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The Use of Total Loss Refrigerants in Transport of Foodstuffs

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Introduction

The use of total loss refrigerants is an alternative to mechanical refrigeration, which has advantages in some transport applications. Instead of a refrigerant being cooled by machinery at the place and time of the refrigeration requirement, these refrigerants are cooled, stored, and transported to another location before use is made of the stored refrigeration effect. After use, the refrigerant is released to atmosphere, hence the term" total loss".

Economic and environmental safety factors both dictate that any total loss refrigerant must be readily available and harmless. With the exception of water ice this limits the choice to atmospheric air and its components. Liquid air has been used, but in equilibrium at atmospheric pressure this contains a dangerously high proportion of liquid oxygen which is a very powerful oxidizing agent. The total loss refrigerants in general use which will be considered in some detail in this paper are liquid nitrogen (LN) and liquid or solid carbon dioxide ($C0_2$), Applications include grinding of polymers and fats, cryogenic cooling for very low temperature storage, rapid freezing of foodstuffs, and in-transit refrigeration. The present paper is restricted to applications concerning the in-transit refrigeration of perishable foodstuffs.

Physical Properties

Nitrogen is the main constituent of atmospheric air, and it liquefies at atmospheric pressure at a temperature of -196°C. It is usually supplied and stored at a pressure of 3 t06 bar, with corresponding boiling points of -IS5°C and -177°C. There are various methods of use which will be detailed below, all of which make use of both the latent heat absorbed by boiling liquid and the sensible heat absorbed by the resulting cold gas. For liquid at -196°C converted to waste gas at - *20°C,* the total refrigeration effect is 37SkJ/kg, of which 19SkJ/kg is latent heat. In particular applications, the refrigeration available depends on both the liquid storage temperature and the waste gas temperature.

Liquid nitrogen is produced by liquefaction of air, either as a principal product or as a byproduct of liquid oxygen. The energy required to produce 1 kg of liquid nitrogen is around 3000 kJ, or eight times the consequent stored refrigerating effect.

Carbon dioxide gas is present in air at a concentration of 0.03 to 0.05%. It is also a byproduct of fermentation processes and a constituent of natural gas, is present in flue gas, and occurs naturally in underground pockets in some parts of the world. In the UK it is mainly produced from decomposition of natural gas into carbon dioxide, hydrogen, and ammonia. Its physical properties are unusual, in that it does not exist in liquid form at atmospheric pressure. If stored as a pressurized liquid and released into the atmosphere, the liquid changes partly to gas and partly to a frozen solid at *-78.5°C* which sub1imes directly into gas without going through a liquid phase. If there are no heat gains in the transition from liquid to solid, there is a considerable reduction in mass associated with gas production, but the solid has a much higher latent heat per unit mass than the liquid.

Liquid carbon dioxide stored at a pressure of 20.7 bar and a temperature of –18°C will absorb 313 kJ /kg in converting to gas via the solid form. At 6.9 bar and *-46°C* this increases to 371 kJ /kg. Solid carbon dioxide at -7S.5°C has a refrigerating effect of *620kJ/kg* for a - *20°C* waste gas temperature, and of this amount 575 kJ /kg is required to vaporize the solid.

From these figures it can be calculated that 1 kg of liquid carbon dioxide at –18°C converts at atmospheric pressure into 0.466 kg of solid and 0.534 kg of gas. 92.3% of the refrigerating effect is stored in the solid, and 7.7% is available as cold gas. The majority of the" refrigeration effect" stored in solid CO_2 is latent, whereas in liquid nitrogen almost half the effect is due to sensible heat transfer to cold gas.

The energy requirement for CO_2 liquid. production in the US has been quoted as 650 kJ/*kg,* about twice the stored refrigeration effect, but this figure is not representative of European production.[1]

The available refrigerating effect from 1 kg of each of· the above total loss refrigerants is shown pictorially in Fig. 1.

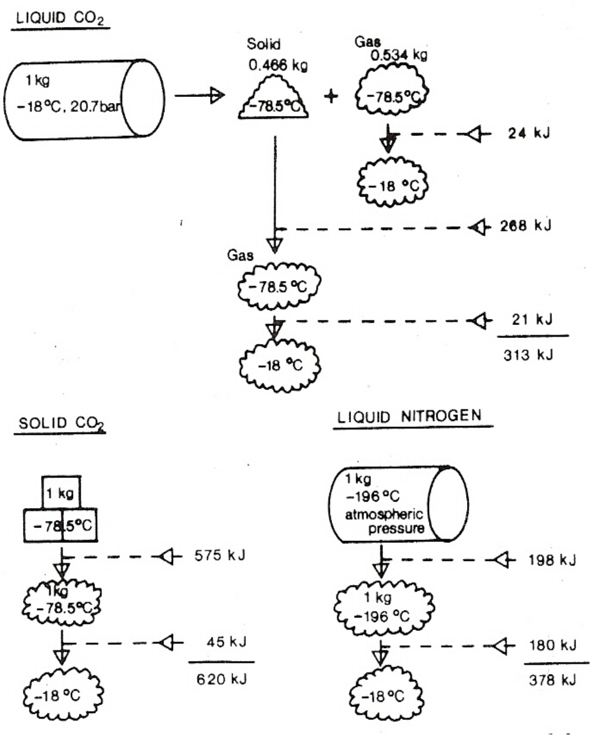

Fig. 1. *Available refrigeration effect from 1kg of total loss refrigerant*

Scale of Use

Exact figures for the use of total loss refrigerants in the transport of frozen foodstuffs are not available, but' estimates for UK sales, based on discussions with suppliers, are as follows.

Total annual sales of liquid nitrogen for in-transit use are running at around 23,000 tonnes, most of which is used in maybe 2,000 road transport delivery vehicles. Carbon . dioxide is sold for transport use as a solid ("dry ice"), and the annual total is around 12,500 tonnes of which over 20% is used in airline catering from Heathrow and Gatwick. This material is available either as blocks weighing a few kilogrammes or as small pellets. There is substantial use of dry ice blocks for road transport of dairy products, but this market is declining in favour of mechanical refrigeration.

Safety Aspects

Both nitrogen and carbon dioxide are incombustible, non-toxic and non-corrosive, but'a certain amount of care is necessary in handling them. Apart from the obvious dangers of pressurized storage and cold "burns", they can displace air and produce oxygen deficient atmospheres in areas where they are being used. The effect of entering a low oxygen atmosphere is immediate and unless assistance is available within two or three minutes the effects are permanent. Adequate fresh air ventilation and avoidance of use over cellars in which pockets of gas could collect overcome the problem. Liquid nitrogen is colder than the liquefaction temperature of oxygen (-183°C) and attention has been drawn to the possible danger of oxygen liquefaction from air in some applications, particularly where fats are being ground at low temperature. The authors are aware of no specific hazard of this sort in transport applications.

In designing and using liquid gas pipelines it is essential to avoid possible liquid traps between valves. If this is not done, vaporizing liquid can produce pressures of up to 200 bar, for which the pipework and fittings may not be suitable.

Operating Restraints

Total loss refrigeration is different from mechanical refrigeration in a number of ways. These differences may be used to advantage for particular trades with various types of equipment, some of which will be described later. Particular characteristics which may be regarded as advantages or disadvantages by comparison with mechanical refrigeration are listed in Table 1 .

TABLE 1

Possible advantages and disadvantages. of total loss refrigerants by comparison with mechanical refrigeration

Advantages

1. Low capital investment
2. Low weight when out of use
3. No noise.
4. Low maintenance requirements
5. High refrigerating capacity
6. Advantageous storage atmosphere (N,)
7. Bacteriostatic effect (CO_2)
8. No residual weight (dry ice)
9. Foolproof once installed (dry ice)

Disadvantages

1. Limited availability
2. High operating cost
3. Poor temperature control
4. Reduced humidity
5. Limited duration without filling
6. High weight at start of use
7. Suffocation hazard
8. High refrigerating capacity

The advantages of low capital cost and low maintenance requirements are the main reasons for considering total loss systems, and the extent to which they apply can only be studied for particular cases. Low weight, and indeed no residual weight for dry ice packed with frozen produce, is a particularly attractive aspect for airline catering applications.

There are obvious benefits for long rail journeys in using dry ice for which no further attention is required once the cargo and refrigerant have been loaded. In road transport, overnight parki.'1.g of mechanically refrigerated vehicles is sometimes difficult in noise-sensitive areas, and total loss refrigerants overcome this problem. The bacteriostatic effect of carbon dioxide is useful for some products, but the often-claimed advantage of a low oxygen atmosphere for storing fruit with nitrogen refrigeration in slowing ripening is of dubious benefit if it is not part of a complete controlled atmosphere transport and storage chain. High refrigerating capacity is an advantage if it is required, but can be a disadvantage when it results in rapid cooling and associated high refrigerant use. Very rapid cooling can cause damage to materials and assemblies used in vehicle or container construction.

Most of the disadvantages listed in Table 1 are self-explanatory. Limited availability must be allied to possible dangers of industrial action in preventing deliveries and temperature control is discussed in detail below. Reduced humidity could lead to increased weight loss for some products, with consequent loss of value.

Liquid Nitrogen Systems

Liquid nitrogen refrigeration systems have been used regularly in road vehicles since about 1961, the year of introduction of the "Polarstream" system in the United States. This comprises a vehicle mounted storage tank, a spray rail above the cargo space, and a thermostatically operated control system to inject nitrogen as required. The system, which was designed for frozen food delivery vehicles, was evaluated by the USDA in 1960[2] and was established for use in both trucks and railcars by 1967.[3] A similar system with a clip-on tank and control unit was subsequently produced for use with insulated freight containers, and at least one major container operator incorporates a suitable spray rail as standard equipment in such containers.

Road vehicle systems with thermostatic control are available in the UK with tank capacities from 120 to 340 kg of nitrogen and smaller, uncontrolled units are available down to 8 kg capacity. For frozen foods, the control requirements are not severe and the main design requirement is correct storage tank sizing. In SRCRA's experience control thermostat settings can often be in error by several degrees, and this can result in large variations in apparent efficiency of nitrogen use.

An alternative to thermostatically controlled injection is timed injection, either in frequent, short pulses or on a slower basis. This has a particular advantage for cargoes, which are received a little on the warm side, in that the available refrigeration is spread over time and the nitrogen use is more predictable.

Trials in Australia in the late 1960s demonstrated that, for storage over several days, a once daily injection of nitrogen in sufficient quantity would maintain the condition of frozen produce as well and as economically as timed or thermostatically controlled injection. Such daily injection is commonly known as "dump charging", and it may be effected either through a spray rail or, in the case of insulated containers with no such spray rail fitted, through a nozzle inserted through an open porthole. Rates of injection must be limited to around 4 to 5 kg per minute to prevent damage due to over-rapid cooling, and the cargo space must be vented to prevent a build-up of gas pressure.

Dump charging is possible using very limited equipment, and it was used to particular effect at the Tilbury container terminal during the lorry drivers' strike in the winter of 1978-1979. Large quantities of frozen meat were kept in good condition for several weeks by this means. At about this time another system for refrigeration at container terminals was developed by Air Products Ltd and installed 'at ECT's terminal at Rotterdam. This system combined nitrogen injection with continuous air circulation, and was based on single container "press-on" modules, the basics of which are shown in Fig. 2. The Rotterdam installation has 48 such modules connected to a common nitrogen storage tank.

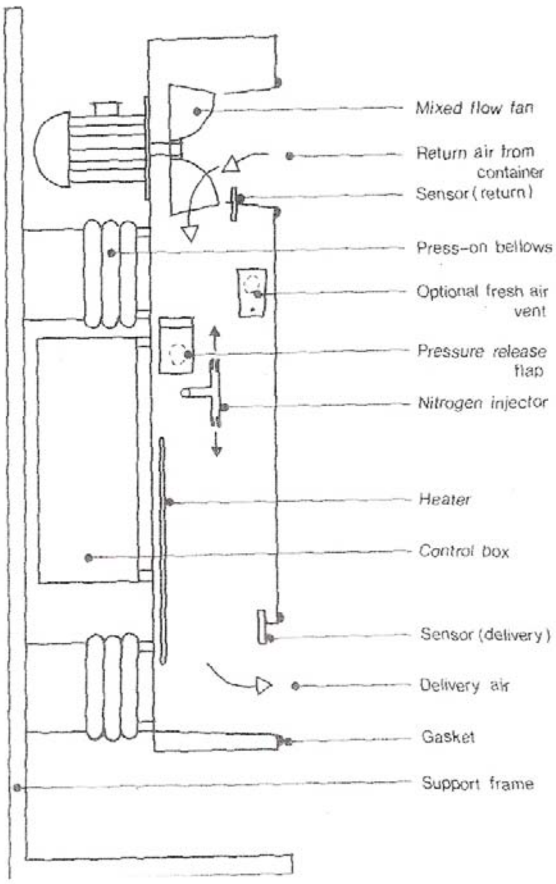

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Fig. 2. Schematic drawing of Air Products press-on unit.

Each module contains a fan capable of circulating either 1500 or 700 m^3 h^{-1} of air through the cargo, and a nitrogen injector, which is controlled by both a timer and a temperature controller. When the temperature controller demands cooling, the timer allows injection cycles of a few seconds followed by a few seconds "off" period, thus limiting the maximum rate of cooling available. The temperature controller also prevents air delivery temperatures being more than a few degrees below the temperature of the air returning from the cargo space. There is an electric heater, and temperatures may be controlled at between - 25 and +15°C. An optional vent in the unit may be opened to prevent the oxygen content of the circulated air falling below 8%.

An alternative design of container terminal module has been investigated by British Oxygen Company, in which a mixture of air and nitrogen is circulated intermittently to a group of up to eight containers. Such forced evaporation of nitrogen by fan-assistance is successfully used in spiral freezers and elsewhere in cryogenic equipment. A prototype dockside terminal was constructed and evaluated in which, on an hourly cycle, a mixture of nitrogen and air was circulated through a single duct to all the containers, each of which was disconnected by a closure valve once its desired temperature was reached. Once all containers were satisfied, the air circulation ceased until the start of the next cycle. Closure valves were operated by a nitrogen pneumatic system.

All the systems detailed above have been investigated by SRCRA and information has been obtained on nitrogen consumptions and on temperature spreads in frozen cargoes.

Nitrogen Consumption

SRCRA trials on loaded freight containers of known thermal characteristics have been carried out under steady conditions in controlled temperature chambers. From these trials it is clear that all the direct injection systems, whether thermostatic, timed, or dump charging use similar amounts of nitrogen for any given duty. A nitrogen consumption of 10 kg/hr per kW of cooling effect required corresponds to 95% of the theoretical value for liquid at -196°C converted to gas at -18°C (a typical storage temperature for frozen produce), and if this quantity enters the cargo space then the required effect can be produced. A nomogram based on this amount is shown in Fig. 3, which relates the nitrogen requirement to the heat leakage through the insulated enclosure and to the required steady temperature difference. The nomogram makes no allowance for cargo cooling, for heat generated within the enclosure, or for nitrogen losses in the system between storage tank and cargo enclosure.

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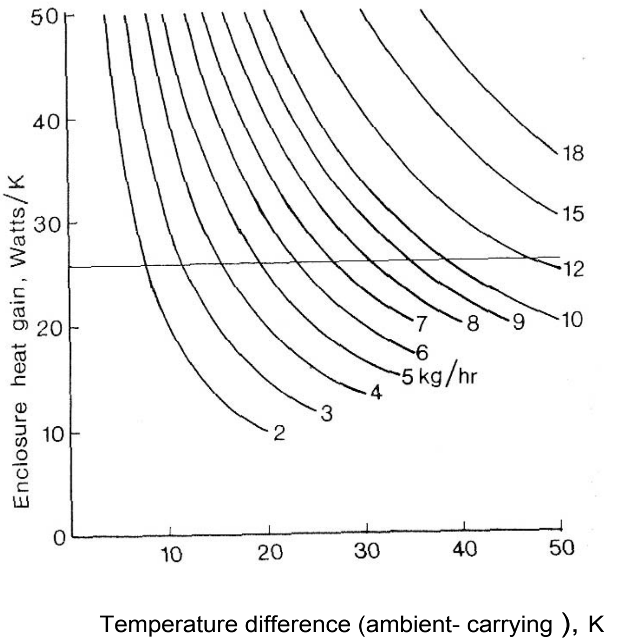

Fig. 3. Liquid nitrogen requirement, kg/hr, to balance heat leakage

Cargo cooling will increase consumption considerably. For example, under typical conditions a container load of butter cooled through 5 K over a day would require twice as much nitrogen as it would if held at a steady temperature.

Tests at SRCRA have demonstrated a 95% efficiency of use"(relative to 378kJ/kg as 100%) when dump charging frozen cargo in a range of ambient temperatures up to 30°C. A range of tests using a clip-on tank and spray rail with thermostatic control have shown efficiencies between 72 and 94%. Limited tests on the BOC prototype gave 96% efficiency when used with empty containers and 83% with a frozen cargo, after allowance for nitrogen used in counteracting fan heat and air duct heat gains and for operating the pneumatic system. Tests on an Air Products press-on module in direct comparison with dump charging showed a relative efficiency of 74%.

There are two aspects of liquid nitrogen systems which can lead to increased consumption. In a timed injection system, if the cycle time is neither very short nor very long . then liquid in the pipework between storage tank and injection point can absorb a substantial amount of heat from the ambient, and can vaporize. This represents a loss of refrigerating effect which can be substantial. The other aspect concerns the "parasitic" losses of refrigeration effect due to fan heat, tank boil-off of nitrogen, air duct heat leakage, and losses on delivery transfer. The extent of these losses differs from system to system dependent on refrigeration load factors.

If the storage tank is within the refrigerated space, as is the case with smaller delivery truck systems and some rail cars, there are no standing losses. At the other extreme, a centralized fan blown system such as the BOC prototype operating with only one container can have parasitic losses of over twice the required refrigeration effect. If a nitrogen system is used for standby purposes only then tank losses, which can be 50 kg per day for a large tank, can become appreciable. With small tanks there are likely to be higher proportional losses associated with fJ1ling and pressure regulation.

Carbon Dioxide Systems

In the UK carbon dioxide is principally used for intransit refrigeration in block or pellet form. In the US, Canada and Australia it is frequently purchased as liquid for use either in clip-on tanks or as dump charged "snow".

For delivery vehicles, carbon dioxide blocks can be used in fan blown systems in which air is circulated under thermostatic control across blocks contained in an insulated enclosure. As has been seen above, solid CO_2 has a large refrigerating capacity per unit mass, and the stored effect is mostly latent. Maintenance requirements for such systems should be minimal.

The simplest way of using blocks is simply to stow a few in with the cargo. This is uncontrolled and can lead to local excess cooling. A more sophisticated technique has been developed using graded insulated containers, "heat sink enclosures", with an active life of 3 to 7 days after filling. [4] These heat sink enclosures are placed above the cargo in sufficient numbers to provide the necessary cooling. A box designed for 7 days' use with an internal space of 0.25 m cube has a design cooling power of 17 W, a similar 3 days' box supplies 40 W. For airline catering, the judicious packing of pellets in with foodstuffs provides satisfactory results.

Dump charging of CO_2, or "snow shooting" as it is often called, consists of introducing liquid CO_2 from a storage' tank through an expansion nozzle and spraying the resultant solid CO_2 snow over the frozen cargo. The quantity used is normally 0.5 to 1.0 tonnes per freight container or up to 10 tonnes in a railcar, for journeys of a few days' duration.

The results of tests on railcars in the USA have been reported recently[5]. Cargoes of 35 to 54 tonnes of frozen food were successfully carried for periods of 5 to 8 days after single injections of 5 to 9 tonnes of carbon dioxide. This technique has the advantage that, once injection is completed, no further attention is needed during the journey.

A large proportion of the refrigerating effect is transferred to the cargo, which becomes very cold very quickly. SRCRA has carried out a trial with a container load of 8 tonnes of frozen lamb in which 2.22 tonnes of CO_2 were injected over a 75 min period. At the end of this period the increase in container weight was 0.52 tonnes, showing that half the snow formed had sublimed during this period. This injection was sufficient to maintain the cargo below -12°C over a period of 3 days in an ambient temperature of 27°C. An energy balance chart for this trial is shown as Fig. 4. The carbon dioxide gas which is released from the remaining snow requires adequate pressure release areas in the container during and after injection, and there is a continuing suffocation hazard if the container is placed in an enclosed area. CO_2 concentrations of a few percent are not immediately harmful, but exposures over a few minutes should be avoided.

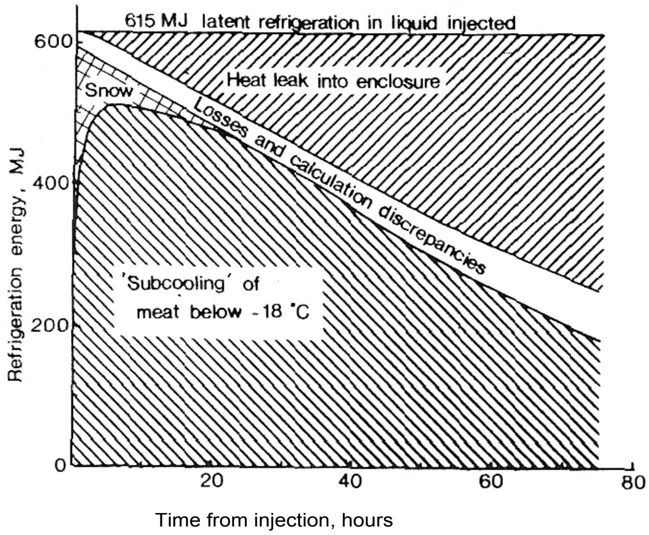

Fig. 4. Change of energy balance with time for a cargo of 8 tonnes of frozen lamb carcasses cooled by carbon dioxide "snow shooting" in 2.7°C ambient. The trial was concluded at a maximum meat temperature of -12.8°C, with a corresponding mean temperature of-27.4°C.

With this technique, very large temperature gradients are produced within the cargo. This means that perhaps one third of the available refrigeration effect cannot be used in transit as carriage times are limited by the warmest areas. However, if the cargo is subsequently mechanically refrigerated the extra cooling of the colder areas of the cargo will not be wasted.

Carbon dioxide systems which are integral to railcars and which emit small quantities of cold gas under thermostatic control have been developed for use in Canada and the USA. Such systems are technically similar to the liquid nitrogen systems described above, except that storage tanks must operate at higher pressures and temperatures than for nitrogen.

Temperature Ranges in Frozen Cargoes

Over a number of years SRCRA has investigated temperature distributions in many cargoes. As a matter of convenience, most of the recent trials have been carried out in a controlled environment test chamber at Cambridge using loaded insulated ISO standard freight containers of 20 ft nominal length. From 12 to 20 temperature sensors have been placed in the cargoes in positions to show maximum variations in temperature in a way, which allows comparison between different trials. A great deal of detailed information has been collected, and the most relevant data relating to total loss refrigeration by comparison with mechanical refrigeration is summarized in Table 2.

TABLE 2
Temperature ranges in frozen cargoes

Refrigeration method	Container heat gain (kW)	Temperature range (K)	Range per kW heat (K)
Containers of carton butter			
Mechanical refrigeration	0.917	2.8	3.1
Mechanical refrigeration	1.400	3.2	2.3
Mechanical refrigeration	1.505	3.0	2.0
Press-o n unit (LN)	1.496	6.1	4.3
Dump charge (LN)	1.474	11.7	7.9
Clip-on tank (LN)	1.247	28.3	22.7
Containers of carcase lamb			
Mechanical refrigeration	0.744	2.1	2.8
Dump charge (LN)	0.725	8.5	11.7
BOC prototype (LN)	0.562	7.9	14.1
Snow shoot (CO,)	1.375	27.2	19.8

Container heat gain is a function of container insulation, cargo temperature, and ambient temperature. Temperature range is the difference between highest and lowest measuring points at the time when they are furthest apart, except in the cases of dump charging and snow shooting when they are taken at the end of a warming cycle, prior to further dumping. There is of course considerable scope for experimental scatter in these results, but it is clear that, with the sole exception of the press-on unit, total loss systems produce much greater temperature gradients than a forced air mechanical refrigeration system. This is clearly a consequence of whether or not there is continuous forced air circulation.

Economic Considerations

Detailed economic assessments of particular total loss refrigeration systems are highly dependent on local costs and on likely utilization factors, and are thus beyond the scope of this paper. However, there are some general considerations which apply universally.

In overall energy or fuel terms, there is no way in which total loss refrigerants can compete with well controlled .mechanical refrigeration. Generally speaking, total loss refrigeration offers lower capital and maintenance costs but incurs higher running costs. This means that for large, regularly used installations mechanical refrigeration is the first choice.

In several transport applications, the advantages listed in Table 1 are sufficient to overcome the running cost penalties of total loss systems. The weight and simplicity advantages for airline catering are readily apparent. The overall economics can be favourable for road delivery vehicles with only short hours of use for carrying frozen foods. For static standby installations or those with very low loading factors, low capital cost can be a major attraction. For rail transport where unattended refrigeration over several days is essential, the certainty of once-off total loss refrigeration can be an overriding consideration.

If close temperature control is necessary, it is not possible to achieve this without continuous air circulation. This requires a power source to operate a fan, and the fan heat adds to the refrigeration load. The press-on unit described above provides good control, but at the expense of a higher running cost than that of other total loss systems.

The choice between carbon dioxide and nitrogen systems depends on local availability and costs. In Europe, carbon dioxide is only used where a solid refrigerant is needed, as it is relatively expensive. In the US and Canada, CO_2 is sufficiently cheap for it to be advocated as a competitor for mechanical refrigeration. In Australasia the availability; of CO_2 gives it the advantage over nitrogen.

Conclusion

Total loss refrigerants can be used effectively to provide refrigeration for the transport of foodstuffs, and a range of equipment and of techniques is available using either nitrogen or carbon dioxide. There are disadvantages of poor temperature control and high operating cost, but there are many situations in which advantages of low capital or maintenance costs or other operational factors make these techniques worth while.

Acknowledgements

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References

1. Sebranek, J. G. Use of cryogenics for muscle foods, *J. Food Tech"* 120-127 (April 1982).
2. Dougheity, J. J. Test of liquid nitrogen refrigeration system installed in frozen food delivery truck, USDA report AMS·426, Washington (December 1960).
3. Lichtenberger, H. W. Progress report on liquid nitrogen in·' transit refrigeration, Paper 19C, International Conference on Handling Perishable Agricultural Commodities, Purdue Uni: versity, Lafayette, Indiana (March 1967).
4. hYing, A. R. and Sharp, A. K. Use of dry ice for controlling the temperature of chilled foods in insulated containers, HR com~ missions C2, D1, D2, D3, El meeting, Melbourne, Annexe 1976·1, Bull. 1.1. R.
5. Ashby, B. H., Hill, R. P., McCollister, C. W. and Fink, J. K. Feasibility of using CO, snow for refrigerating railcars shipping frozen *foods,Int. J. Refrigeration,* 5,3, 146-8 (1982).