/, /13/, /14/, /16/, /17/

.1 High Volumetric Performance
In the range of -55°C to 0°C evaporating temperatures, the volumetric performance of CO₂ is 4-12 times better than that of NH₃. This means that CO₂ compressors and piping systems are much smaller than for equivalent capacity NH₃ systems.

.2 Low Compression Pressure Ratio
.1 In the case of CO₂, the pressure ratio is about 20 to 50% lower when compared with HFCs and Ammonia.
.2 The lower pressure ratio combined with the higher pressure levels give greater volumetric and isentropic efficiencies.
.3 The overall benefit of low pressure ratios is that the Real relative COP (Immediate COP) is 15 to 20% higher than the Theoretical Relative COP in the case of CO₂.

.3 High Heat Transfer During Evaporation
Referring to Figure 8 /6/ Prof Emeritus Will Stoecker presents a very interesting comparison and variation of the overall heat transfer co-efficient of CO₂ and R22 with Log Mean Temperature Difference (LMTD). A most outstanding feature of CO₂ is the almost constant U-factor for CO₂ with LMTDs ranging from 2 to 9K.

.4 CO₂ may be used in direct systems in the spaces to be cooled and this would give the highest possible evaporating temperature at the highest efficiency. /2/

.5 Inert Gas /2/
CO₂ is an inert gas and hence the choice of metallic materials for piping and components does generally not present a problem, provided dry CO₂ is used and the maximum design pressures may be handled by system components. Attention must be paid to the compatibility of elastomers in contact with CO₂ (gaskets, o-rings etc)
.6 Environmental Implications /2/

.1 Global Warming Potential (GWP)

The effect of CO₂ refrigerant escaping into the atmosphere is neutral as CO₂ is already present in the air.

Although CO₂ is a greenhouse gas, its use as a refrigerant will be completely neutral because of the fact that CO₂ is a byproduct of existing processes (internal combustion engines, thermal power generation) or as part of an ecological cycle. /10/

.2 Ozone Depletion Potential (ODP)

The ODP of CO₂ is zero. /2/

.7 Occupational Health and Safety

In Australia, the TLV is 5,000 ppm with a STEL of 30,000 ppm. These numbers were set in 1990. /8/

The TLV of 5,000 ppm is almost universally accepted with STEL levels varying between 10,000 to 30,000 ppm with time limits imposed on the duration of exposure. /8/

.8 CO₂ can not burn or explode. Also, at very high temperatures, such as during a fire, CO₂ does not create hazardous gases, such as phosgene and hydrofluoric acid which are created at high temperatures with CFCs and HCFCs and hydrofluoric acid, when incinerating HFC at high temperatures. /2/

.9 Existing CO₂ Production Facilities

Compared to the present production and consumption of CO₂, the consumption of CO₂ by refrigeration plants in future will be very small indeed.

.10 CO₂ is very cheap when bought in industrial quantities. Pure CO₂ required for refrigeration is estimated to cost much less than ammonia and a small fraction of the high cost of modern HFCs.

.11 Because of smaller pipes, evaporators and compressors, a smaller charge of CO₂ may be required compared to an ammonia system of equivalent capacity.

However it must be noted that the density of liquid CO₂ compared to liquid NH₃ is about 1.5-times higher. Meaning that for large industrial systems with most of the liquid refrigerant in pump-recirculators and pump-feed evaporators (large plate freezers, large air coolers etc!) the mass charge of CO₂ will be usually larger than for a comparable NH₃-system - even if the volumetric charge should be somewhat smaller.

.12 Easy to Service

CO₂ may be blown off when servicing refrigeration system components, as it is harmless and cheap.

However, special procedures are required to ensure that no dry ice is formed in a system when it needs to be opened up.

.13 Disadvantages of CO₂ /2/

.1 Limited Flexibility

The temperature range from the triple point at -56.6ºC and the critical temperature of +31ºC, which limits the application in conventional cooling cycles considerably.

As the discharge pressure approaches or exceeds the critical point (trans-critical cycle process), the COP reduces to low levels due to a reduction in the enthalpic difference of evaporation. In such cases, additional devices such as water heaters and expanders/compressors would be needed to enhance the overall system COP /2/, /9/, /10/

.2 High Design Pressure

If full CO₂ systems are to be built, they would need to be designed for 120 to 140 bar Maximum Working Pressure (MWP) for trans-critical operations. Completely new compressors would need to be developed for these high pressures.

.3 Special Precaution, Equipment Or Procedures For Long Shut Down Periods Of CO₂ Plants

CO₂ plants for low temperature operation with design pressures up to 45 bar require special consideration as follows:

.1 A fade out vessel would permit the entire charge to be accommodated in vapour form at a pressure of say 45 bar at an ambient temperature of say +30ºC. See Figures 21 and 22 /6/. This method is usually only applicable for low charge systems.

.2 Transfer of the entire CO₂ charge to high pressure bottles for a prolonged shutdown.

.3 Cooling down of the CO₂ charge by means of a small independent refrigeration plant with a diesel engine driven compressor or generator.

.4 Pressure control by means of CO₂-vapour recondensing using a small independent refrigeration unit with a diesel engine driven compressor or generator.

.5 Absorption into another medium.
4. High Density of CO₂ Vapour

CO₂, like CFCs, HCFCs and HFCs, is more dense than air and tends to displace the atmosphere. In confined spaces (basements, ship holds) CO₂ could reach too high concentrations. Any person entering such a space would risk health damage. The similar danger exists with CFC, HCFC and HFC refrigerants.

In practice, this is considered to be a controlled risk with proper leak detection and space ventilation in place.

5. CO₂ is odourless and, as such, will not be noticed by people when entering a space containing a high concentration of CO₂. Thus, reliable CO₂ detectors are required to ensure personnel safety in confined spaces.

4. LOW TEMPERATURE REFRIGERATION SYSTEMS USING CO₂

All the systems to be considered here are CO₂-Ammonia Hybrid systems as follows:

4.1 The Use of CO₂ as a low Temperature Brine

Using CO₂ as a secondary coolant as a brine. i.e. a one phase liquid flow. All heat to the fluid is sensible heat and results in a temperature rise in the fluid. This results in turbulent flow at low fluid velocities and even in small pipes. Compared to other brines such as calcium chloride, Ethylene and Propylene glycol, Ethanol and other brines, we observe the following.

.1 The heat transfer factor for CO₂ is 3 to 5 times better than conventional brines.

.2 The pressure losses of CO₂ are about one third of conventional brines.

.3 CO₂ is four to 10 times better than conventional brines in the case of the temperature difference factor. This relates to the necessary temperature difference in the heat exchanger to ensure a satisfactory and consistent pumping performance.

The only disadvantage is the need for the systems to be designed for high pressures.

Also, defrosting requires special attention. Defrosting will be dealt with later.

4.2 CO₂ as a Volatile Brine

Using CO₂ as a secondary coolant as a volatile brine i.e. two phase flow for the CO₂ with vapour being condensed by an ammonia plant. The wet boiling fluid temperature reduces due to the pressure drop i.e. the boiling point reduces.

CO₂ liquid is pumped to the frozen food cabinets from an accumulator where part of the CO₂ evaporates. The wet CO₂ vapour is then piped to an ammonia evaporator operating at -35°C with a capacity of 145 kWR. The CO₂ vapour is condensed and the reduction in volume from vapour to liquid creates the “suction” on the evaporators.

A tank filled with cold propylene glycol is installed in the wet return from the evaporators in the case of a breakdown.

The secondary CO₂ system is designed for 25 bar (-10°C). Should a prolonged breakdown occur and the temperature of the glycol rise above -10°C, the safety valve will keep blowing CO₂ charge into the atmosphere at the rate of 4 to 6 kg per 24 hours.

The circuit for a CO₂ brine system would be identical except that an expansion tank would need to be incorporated to accommodate changes in CO₂ volume due to temperature changes.

4.3 Flash Cooling by CO₂ /11/, /12/

Flash cooling systems by sensible heat transfer to CO₂ as a one phase fluid, allowing to flash off by reducing the pressure to the saturation pressure corresponding to the CO₂ brine supply temperature to the system. Originally proposed by Lorentzen. /11/, /12/

A hybrid of the two systems i.e. one phase flow and two phase flow, would be to use one phase flow and use sensible heat transfer in all heat exchangers by maintaining the pressure in the heat exchangers above the boiling point of the CO₂ fluid.

The heated CO₂ would then be piped to a vessel operating at saturation temperature of the CO₂ brine supply temperature.

“Flash cooling” would occur, as at the sudden pressure reduction, the sensible heat would be used to evaporate part of the CO₂ liquid.

The “flash gas” vapour would then be condensed in an ammonia/ CO₂ evaporator.

4.4 CO₂/NH₃ Cascade Systems.

CO₂/NH₃ cascade systems with a low temperature CO₂ stage and an ammonia high temperature stage. NH₃ is preferred as HT-refrigerant for large industrial refrigeration systems due to its excellent thermodynamic and environmental properties.

The philosophy of the system is to employ as many standard components and as much standard plant
design as possible. Keeping the pressure in the CO₂ cycle within the range normally encountered in refrigeration plants has enabled the designers to use standard refrigeration valves, vessels and compressors in the main part of the system.

In the CO₂ cycle, a pump separator supplies liquid to the pumps that feed the plate freezers and air coolers. The evaporators are built for liquid recirculation operation with a circulation rate of 4-6 to 1. The two-phase return is piped back to the pump separator. The CO₂ refrigeration compressors suck from the pump separator and supply gas to the cascade cooler. In the cascade cooler, the gas is condensed and fed back to the pump separator. Evaporating another refrigerant, which could be hydrocarbons, ammonia or even HFCs, cools the cascade cooler. This concept is based on ammonia due to its technical/environmental advantages. Since the ammonia is not in the plate freezers and air coolers, the charge can be minimized and kept in an isolated room, reducing the risk in the event of an ammonia leak.

Most of the system is in accordance with normal practice, but the defrost system is a new development. There are several ways of creating a 50 bar defrost system. It is possible to evaporate CO₂ liquid at 50 bars, but this involves several problems. First of all, is the control of such a system, where extremely accurate valves are required to have a fine regulation. Secondly, it is not advisable to have vessels under 50 bar MWP.

In the opinion of the designers, the safest system involves a high-pressure compressor for a number of reasons. No vessel in the high-pressure system overcomes most of the problems mentioned above. Starting the compressor means a relatively gentle pressure build-up. Furthermore, this concept simplifies the valve installations on the air coolers, limiting the defrost pressure control to the compressor and a single by-pass valve. In this concept, only the evaporators, the defrost compressor and a small amount of valves and pipes have to be at 50 bar pressure. By careful selection of the components, especially the valves, normal refrigeration components can be used.

Another benefit of this defrost system is the actual savings in power consumption when defrosting. The defrost compressor sucks from the cascade cooler and will as such, reduce the necessary cooling capacity for the ammonia system. Since the defrost compressor runs with a significantly higher COP than the ammonia compressors, every KW spent on the defrost compressor, including heating of floors in cold stores, production areas and keeping equipment ice free. In cases where these tasks are met by electrical heating resulting in large power consumption, using such a system, it will result in reduced operating costs.

The compressor used for defrosting in this system is a modified high-pressure ammonia heat pump compressor, which can be used for refrigeration as well. This has two important implications. First, the defrost compressor can perform cooling duty while defrosting is not required. Furthermore, if more compressors of the same type are employed for cooling duty, these can take the place of the defrost compressor in case of maintenance ensuring continuous defrosting.

Furthermore, the separate defrost system means that the cooling system can remain in optimum operating conditions while defrosting, yielding a highly power effective system.

The COP of cascade systems is influenced negatively by an increasing temperature difference in the cascade condensers and a decreasing CO₂ condensing temperature.

The optimum COP is reached when the compression pressure ratios of both sides of the cascade are equal with a slight upward adjustment of the CO₂ pressure ratio to compensate for the cascade condenser.

With modern control technology, it is possible to optimize the COP of a cascade system with fluctuating heat loads and a floating condensing temperature due to changing ambient conditions during the seasons. Such a control strategy would be similar to the automatic V₁ control strategy used on some screw compressors.

5. CO₂ AIR COOLER DEFROSTING METHODS

There are a number of ways in which defrost may be effected:

5.1 Electric Defrost Evaporators

This is standard and well proven technology and would be applicable to CO₂ evaporators.

5.2 Water Defrost

Again, this is well proven. Care needs to be taken to ensure that there is no residual CO₂ liquid in the evaporators before applying warm to hot defrost water. The same applies to electric defrost.

5.3 A Separate Defrost Compressor Function

This is described in Section 4.4 and is eminently sensible. The writer has done similar things with ammonia compressors in cold climates with low
discharge pressures on the high stage compressors during winter.

5.4 A High Stage Hot Gas Fired CO₂ Boiler /10/

This method was devised by Dr Forbes Pearson and fully endorsed by none other than Gustav Lorentzen. Primary refrigerant (say ammonia) hot gas is used to generate CO₂ hot gas in a vessel of adequate pressure rating at say 50 bar. CO₂ is pumped to this vessel by means of an additional liquid pump.

The CO₂ vapour generated at 50 bar is admitted to CO₂ evaporators where the CO₂ condenses at say +10°C (46 bar). This method of CO₂ hot gas defrosting is eminently sensible.

All relevant parameters as to capacity, size and so on are readily calculable using standard refrigeration design methods.

5.5 Ambient Air Defrost

In warm climates such as Australia, ambient air defrost is suitable. This is well developed in this country and works very well in practically all areas in Australia including Ballarat.

It is necessary to fit the evaporators in external pods, which may be isolated from the refrigerated space and opened up to the ambient air for defrosting.

5.6 Circulate warm brine through auxiliary tubing installed in lieu of electrical heating elements.

6. PRESSURE LIMITATION

6.1 During Operation

.1 Design secondary systems for low temperature for a MWP of 50 bar where CO₂ hot gas defrosting is used.

.2 Where other defrost methods are used, design the CO₂ low side for 25 bar. This includes the evaporators.

6.2 During Shutdown

A number of methods are available.

.1 Place the CO₂ receiver/accumulator in a cold store if available. /17/

.2 Provide a receiver with thermal storage. /17/

.3 Allow a bleed off from the storage vessel as heat entering evaporates part of the CO₂ charge. /21/, /17/

.4 Use a small re-condensing unit. /6/, /17/

.5 Use a fade out vessel, permitting the entire CO₂ charge to be stored in the gaseous phase. This method is practicable for low charge systems only!

7. POSSIBLE FUTURE DEVELOPMENTS FOR CO₂

7.1 Large scale trans-critical multi-stage CO₂ heat pumps with a temperature glide for water heating and free piston or turbine expanders/compressors to extract energy to enhance the COP /21/, /8/, /10/.

7.2 Provide large scale air conditioning systems either independent or coupled to heat pumps /21/, /8/, /10/. Suitable for district heating and cooling.

A CO₂ car air conditioning system has already been successfully developed. /1/

7.3 A portable CO₂ system for container and reefer refrigeration systems. /2/

Efforts are also being made to apply CO₂ system to railway car air conditioning.

7.4 “Dry-Ice-Slurry” For Low Temperatures /2/

This is the fluidization of dry ice (solid CO₂) in a liquid transportation medium with a low freezing point.

Experiments have taken place with d-limonene (C₁₀H₁₆) with a freezing point of -97°C. As the mixture of transportation medium and dry ice particles is pumped through heat exchangers, the dry ice will vaporize and be recompressed to a cascade condenser. The theoretical temperature range is between -56 and -80°C. This system is not unlike ice-slurry systems.

7.5 CO₂ as a Mixed Refrigerant /2/

FKW in Hannover, Germany and others have experimented with mixtures of CO₂ and propane. The combined effect of this is lower pressure for CO₂ and reduced flammability for propane.

A distinct zeotrope refrigerant mixture with a considerable temperature glide is created when mixing CO₂ and propane. Such mixed refrigerants may be used in:

.1 Conventional refrigeration plant and systems with counter flow heat exchangers to accommodate the temperature glide.

.2 In a mix-cascade system, which would have the advantage of a lower compression ratio than corresponding traditional CO₂ vapour compression cycles.
In resorption systems where a vapour compression plant operating at lower pressures and lower general pressures on the dissolving cycle comprising desorber and resorber.

8. **CO₂ and Oil**

8.1 **Oil Free Compression /15/**

When converting the large R22 plant to a CO₂ / NH₃ cascade plant /15/ A Pearson, and his client Nestle-UK decided to use oil free CO₂ compressors at significant extra cost.

The main reason for selecting oil free compressors was the unknown long term effect POE oil would have on the evaporators. Also, the effect of moisture on POE oils was not known. POE oil was used with some success in a test pilot plant screw compressor.

This decision was made to ensure no oil-related problems would be experienced in this first of a large number of conversions throughout the large international group.

Since 2001 this CO₂/NH₃ cascade system with a capacity of 2400kW at -54/-48°C is fully operational.

8.2 **Lubricants may be avoided if a secondary system using CO₂ as a brine or volatile brine. /17/**

8.3 **CO₂ and Oil Miscibility**

Between oil temperatures of 20 and 100°C, the CO₂ solubility in mineral oil reduces from 7% to 4% whilst over the same oil temperature range R22 solubility in mineral oil ranges from about 13% to approximately 1.5%.

Non-polar sub-critical CO₂ shows no miscibility in non-polar mineral oils. /5/

Polar oils such as ester and polyalkylene glycol show a limited miscibility in sub-critical CO₂ /5/. Whether this miscibility may be beneficial depends largely on the design of sub-critical CO₂ plants. /5/

CO₂ is an inert, inactive gas and thus many of the currently available refrigeration oils can be used in reciprocating and screw compressors. /5/

In /10/ Lorentzen states that normal lubricants are completely compatible with CO₂.

9. **SYSTEM AND COMPONENT DESIGN IMPLICATIONS**

9.1 **Oil Separators**

Braengaard /5/ recommends two stage oil separators comprising a normal demister pad followed by a coalescing element with an entry velocity of about 0.2m/s/ sec. With these design parameters, an oil discharge of 2-5 ppm may be obtained at discharge temperatures of 50 to 80°C when using mineral or synthetic oils.

It is frequently not difficult to add impact and change of direction of the hot vapour steam passing through an oil separator and these features are recommended in addition to the demister pad and coalescers.

9.2 **Materials**

CO₂ is an inert gas and hence the choice of metallic materials for piping and components does generally not present a problem, provided dry CO₂ is used and the maximum design pressures may be handled by system components. Attention must be paid to the compatibility of elastomeres in contact with CO₂ (gaskets, o-rings etc).

Because of the coinciding conditions of relatively high saturated vapour pressures with relatively low saturated vapour temperatures, it is recommended that ASTM A333 grade 1 pipe be used. /15/

ASB223, which is based on BS3603, specifies pipe material 27LT50 as an equivalent of ASTM A333 Grade 1, low temperature pipe.

ASB223 covers carbon and alloy steel piping for low temperature duties in both HFS and CDS fully killed condition.

Pressure vessels should be made from LT50 plate /15/.

9.3 **Suggested design pressures**

| 1 | CO₂ high side design pressure (+15°C sat temp) 30(50*) bar |
| 2 | CO₂ low side design pressure (-10°C sat temp) 25(30) bar / -60°C** |
| 3 | High side test pressure 75 bar |
| 4 | Low side test pressure 40 bar |

* Only for system components exposed to HP defrost gas

** For LT-application to < -45°C

10. **APPLICATIONS**

10.1 After more than 40 years involvement with marine and large scale shore based industrial refrigeration plants all over the world, it is fair to say, that in most low temperature applications, a CO₂ cascade system would have been able to fill the bill. The high stage of the cascade could have been ammonia HCFC, HFC, etc.

This applies to:

1. Cold storage plants
2. Large scale blast freezing and plate freezing systems
3. Other freezing equipment - spirals, IQF, etc.
4. Ice cream plants
5. Dairy plants with cold storage and freezing facilities.
6. Fish processing plants
7. General food processing plants manufacturing frozen food.
.8 Fishing vessels and mother ships.

10.2 Other potential applications

.1 Supermarkets (already being done in Sweden)
.2 CO₂ condensing plants
.3 Freeze drying
.4 Any other application requiring evaporating temperatures down to -55°C is now possible.
.5 The writer is convinced that 99% of all low temperature refrigeration duties may be done with CO₂ / NH₃ cascade systems.

11. CONCLUSION

Having regard to all the preceding, it is fair to say that the revival of CO₂ presents the international industrial refrigeration industry with a gifted opportunity to make a major contribution to both the environmental health of the planet and the Occupational Health and Safety issues associated with the use of ammonia, the hitherto widely used natural refrigeration.

The CO₂ contribution to the environment is that it has zero ODP, CO₂ / NH₃ cascades use less energy below about -35°C saturated section and thus leads to less CO₂ from power generation adding to the global warming.

CO₂ comprises about 350 ppm (.35 promille) of our natural atmosphere and thus the GWP of CO₂ used in refrigeration systems is more apparent than real.

Further, the low cost and universal availability of CO₂ make it attractive and most, if not all, users will welcome the predicted lower capital cost of CO₂ / NH₃ cascade systems for low temperature applications in future.

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GLOSSARY

CFC Chlorofluorocarbons
HFC Hydrofluorocarbons
HCFC Hydrochlorofluorocarbons
COP Coefficient of Performance
LMTD Log Mean Temperature Difference
GWP Global Warming Potential
ODP Ozone Depletion Potential
TLV Continuous safe exposure level over 8 hours
STEL Safe short term exposure level max. 15 minutes
POE Polyolester
PHX Plate Heat Exchanger
ET Evaporating temperature
CT Condensing temperature
K Degrees absolute temperature
KWR KW refrigeration capacity
Klaas Visser is the Principal of KAV Consulting (KAVCONSULT@bigpond.com) This paper was first presented at the AIRAH Natural Refrigerants Conference, April 2002 and has been abbreviated for publication. A full transcript is available from AIRAH, email, Brendan@airah.org.au