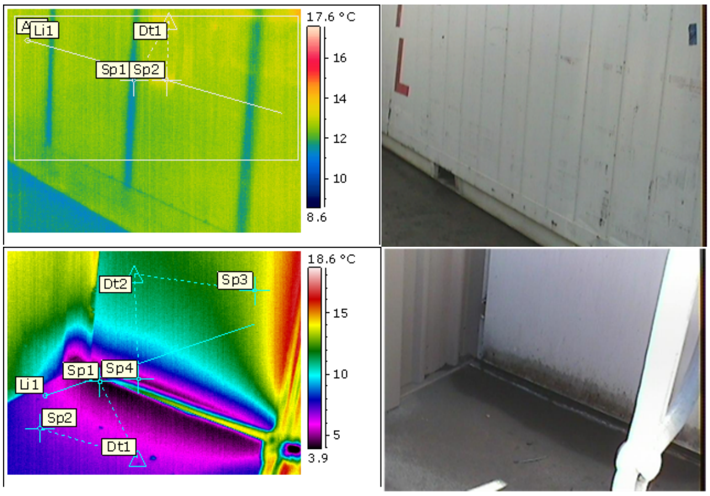
Chain of Thought

Food Chain Intelligence

Knowledge...Innovation...Action

Vol.1 No.3 Sept 2008

Welcome to our September newsletter



This is our third edition of ‘Chain of Thought’. After six months, the newsletter has been downloaded by more than 700 people from 55 countries, from Iceland to New Zealand. It is true, Google Analytics tells me so ☺ Interestingly, my blog “Chain of Events” has been visited by more than 800 people three months after I started this service. I am a believer in blogs now and I think that blogging can be a powerful communication tool in present times.

In this issue we explore the use of thermography as a predictive maintenance tools for cold stores and containers. Present environmental concerns and energy prices require an in-depth understanding of how refrigerated equipment works and the opportunities to save energy through better insulation and door seals in refrigerated land-base and transport equipment.

A second part of this article will be published in our next edition of ‘Chain of Thought’. Our next number will detail two surveys carried out in collaboration with Thermoview, a company formed in 1986 that performs preventive maintenance through thermal imaging. FCI and Thermoview are working on the development of thermography as a tool to detect heat leakages and air infiltration in air-conditioned buildings, cold stores and refrigerated containers and trucks.

If you have any comments or suggestions about this newsletter, please send feedback to info@food-chain.com.au. Feel free to forward this newsletter to colleagues that may find it of interest.

Happy reading,

Silvia Estrada-Flores

In this issue...

© ‘Chain of Thought’ is published quarterly by
Food Chain Intelligence
PO Box 1789 , North Sydney, 2059.
Ph: 0404 353 571. Fax: (02) 9460 1239

Web: www.food-chain.com.au
Writer & Editor: Dr Silvia Estrada-Flores
Email: silvia@food-chain.com.au

Thermography as a tool to detect energy-saving opportunities in cold chain equipment

SUMMARY

Heat leakage through the envelope of refrigerated equipment and air leakage through defective or damaged door seals have both consequences on heat load and refrigeration costs. Unlike other heat loads, heat leakage and air infiltration are present during the entire working time of a cold store or container.

Thermography is a technique that enables engineers to determine why some insulated bodies fail in achieving the insulation effectiveness and air tightness standards required in the industry. Defects such as thermal bridges, airflow through gaps and insulated sections that have been damaged or that have aged at different rates from the rest of the panel can all be visualised through thermography.

We calculated the energy costs of heat leakage through the panels of a large cold store (58,500 m^3) for frozen products as a function of the insulation effectiveness (k_{value}) factor. Panels with low insulation effectiveness (k_{value}=2.98 m^2 K/W) can lead to extra energy costs of AUD$32,000.00 per year, in comparison with panels with a k_{value} of 7.1 m^2 K/W. Although ASHRAE recommends a k_{value} ranging from 6.2 to 7 m^2 K/W, it is well known that ageing and damage to panels can lower the insulation efficiency in 5 to 12% per year. Additionally, we calculated the energy costs resulting from varying degrees of door sealing efficiency for the same cold store, assuming the existence of five sliding doors (2.3 m x 2.7 m) and two staff access doors (0.8 m x 2 m) . Our estimates indicate that even with a few gaps representing 10% of the total door seal area per door, the annual energy costs due to air leakage are substantial (i.e. about $5,000 per year).

We also estimated energy costs resulting from varying degrees of insulation efficiency in a 20 ft ISO container at –18 °C. An increase in k_{value} from the optimum value of 0.4 W/m2 K to 0.8 W/m^2 K would lead to an extra energy expenditure of US$2,000 per year. If the K_{value} increases to 1.2 W/m^2 K, the extra energy costs would be US$4,000 per container per year as compared with a new container with optimum insulation. In regards to the effect of air infiltration through defective door seals, we estimate that gaps representing 10% of the total door seal area lead to annual extra energy costs of about US$4,480 per year.

In a global context, there are about 1,380,000 refrigerated containers in use. If only 3% of these present a k_{value} of 1.2 W/m^2 K and leaky door seals with gaps equivalent to 20% of the total sealed area, the annual extra energy costs required to operate these containers (as opposed to containers in good conditions) would be US$325.5 millions. Further, the use of these 41,400 containers would increase the carbon footprint of refrigerated shipping operations in 1.4 million tonnes of CO2 equivalent per annum.

In our cold store and container case studies, the financial case for the use of annual thermographic surveys to detect uneven degradation of insulated panels and air leakages through door seals in cold stores and containers is strong. The cost-benefit ratio of corrective and preventive maintenance (including an annual thermographic survey) in a cold store with an annual 10% increase in door seal gaps and a 6% decrease in k_{value} (due to ageing and damage) is 1.56. In a container powered by marine diesel oil, for each dollar invested in maintaining good seals and insulation values the return would be $1.78. Thermography is an attractive preventive maintenance solution for cold stores and containers.

Thermography as a tool to detect energy-saving opportunities in cold chain equipment

Introduction

Thermography is a two-dimensional, non-contact technique that allows fast surface temperature mapping of objects subjected to a large temperature difference from their surroundings. Given certain assumptions in terms of the radiative heat transfer, the radiation captured by a thermographic camera can be interpreted as surface temperatures. The temperature values can then be displayed in images that show temperature gradients in a colour scale.

Thermography and its use to detect heat leakages

The use of thermography to assess the insulation efficiency of buildings and cold stores has been thoroughly investigated since the 1970's. A less investigated application is the use of thermography to improve refrigerated transport equipment design. Although there are other methods available to test insulation efficiency in trucks and containers (e.g. thermal tests), these are based on the average temperature responses of the entire insulated body. These methods do not highlight specific thermal bridges that contribute to poor insulation effectiveness.

Conventional thermal tests for refrigerated trucks and containers are the AS 4982-2003, AS3711.5-2000, European ATP, US ARI Std 1110 2001, ISO 1496-2:1996. These techniques used to measure insulation efficiency require special conditions (e.g. temperature, air velocities) that can only be achieved in special testing chambers. In cold stores, thermal testing of the insulation requires an empty condition, disrupting the normal cold store operation and requiring temperature changes that may go on for days. Thermography is a technique that can be applied frequently (e.g. six-monthly or yearly), even when the cold store/container/truck is full of product, with little interruption of the equipment's operation.

Particular defects that can be detected through thermography in cold stores and transport equipment are highlighted in Table 1 [1,2].

Heat transfer from the external (ambient) space to the internal cargo/storage space through the walls, roof and floor of an insulated equipment is an ever present heat load during the operation of the equipment. Therefore, low insulation effectiveness due to one or more of the defects discussed in Table 1 will significantly increase the energy spent to keep the desired temperature in the cold store/container, when compared with optimally insulated equipment.

TABLE 1. HEAT LEAKAGE SOURCES IN INSULATED EQUIPMENT THAT CAN BE DETECTED THROUGH THERMOGRAPHY

EQUIPMENT	DEFECT
COLD STORES	• Thermal bridges protruding through the insulation (e.g. hinges, corners and brackets). • Uneven destruction of the insulation (e.g. forklift damage). • Defective insulation 'curing'. In new insulation, a period of one or two months after manufacture is needed before the panel is installed, to allow for a settling of the insulation material in the panel. If the panel is installed too soon after manufacture, the insulation can retract and separate from the outer layers of the panel/wall. Poor adhesion of the insulation layer to the rest of the wall materials can also arise from thermal stress of the wall components during particularly warm days. • Defective door seals and gaskets that allow the entrance of warm air through gaps. Pressure differences between external and internal environments can also lead to an increase in air infiltration through door seals. • Water seepage and moisture migration within the insulated wall. This leads to an increase in the wall's thermal conductivity and an increase in the volume and weight of the insulation, thus increasing the mechanical stress in structures. If the equipment operates at temperatures below 0 °C, the presence of ice will create cracks in the insulation and a separation of the wall layers. • Deterioration of insulation due to uneven ageing. • Defects in joining methods. Poor bonding of materials and sub-optimal distribution of insulation thickness between roof, floor and sidewalls can create air gaps, which also decrease the insulation effectiveness of the body.
CONTAINERS AND TRUCKS	All of the above, plus: • Structural pockets to fit lights and handles usually decrease the thickness of the insulation by 12 to 15 mm in those areas. • Metallic latches, structural ribs, hinges, rivets or screws often impinge on the insulation layer. • Accelerated aging of the insulation around gaps in the seams or rivet holes.

Insulation aging, insulation damage and the effect of cold air leakages through defective door seals and gaskets are three common defects that decrease insulation effectiveness in insulated bodies. These defects may pass unnoticed during visual inspections. However, symptoms such as a decrease in temperature control or an increase in energy costs are likely to be noticed. To undertake corrective measures, the engineer must find whether the decrease in insulation performance is due to leaky door seals, mechanical damage or water damage . In these cases, a thermographic survey can detect specific "cold spots" that indicate the existence of thermal bridges, insulation damage or air infiltration. A careful interpretation of these results provides information that allows calculation of the extra energy costs and cost-benefit ratios of repairs and corrective actions.

Energy use in refrigerated systems

Performance of a refrigeration cycle is usually described by a coefficient of performance (COP), defined as the benefit of the cycle (i.e. amount of heat removed) divided by the required energy input to operate the cycle [3]. This concept is highly relevant to understand energy use in refrigeration plants, given that the electricity used by the compressors is the major energy input in a refrigerated equipment. Although pumps, condensers and other ancillary equipment also consume electricity, the cumulative use of all ancillaries is only 10 to 15% of the compressor energy use [4]. The calculation of the COP is performed by means of Eq. (1):

$$COP = \frac{\phi_t}{E_c} \cdots\cdots\cdots (1)$$

Where E_c = compressor energy use (kW) and $\varnothing_t$ = total facility heat load (kW).

A 'heat load' is an energy flow entering the refrigerated space. The refrigeration system must be sized to cope with a variety of heat loads, including the energy required to cool product and packaging, the transmission of heat through the equipment's envelope and in the case of fresh fruits and vegetables, the heat of respiration and the air exchanges required to keep a suitable gaseous atmosphere for respiring produce. There are also miscellaneous heat loads arising from door openings, fan motors, defrost, lights and product weight loss, amongst others.

Heat leakage through insulated panels

Typically, the manufacturer's information on the insulation efficiency of panels mentions the "un-installed" thermal performance of the panel, or how the panel performs as a uniform slab of insulation. During the installation process, the panel's integrity will decrease as rivets, holes and other invasive techniques are used to build the insulated body. Therefore, the insulation efficiency of an installed panel is normally lower than the efficiency estimated by the manufacturer. The "installed" insulation effectiveness value reflects the properties of the insulation, the building techniques used during the equipment's manufacturing, the "tear and wear" and the age of the equipment. In cold stores, researchers found that the thermal insulation of a 2 year-old store, built with expanded polystyrene (EPS) sandwich panel, was 23% less efficient than the nominal efficiency of the EPS panel, as established by the manufacturer [6]. Other study showed that the insulation of a 21-year old cold store was about 47% less efficient than the nominal EPS efficiency [7].

The insulation effectiveness is normally referred to as a k_{value}. The k_{value} reflects the properties of the "installed" insulation, considering the design and manufacturing process of the insulated body. A low k_{value} indicates high insulation efficiency; a high k_{value} indicates poor insulation effectiveness.

At a normal rate of ageing, the k_{value} of insulation increases at a rate of 5% per year [8]. However, if the insulation is damaged due to water seepage or by impacts from forklifts or other containers during loading/ unloading maneuvers, the k_{value} will increase more than the expected 5% per annum.

The heat load through each insulated panel of the cold store/container is calculated through the general Eq.(2):

$$Q_{wall} = k_{value} A\left(T_{out} - T_{in}\right) \cdots\cdots\cdots (2)$$

Where Q_{wall} is the heat leakage through the cold store's walls, ceiling and roof; A is the panel's area (m^2) k_{value} is the wall's overall heat transfer coefficient (W/m^2 ^{o}C) and T_{in} and T_{out} are the average internal and external temperatures of the cold store/container.The k_{value} is a parameter that is better estimated through thermal tests specially designed for cold stores and containers. In the absence of a measured k_{value}, an approximation can be made through Eq.(3):

$$k_{value,wall} = \frac{1}{\frac{1}{ho} + \sum \frac{x_i}{k_i E} + \frac{1}{hi}} \cdots\cdots (3)$$

Where *ho* and *hi* are internal and external the convective coefficients (W/m^2 ^{o}C); *x* is the thickness of each of the wall's layers (m);*k* is the thermal conductivity of each of the wall's layers (W/m ^{o}C); and *E* is an insulation effectiveness factor. This factor is selected according to the size and age of the cold store. For sandwich panel, a factor of 1.2 for large (>5,000 m^3) new cold stores can be selected. For cold stores older than 10 years, the *E* factor increases to 2 [4].

The estimation of the refrigeration energy costs due to heat leakage through panels during a year's performance also requires the COP of the compressor and electricity costs. The average compressor energy is calculated from Eq.(1).The energy use by ancilliaries is assumed to be 15% of the compressor's energy.

Assumptions about the equipment's working days per year are also necessary to calculate the annual energy costs introduced by heat leakage through walls. The annual energy costs due to heat leakage are calculated through Eq. (4):

$$EC = Cost\ \ of\ \ energy\ \left(\frac{\$}{kWh}\right)\left(\frac{kWh}{year}\right)...(4)$$

Where *EC* = annual energy costs ($). In the case studies that follow, the electricity cost used was AUD$0.14/kWh, which is a rough estimate of current electricity charges in Victoria (AUS) when network and energy charges, line loss, metering and renewable energy levies are included. This is an average rate for plant operating 24/7 and using peak and off peak energy on roughly equal proportion[a].

The operation of refrigerated containers onboard ships is normally reliant on diesel generators that run in fuel and lubricant oil. These consumables represent the most significant operating costs in a refrigerated container operation.

A study carried out in 2005 [5] investigated the energy costs involved in the operation of refrigerated containers. The study developed correlations between the specific fuel consumption and the cost per kWh in refrigerated containers. These correlations were used to build Table 2, which shows the costs per kWh of refrigeration expected for the three most common types of energy generation for containers onboard vessels (power packs, diesel generators and main engine with shaft generator) at current fuel prices.

TABLE 2. EXPECTED SPECIFIC FUEL CONSUMPTION AND ENERGY COSTS FOR THE THREE MOST COMMON TYPES OF ENERGY GENERATION FOR CONTAINERS ONBOARD VESSELS.

Type of generator	Type of fuel	*Range of fuel oil prices considered for this calculation	Specific fuel consumption	Specific operation costs (including fuel and lub oil), corrected at 2008 fuel prices
Mobile diesel generators (power packs)	Marine diesel oil (MDO)	US$ 1,000 to US$ 1,100 per ton	280 to 330 g/kWh	US$0.27/kWh to US$0.36/kWh
	Marine gas oil (MGO)	US$ 1,000 to US$ 1,100 per ton	210 to 260 g/kWh	US$0.21/kWh to US$0.28/kWh
Diesel generator	Intermediate and heavy fuel oils (HFO/IFO)	US$ 500 to US$600 per ton	240 to 290 g/kWh	US$0.11 ct/kWh to US$0.18 ct/kWh
Main engine with shaft generator	Intermediate and heavy fuel oils (HFO/IFO)	US$ 500 to US$600 per ton	190 to 220 g/kWh	US$0.10/kWh to US$0.13/kWh

Energy costs and carbon footprint of heat leakage through insulated panels

The cold store case study in this article is a facility with the characteristics shown in Figure 1. Figures 2a and 2b show the heat leakage and energy costs (in AUD and carbon emissions) assuming a range of k_{values}, from the "best practice" insulation effectiveness factor for a frozen cold store [9] to the value expected from a 10-15 year old cold store with insulation damage.

The characteristics of the container used in this case study are shown in Figure 3. Figures a and 4b show the heat leakage and energy costs in USD and carbon emissions[b] respectively, assuming a range of k_{values}, from the "best practice" insulation effectiveness factor for a container [9] to the value expected from a 10 -15 year old container with insulation damage.

[a] Gabor Hilton, 2008. Personal communication. Oxford Cold Storages, Laverton North VIC.

[b] The emission factor used were: Electricity (end user): 1.22 kg CO2 eq/kWh, used for sites in Victoria (AUS) [10]; MDO and MGO: 3,206 kg CO2 eq/ton fuel) [11]; MGO: 3,114 kg CO2 eq/ton fuel [11].

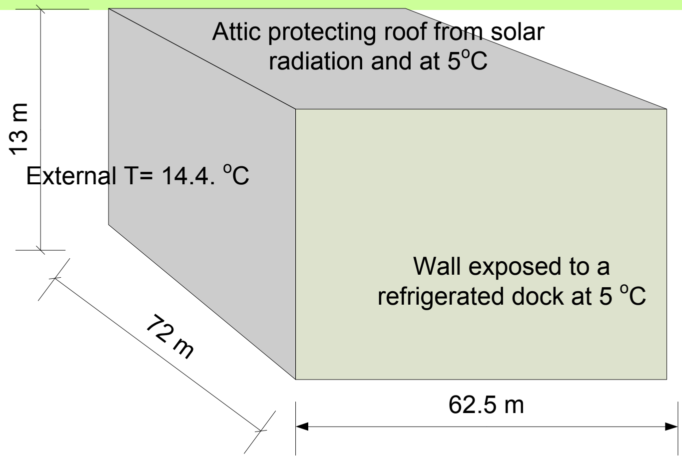


FIG. 1. Hypothetical cold store used in the heat leakage case study. Note: only panels in sidewalls and roof were considered. The concrete floor is a special case not considered in this study.

- Frozen cold store used 344 days per year, 24 hrs/day.
- Walls and ceiling made on sandwich panel (insulation thickness = 200 mm in sidewalls and 250 in ceiling).
- External cladding, thus avoiding direct solar radiation.
- One wall (62.5 m x 13 m) is exposed to a refrigerated dock at 5 °C.
- An attic protects the roof from solar radiation.
- Convective currents from the coldstore to the attic lower the external temperature to about 5°C in the roof.
- Three walls are exposed to an ambient temperature of 14.4°C (which is the average annual temperature in Laverton VIC).
- Cold store temperature= –23 °C.
- COP = 2
- Electricity costs = $0.14/kWh.

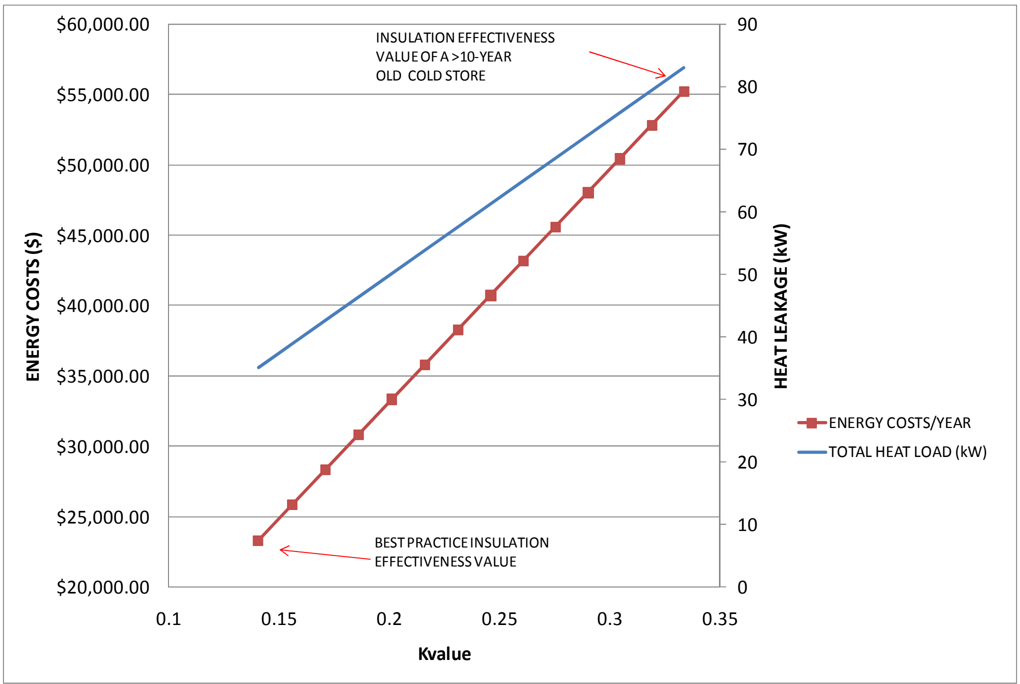
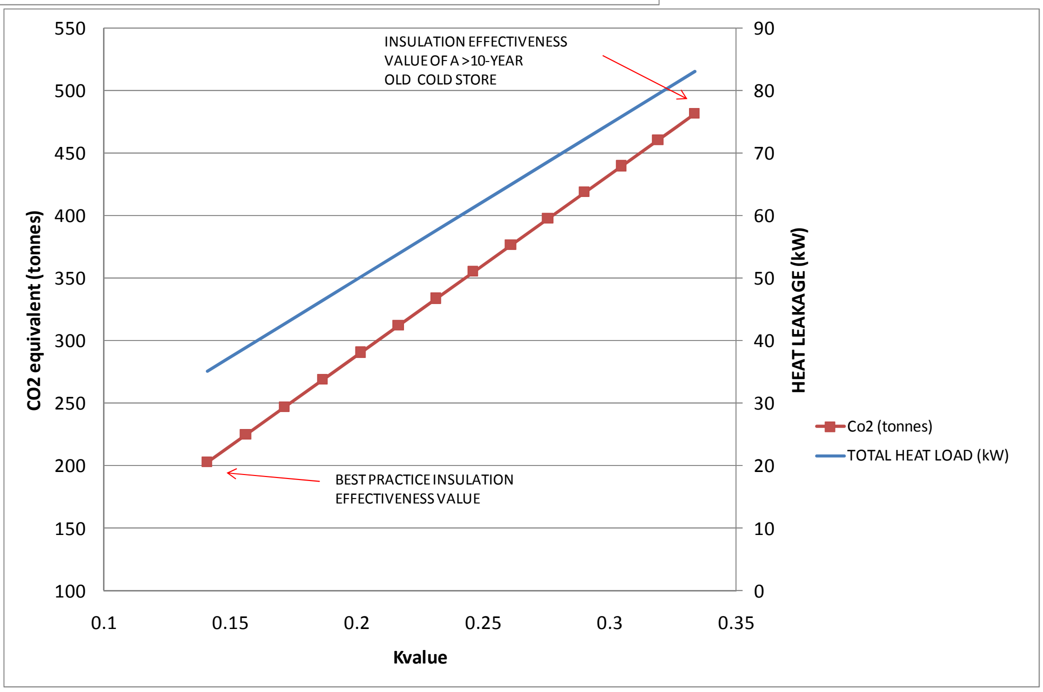


FIG. 2a (left). Electricity costs arising from heat leakage through the envelope of the frozen cold store described above, at various levels of insulation effectiveness ($k_{value,}$ W/m^2 K). The best practice k_{value} is representative of a new cold store with a typical degree of thermal bridging introduced during construction. A k_{value} above 0.33 is representative of a 10-15 year old cold store for frozen products.

FIG. 2b (right). Carbon emissions arising from heat leakage of the frozen cold store described above, at various levels of insulation effectiveness (k_{value}, W/m^2 K). The best practice k_{value} is representative of a new cold store with a typical degree of thermal bridging introduced during construction. The highest carbon emissions were found for a k_{value} representative of a 10-15 year old cold store.



Chain of Thought

FIG. 3. Container used in the heat leakage case study.

- ISO 20 ft frozen container used a cumulative 260 days per year, 24 hrs/day.
- K_{value} (new) = 0.4 W/m^2 K
- Exposed to an average ambient temperature of 21°C.
- Internal temperature= –18 °C.
- A ratio of cooling capacity-to-power consumed of 0.93 (which includes energy use by ancilliaries) was assumed.
- External dimensions: 6 m (L) x 2.42 m (W) x 2.38 m (H)
- Insulation thickness:
    - Slides and door = 70 mm
    - Roof = 100 mm

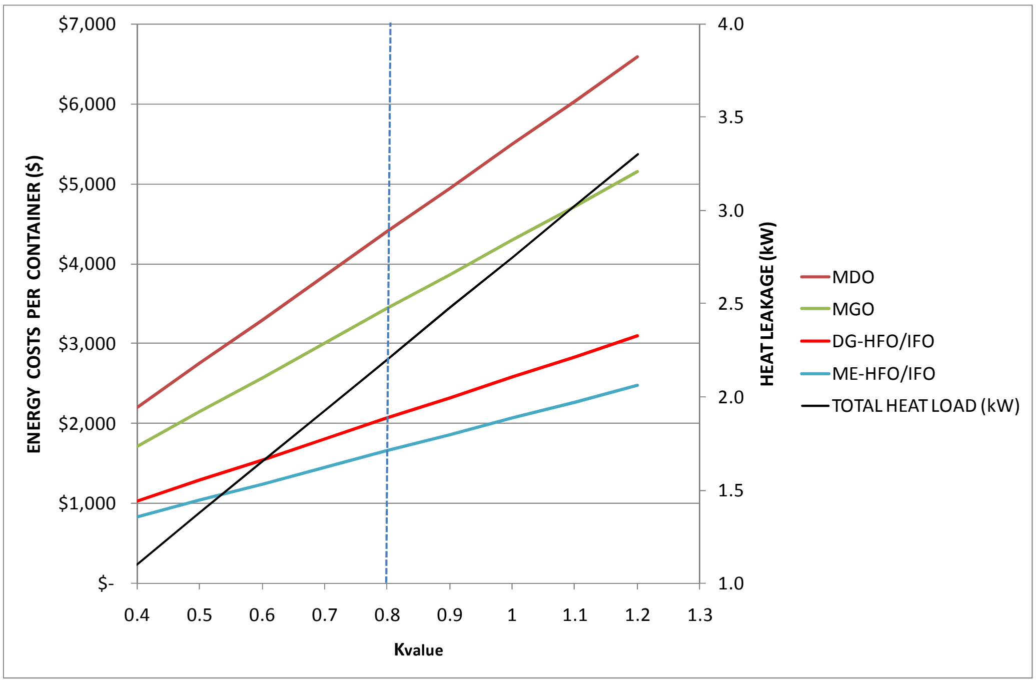
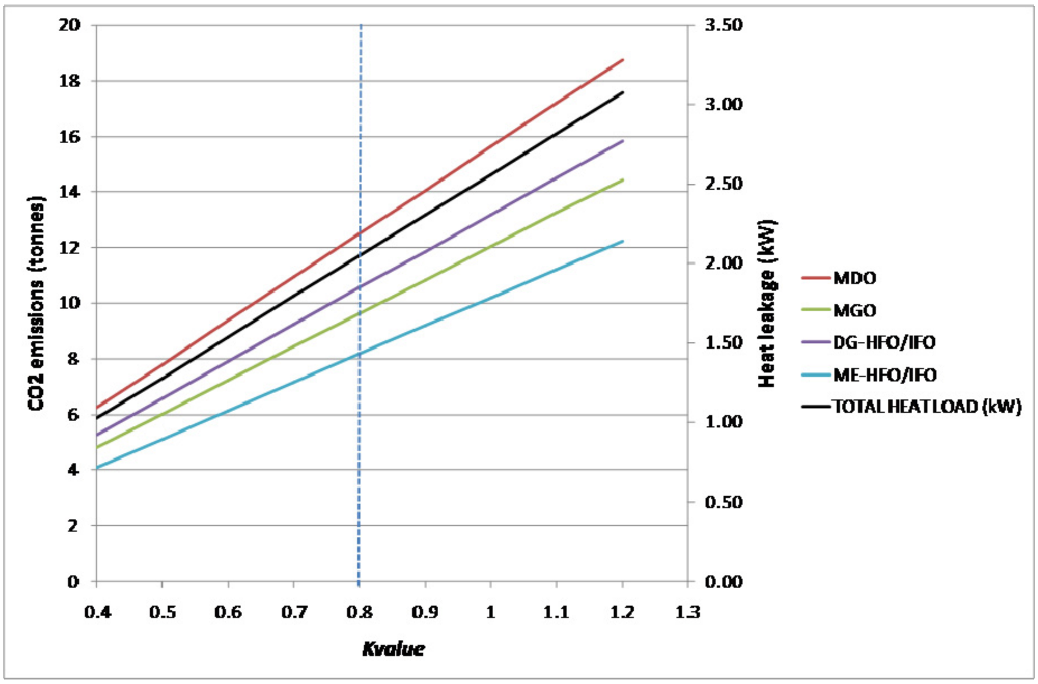


Fig. 4a (left). Annual energy costs arising by heat leakage in a frozen 20 ft container, at various levels of insulation effectiveness (k_{value}). The best practice k_{value} =0.4 W/m^2 K is representative of a new container with a typical degree of thermal bridging introduced during construction. A k_{value} =0.8 W/m^2 K is representative of the normal ageing of the insulation after 15 years of use. A k_{value} =1.2 W/m^2 K is representative of a +15-year old container with insulation damage.

Fig. 4b (left). Annual carbon emissions arising from heat leakage in a frozen 20 ft container, at various levels of insulation effectiveness (k_{value}). The best practice k_{value} =0.4 W/m^2 K is representative of a new container with a typical degree of thermal bridging introduced during construction. A k_{value} =0.8 W/m^2 K is representative of the normal ageing of the insulation after 15 years of use. A k_{value} =1.2 W/m^2 K is representative of a +15-year old container with insulation damage.



Notes: MDO= mobile diesel generator using marine diesel oil; MGO= mobile diesel generator using marine gas oil; DG-HFO/IFO= Diesel generator using fuel oils; ME-HFO/IFO= Main engine with shaft generator using fuel oils. Costs in US dollars.

Air infiltration through leaky door seals

The effect of leaky door seals is often seen as a factor decreasing the insulation effectiveness of a refrigerated space or as an insignificant air infiltration flow when compared to door openings. However, air leakage through defective seals occurs at all times during the equipment's operation and thus it is a constant drain of energy. In particular, the cost of the increased defrosts due to permanent air leakages is significant.

Air infiltration into refrigerated spaces has important implications in the design and operations of these, including [7]:

- Latent and sensible heat loads: warm moist air entering the refrigerated space must be cooled (i.e. sensible heat) and the moisture introduced must undergo heat and mass transfer phenomena to reach the conditions inside he refrigerated space.
- Defrosting: the moisture in the air infiltrated is deposited as frost on the cooling coils resulting in a reduction of refrigeration efficiency and the need to defrost, which in turn increases the energy bill.
- Refrigeration costs: the capital (e.g. refrigeration plant size) and operating (e.g. energy) costs of the refrigeration system are proportional to the heat load.
- Frosting: the moisture in the entering air can also be deposited as ice on the product, affecting its appearance. Any frost formed in the walls of the insulated body will create a safety hazard for operators.

Although research on door openings in cold stores has been published, little is known about the effect of pervasive air infiltration to cold stores and containers through door seals. East et al [7] found that Tamm's equation predicted accurately the air infiltration through narrow vertical gaps, as measured by a tracer gas decay methodology. Air infiltration through horizontal gaps was better represented by hydrodynamic theory for a flow through an orifice. In this article we used a combination of Tamm's equation and the hydrodynamic approach to investigate air leakage through door seals (Eq.5):

$$V_{air\_leak} = 0.67 \ \ Av \sqrt{2\, g \ H \ (1-s)\,/\,(1+s^{1/3})^3}$$
$$+$$
$$0.68\, Ah \sqrt{2*(\rho_{in} - \rho_{out})\, g\, h / \rho_{in}} \text{.......}(5)$$

Where V_{air_leak} is the volumetric air infiltration (m^3/s); Av is the area of vertical gaps (m); H is the door or gap height (m); g is the gravitational acceleration (m/s^2); s is the ratio of warm (outside) air density to cold (inside) air density; Ah is the area of horizontal gaps (m^2); r_{in} is the density of the air inside the cold store (kg/m^3); r_{out} is the density of the air outside the cold store (kg/m^3); and h is the separation between the cold store's door and the floor (m).

The area of vertical and horizontal gaps were calculated as follows:

*Av= gap factor*total vertical area covered by the seal* …………(5a)
*Ah=gap factor*total horizontal area covered by the seal* …………(5b)

The gap factors (also expressed as a % gap) is a fraction from 0 to 1 used to assess the effect of varying degrees of sealing effectiveness.

The heat load due to air leakage was calculated as follows:

$$Q_{air\_leak} = V_{air\_leak}\ \rho_{in}\left(h_{in} - h_{out}\right)...(6)$$

Where Q_{air_leak} is the average air infiltration heat load (W) and h_{in} and h_{out} are the enthalpies of the air inside and outside the cold store/container, respectively (J/kg).

The defrost heat load required to melt the extra humidity in the evaporator's coil added by the air leaked into the refrigerated space is calculated as:

$$Q_{defrost} = V_{air\_leak}\rho_{in}\left(H_{in} - H_{out}\right)\Delta hl....(7)$$

Where $Q_{defrost}$ is the average defrost heat load (W), H_{in} and H_{out} are the absolute humidities inside and outside the cold store/container, respectively (J/kg) and Δhl is the latent heat of freezing for water (J/kg). The total heat load introduced due to leaky seals (Q_{leak}, W) is:

$$Q_{leak} = Q_{air\_leak} + Q_{defrost} \text{..........}(8)$$

Given that the proposed air infiltration model has not been tested experimentally, a qualitative assessment of published air leakage rates [12] with respect to the gap factors back-calculated through Eq. (5) was carried out. The results are shown in Table 3.

determined. Given the lack of more accurate information, we will assume that the same air infiltration theory through leaky seals applies in both cold stores and containers.

TABLE 3. Qualitative comparison of published air tightness values measured in cold storage doors, as presented in reference [12] and the estimated % gap using Eq.(5). *Notes: SDA, working with sustained door action mode; IDA, working with instantaneous door action mode; SC, strip curtain.*

Door	H (m)	W(m)	T cold store (oC)	Toutside (oC)	Air tightness (m3/s)	Observations	Predicted % gap
A1	2.4	1.8	-0.4	17.7	0.008	Good door seal, No traffic, good SC	2
A2a	2.75	1.8	-14.6	18.2	0.018	Good door seal, SDA, good SC	13
A2b	2.75	1.8	-1	21.2	0.014	Good door seal, SDA, good SC	12
A3	3	2.6	-16.2	14.7	0.012	Good door seal, SDA, reasonable SC (a small gap between strips), enclosed door	7
A4	3	2.7	3.3	18.7	0.02	Good door seal, SDA, good SC	16
A5	3.1	2.4	-18.4	18.4	0.06	Good door seal, IDA, without a SC	30
A6	3.3	2.4	-21.8	20.5	0.066	1.5 cm gap at bottom covered	31
					0.09	IDA, not good door seal (1.5 cm gap at bottom), one strip missing	43
A7	3.05	2.4	-13.9	18.4	0.027	2 cm gap at bottom covered	15
					0.034	IDA, poor door seal	19

Chen *et al* [12] found a correlation between air tightness and door seal length and air tightness and the temperature difference between the cold store and the ambient air at the other side of the door. The authors found the poorest performances in doors A5 and A6, which are reflected in the higher % gap factors back - calculated from Eqs. (5), (5a) and (5b). Further, the authors observed that doors A1 and A3 showed the lowest air iniftration, which coincides with the lowest % gap calculated (2 and 7%, respectively). Although more research on the factors affecting air tightness in installed refrigerated equipment need to be conducted, Eq. (5) seems to be accurate enough to estimate air leakage in closed door scenarios.

In regards to refrigerated containers, most published air tightness values were obtained by means of standard pressure tests. These tests create an artifial pressure differential that can be quite different from the actual pressure differential observed during the container's normal operation. As pointed out by Smale *et al.*, [13] air tightness values obtained through pressure tests provide arbitrary figures that cannot be easily related to actual leakage rates in practical application. Further, container air tightness values available in the literature were measured during off power conditions. Therefore, the effect of temperature gradients between internal and external environments cannot be

The calculation of energy costs as a function of air leakage through door seals was performed using Eqs. (4) and (5) to (8) for the cold store and container examples.

Figure 5 shows a plane view of the cold store case study (also presented in Fig.1) and relevant data used in the air leakage calculations. Figures 6a and 6b show the heat load and energy costs in AUD and carbon emissions, respectively as functions of the % gap.

Figure 7 shows the container case study and data used to assess the air infiltration through door seals. Figures 8a and 8b show the heat load and energy costs in USD and carbon emissions, respectively as functions of the % gap.

Chain of Thought

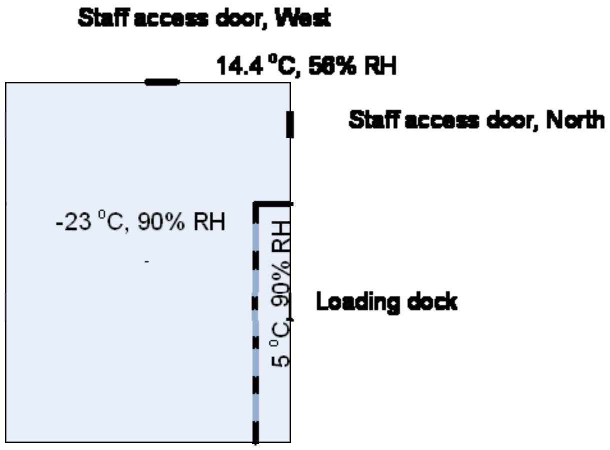


FIG. 5. Hypothetical cold store used in the air leakage case study.

- Frozen cold store used 344 days per year, 24 hrs/day.
- Doors opened during a cumulative period of 15 days during the year.
- There are two staff access doors (0.8 m x 2 m) that lead to the exterior part of the building at ambient conditions (14.4°C and 56% relative humidity).
- Further, there are five sliding doors (2.3 m x 2.7 m) that lead to a refrigerated dock at 5 °C and 90% RH.
- The seals for both staff access doors and sliding doors have a thickness of 2 cm.
- Cold store temperature= –23 °C.
- COP = 2
- Electricity costs = $0.14/kWh.

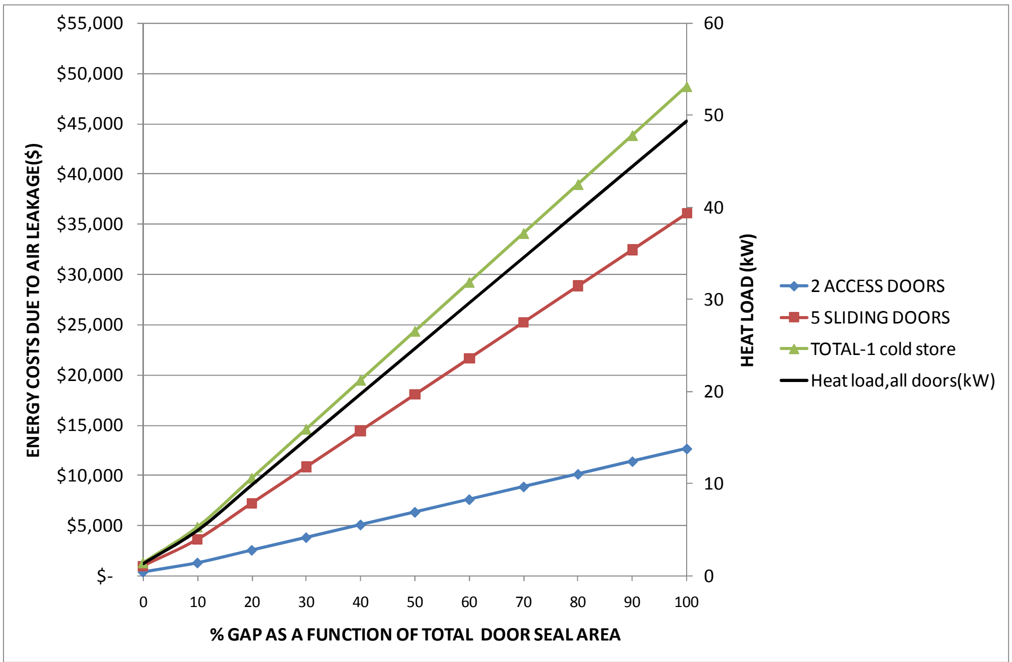
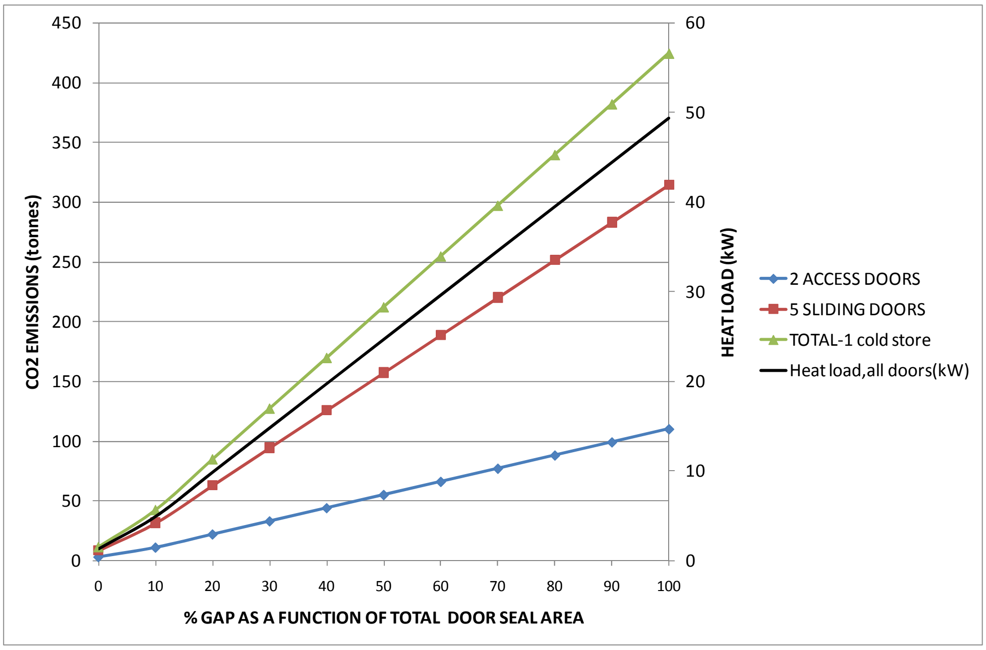


FIG. 6a (left). Electricity costs arising from air leakage through the door seals in a frozen cold store, at various levels of leakage. The blue line is the estimation of energy costs due to leakage through two 0.8 m x 2 m access doors; the red line represents the costs of air leakage through five 2.3 m x 2 m sliding doors. The green line represents the total energy costs due to air leakage in all doors.

FIG. 6b (right). Carbon emissions arising from air leakage through the door seals in a frozen cold store, at various levels of leakage. The blue line is the estimation of energy costs due to leakage through two 0.8 m x 2 m access doors; the red line represents the costs of air leakage through five 2.3 m x 2 m sliding doors. The green line represents the total energy costs due to air leakage in all doors.



Note: the best practice air infiltration value was set at 0.0022 m^3/s, in view of the conclusions of Chen et al. [12], which observed that the air leakage per length of door seals for sliding doors with seals in good condition was about 0.0004 to 0.0008 m^3/s m.

Chain of Thought

- 20 ft frozen container used a cumulative 260 days per year, 24 hrs/day (utilization rate = 72%).
- Exposed to an average ambient temperature of 21°C and RH of 60%.
- Internal temperature= –18 °C and RH=90%.
- Door dimensions = 2.38 m(W) x 2.18 m (H) with a total seal area of 0.182 m^2 (seal thickness= 0.02 m)
- A ratio of cooling capacity-to-power consumed of 0.93 (which includes energy use by ancilliaries) was assumed.

FIG. 7. Container used in the heat leakage case study.

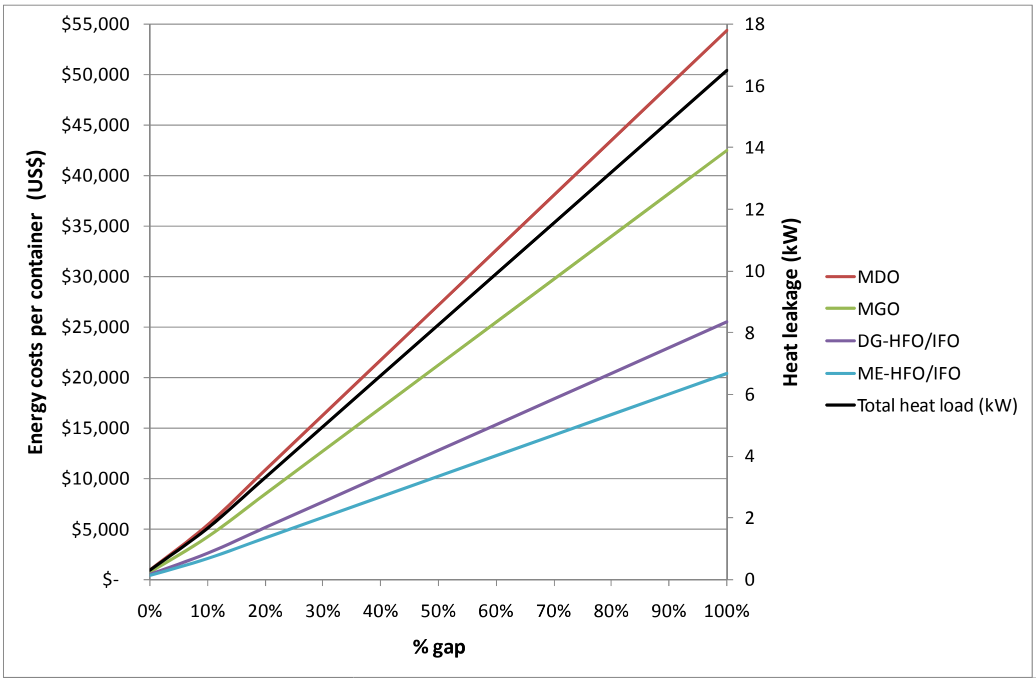
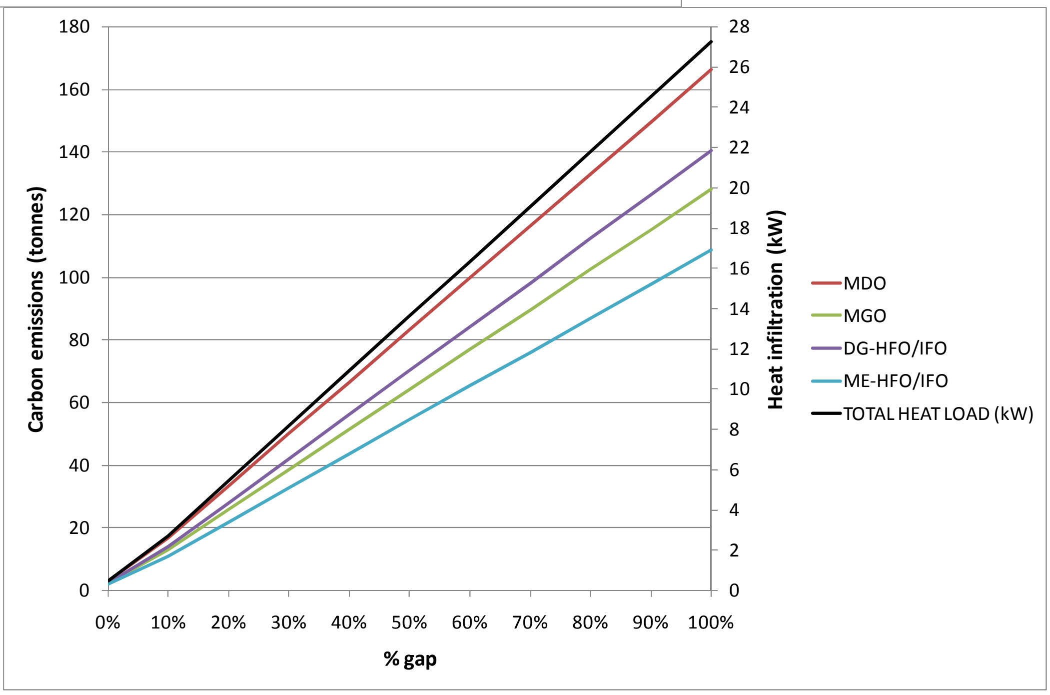


Fig. 8a (left). Annual energy costs arising from air leakage in a frozen 20 ft container, at various % gap factors. The "best practice" air leakage rate is equivalent to 10 m^3/h, which is the accepted maximum leakage in the ISO 1492 standard for thermal containers. Leakages over this initial value are all representative of damaged door seals in containers.

Fig. 8b (left). Annual carbon emissions arising from air leakage in a frozen 20 ft container, at various % gap factors. The best practice air leakage rate is equivalent to 10 m^3/h, which is the accepted maximum leakage in the ISO 1492 standard for thermal containers. Leakages over this initial value are all representative of damaged door seals in containers.



Notes: MDO= mobile diesel generator using marine diesel oil; MGO= mobile diesel generator using marine gas oil; DG-HFO/IFO= Diesel generator using fuel oils; ME-HFO/IFO= Main engine with shaft generator using fuel oils. Costs in US dollars.

From Figs. 6a and 6b, the following conclusions can be drawn:

- Relatively small air leakages through a cold store's door seals (e.g. gaps representing a 10% of the total door seal area) lead to substantial annual extra energy costs per cold store (i.e. about $5,000).
- In sites that have several cold stores with neglected door seals (e.g. 50% gaps), the total energy costs due to air leakage can well be above $100,000, depending on the number of doors.
- When one considers that the cost of replacing seven door seals is about $1,200.00[b], it makes sense to take corrective actions (e.g. fix/ replace the door seals) as soon as door seals present any signs of leakage.

[b] *Including seals priced at $10.00 per meter and 7 hrs of labour at $50/hr.*

From Figs. 8a and 8b, the following conclusions can be drawn:

- Relatively small air leakages through the container's door seals (e.g. gaps representing a 10% of the total door seal area) lead to substantial annual extra energy costs per container (i.e. over US$2,000 for ME-HFO/IFO and over US$5,000 for MDO).
- When one considers that the cost of replacing a door seal ranges between $300 to $500 (including materials and labour), it makes sense to take corrective actions (e.g. fix/ replace the damaged seals) as soon as the container's door present any signs of leakage.
- To add a global perspective of the impact of defective door seals, we should consider that worldwide there is an estimated fleet of 1,380,000 refrigerated containers. If only 3% of the total number of containers worldwide have damaged seals that represent 20% of the total seal area (i.e. increasing the air leakage from less than 10 m^3/h to 113 m^3/h), the extra energy costs due to air leakage would be about US$270 million per year.
- Further, the operation of these 41,400 containers would increase the carbon footprint of refrigerated containment operations in 1 million tonnes of CO2 equivalent per year, in comparison to containers with the original air leakage rate of 10 m^3/h, as required by ISO 1492.

It may be surprising that mild air leakage through the doors seals of a refrigerated equipment (e.g 10%) can lead to higher energy costs per annum than the equivalent of a year's worth of insulation ageing. However, the extra energy required to balance the mixture of leaked warm, moist air and the air inside the refrigerated space is significant. Moisture will eventually move towards the evaporator, producing frost. The evaporator will eventually need defrosting. The latent heat needed to defrost the excess humidity due to air leakage represents about 50% of the total air infiltration heat load due to faulty seals, thus increasing the total energy costs.

The financial case for annual thermographic surveys

In the cold store case study (Fig.5), an annual loss of 6% of insulation effectiveness (k_{value})[c] can add an average of $2,455 per year to the energy bill. The loss of door seal effectiveness is more difficult to assess, because it depends on the type of door, its use and the seal materials. For the sake of this calculation, we will assume that every year the seals lose 10% of performance, therefore increasing the energy bill in $4,868 for five sliding doors and two access doors. Total estimated extra energy costs for this example would be $7,323 per year.

In the container case study, using again an annual loss of 6% in k_{value} and 10% in seal efficiency, the annual energy increase would be about US$5,611 (AUD$6,730).

A thermographic survey at a cost of $2,500 per 2 hrs would enable the owner of the site or fleet to take advantage of energy saving opportunities through improved seals and insulation.

Maintenance expenses can vary. For the cold store example, we have estimated a cost of $1,200 for replacement/fixing of door seals and about $1,000 to repair a panel area of 5 – 10 m^2 per year.

[c] *Although typical loss of insulation value for containers and trucks due to ageing is between 3% and 5% per year [14], these percentages do not consider damages to insulation via water seepage or forklift use. Therefore, we have assumed a 6% loss rate to include tear and wear effects.*

TABLE 4. Estimated cost/benefit ratio weighing expenses and energy saving benefits of preventive and corrective maintenance in the cold store and container case studies.

	COLD STORES	CONTAINERS
Annual thermographic survey/container	$ 2,500	$ 2,500
Repair costs per year	$ 2,200	$ 1,291
Energy costs saved per year	$ 7,323	$ 6,730
Total benefit	$ 2,623	$ 2,939
Cost/benefit ratio	**1.56**	**1.78**
CO2 savings (tonnes)	**63.82**	**17.16**

For the container example, we have estimated a cost of $341 for replacement/fixing of door seals and about $950 to repair a panel area of 5 – 10 m^2 per year.

Table 4 presents the cost/benefit ratios for cold stores and containers, using the assumptions described above.

Our analyses indicate that corrective and preventive maintenance, including an annual thermographic survey, presents an attractive payback for the cold chain industry.

In cold stores, for every dollar invested in maintaining good insulation effectiveness, including an annual thermographic survey program to detect door seal or insulation failure, the return would be of AUD$1.56 per year. These results consider one cold store only. These cost/benefit ratios assume that all affected seals are replaced annually.

In containers, for every dollar invested in maintaining good insulation effectiveness, including an annual thermographic survey program to detect door seal or insulation failure, the return would be of AUD$1.78 per year. These results consider one container only.

The benefits also need to be assessed in view of the decrease in carbon emissions using simple measures such as door seals and insulation maintenance: for each cold store and container that are properly maintained in these two aspects, the carbon emission avoidance would be equivalent to removing 281 and 76 cars from Victorian roads per year, respectively.

These numbers can only get better if we consider the case of Australian refrigerated trucks, which usually present larger air leakage rates and lower insulation effectiveness values than containers. Recent published research has addressed the carbon footprint of refrigerated trucks in Europe and potential energy saving measures in road transport [15].

Further, there are other energy saving opportunities through the optimisation of container design. For example, defective air refresh vents can be another source of unplanned air leakage. Although air exchange is encouraged deliberately during the shipping of horticultural products to avoid the concentration of ethylene and CO2, the control of such vents to efficiently deliver the required air exchange can be challenging. Vents are present in multi-use, non-dedicated containers such as those tested in this report. If these vents have been left partially open or they are damaged, these can lead to significant air infiltration when the container is used for frozen products or non-respiring chilled goods (e.g. meat and dairy). Smale *et al* [15] found that marked vent settings are not an accurate indicator of fresh exchange rates and that even the minimum vent settings can lead to airflows between 3 and 5 times larger than those intended, particularly in certain vent designs. These defects can also be assessed through thermography.

FCI knowledge network partner in this work

Thermoview

THERMOVIEW SA
22 The Parade West
Kent Town
S A 5067
PH 08-83636886 OR 1-300-300-159
Fax 08-83636885
Mobile 0448 920 007

References

[1] S. Estrada-Flores and A. Eddy, A (2006). The use of thermography to aid design of refrigerated road vehicles. Proceedings of the Conference "Innovative Equipment and Systems for Comfort and Food Preservation", Auckland, NZ. International Institute of Refrigeration. Comm B2, E1 with C2, D1, D2. pp. 387-394

[2] S.Estrada-Flores and A. Eddy, A (2007) Thermographic Survey Of Refrigerated Facilities. 22nd Int Cong Ref. Beijing, China. ICR07-D1-126. 8 Pp

[3] ASHRAE Handbook. 2005. Fundamentals. Chapter 1: Thermodynamics and refrigeration cycles. P.1-3.

[4] A.C. Cleland and D.J. Cleland. 1994. Cost-effective refrigeration. Massey University, P.N. New Zealand. P.2.2 .

[5] Y. Wild. 2005. Determination of energy cost of electrical energy on board sea-going vessels. Expert opinion report produced on behalf of Thermoking Corp. 15 p.

[6] P. Chen, D.J. Cleland, S.J. Lovatt and M.R. Bassett. 2000, Measurement of the in-situ insulation quality of refrigerated buildings by a thermal imaging method, Proceedings IRHACE Technical Conference, Queenstown, April 2000, p. 9-21.

[7] A. R. East, D. J. Cleland, M. R. Bassett and S. J. Lovatt. 2002. Refrigerated Buildings Insulation Quality and Door Air Infiltration. In Institute of Refrigeration, Heating and Air Conditioning Engineers of New Zealand (IRHACE) Technical Conference 2002: Proceedings (pp. 135-140), April 26, Christchurch, NZ. Christchurch, NZ: IRHACE.

[8] S. K. Chatzidakis and K. S. Chatzidakis. 2004. Refrigerated transport and environment. Int. J. Energy Res. 28:887–897.

[9] ASHRAE Handbook. 2006. Refrigeration. Chapter 14: Refrigerated facility design. P. 13.

[10] Dept. Climate Change. 2008. National Greenhouse Accounts (NGA) factors. Australian Government. 44 p.

[11] EnSys Energy & Systems, Inc. 2007.Analysis of Impacts on Global Refining & CO2 Emissions of Potential MARPOL Regulations for International Marine Bunker Fuels. Report prepared for the US Environmental Protection Agency. 79 p.

[12] P. Chen, D.J. Cleland, S.J. Lovatt, S.J., and M.R. Bassett, .2002, An empirical model for predicting air infiltration into refrigerated stores through doors,Int. J. Refrig. 25 (2002) 799–812.

[13] N. Smale, D. Tanner, N. Amos and Legg, A. 2003. Container leakage and air exchange rates: a simple measurement method and survey results.Proc. Int. Cong. Refrig. Washington DC. IIR. 8 pp.

[14] TRANS/WP.11/2000/9, Economic Commission for Europe, Inland Transport Committee, Working Party on the Transport of Perishable Foodstuffs (Geneva, 30 October–2 November 2000), Comment to Annex 1, Appendix 2, paragraph 29 Transmitted by the expert from Denmark. Available from: <http://www.unece.org/trans/main/wp11/wp11doc/2000/

Food Chain Intelligence

PO Box 1789

North Sydney 2059, NSW

Australia

Tel. 0404 353 571

Fax +61 2 9460 1239

www.food-chain.com.au