Refrigerant Loss, System Efficiency and Reliability – A Global Perspective

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Summary

This paper seeks to take a broader global perspective on the subject of refrigerant containment, the current legislation in major economies, and what measures they take to minimise refrigerant leaks and venting. It will also take a brief look at why refrigerant containment is not only intended for environmental protection, but is good design, engineering and maintenance practice to ensure peak performance at minimum total cost of ownership.

Introduction

The purpose of this paper is to highlight the issues relating to refrigerant containment that have an impact on the environment, and to the reliability and cost of owning and operating refrigeration and air conditioning systems of all sizes and applications. It will examine the current regulations in various countries to see what changes will be or are already; and why the RAC industry and users and operators should volunteer to make changes 'on their own initiative' - because it makes 'good business sense' in terms of total cost of ownership, reliability and the associated primary production/productivity losses for refrigeration equipment non-availability.

What is the Problem?

Human activity is causing the planet to heat up – the so-called Global Warming effect. This will have severe consequences for humanity if left unchecked. Through the auspices of the UN and organisations and agreements such as UNFCCC and Montreal and Kyoto Protocols we seek to limit global warming to no more than a 2°C increase.

The Montreal Protocol has addressed the issue of Ozone Depleting Substances and has reduced the global consumption of chlorofluorocarbons (CFC's) by more than 95% from its peak value. However to solve this issue we have increased the use of other gases, and in the main part these are the HFC's. Whilst having zero Ozone Depleting Potential (ODP), these gases can have a significant impact on global warming, and hence can be measured 'high' for their Global Warming Potential (GWP). The Kyoto Protocol seeks to reduce the emissions of all Green House gases (GHG's). Carbon Dioxide (CO_2) is a major GHG's.
Global HFC emissions in 2050 are projected to increase to 9–19% of projected global CO_2 emissions. Global HFC emission projections increase strongly after 2013 and could account for a significant percentage of GHG emissions by 2050 [1].

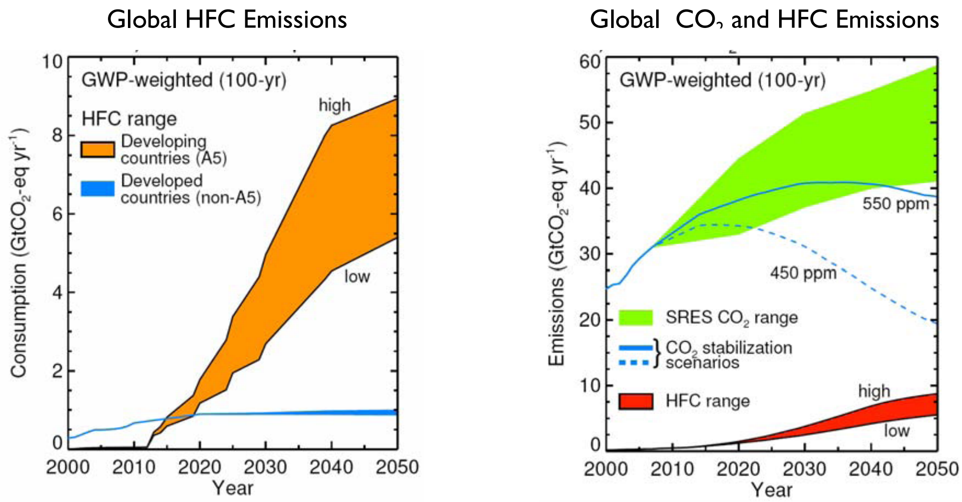

Figure 1 - The large contribution of projected HFC emissions to future CO_2 emissions [2]

Basic Definitions
Refrigerant Containment is the prevention or minimisation of a refrigerant fluid leaking to the atmosphere. Is Zero Leakage Possible? A leak is defined as: *'A leak is a hole or porosity in an enclosure capable of passing a fluid from the higher pressure side to the lower pressure side.'* A leak may be the tail-end of a weld fracture, a speck of dirt on a gasket or a microgroove between fittings. **All sealed systems leak**. The leak could be at 1kg/s or 1g/million years.
What is an Acceptable Leakage Rate? *A sealed system which operates for its useful life (say 20 years) without ever needing additional refrigerant to be added, in order to keep it running within normal operating parameters is considered to be 'leak tight'. That means that it has not leaked enough refrigerant to effect system performance (typically less than 10% of original charge, although some studies show that this may be as high as 20% before performance loss can be detected. Below this 10% lifetime 'benchmark' the system leaks are not practically measurable – and it is deemed a 'leak tight' system* [3].
It is possible however, and indeed is a critical priority, that we adopt a ***'zero tolerance of leaks'*** policy. The present (or hopefully now 'past') ready acceptance of annual leakage rates is very revealing. Even now leakage rates in the EU for commercial systems are quoted in a range of 5 – 20%; although we know that less than 3% is possible for large retail system estates [3, 4].

Refrigerant Containment Regulations - What we 'MUST' do
Regulations and the anticipation of changes to these regulations create enormous uncertainty in the RAC sector about 'where to go next?' So what is the 'state-of-play' TODAY in the US, China and EU?

USA Federal Law
The Montreal Protocol targets are enacted in the USA as the Clean Air Act - Section 608 Stationary Refrigeration and Air-Conditioning. CAA Section 608 prohibits individuals from intentionally venting ODS refrigerants (CFC's and HCFC's) **and their substitutes** (for example HFC's), while maintaining, servicing, repairing, or disposing of air-conditioning or refrigeration equipment [5]. CAA Section 609 covers Motor Vehicle Air-Conditioning. The Environmental Protection Agency (EPA) is responsible for the enforcement of this regulation and has introduced the National Recycling and Emission Reduction Program. The 'maximum' leakage rate in a 12 month period specified under Section 608 for systems containing a refrigerant charge of more than 50 lbs. is shown in Table 1. There are proposals by the EPA to lower these trigger rates to 10% and 20% respectively for commercial and industrial systems, but these are not yet agreed or implemented.

Appliance Type	**Trigger Leak Rate**
Commercial refrigeration	35%
Industrial process refrigeration	35%
Comfort cooling	15%
All other appliances	15%

Table 1 Trigger Rates for Clean Air Act Section 608 Leak Repair Requirements

Although CAA 608 mentions '*ODS substitutes*', it is primarily aimed at the Ozone Depleting Substances, and as the US is not a signatory to the Kyoto Protocol on Climate Change it is still unclear what the enforcement policy of the EPA is, with regard to HFC's. Although the Clean Air Act states that HFC's cannot be released or vented to the atmosphere, according to Lewis [6] *'the EPA has not taken a strong position on enforcement of HFC's'*
Failure to comply with the regulations can however lead to a fine of up to $32,500 per violation **per day**, and so could in theory run into millions of dollars. A clear example of effective EPA enforcement was the

very recent case of Safeway – who are reported to now be committed to spending $4.1 million to reduce ODS emissions in their 659 stores nationwide, and included in this amount is a $600,000 civil penalty. This commits Safeway to reduce their total annual leakage rate from 25% in 2012 to 18% or less by 2015 [7]. This regulation does not specify that regular leak inspection must be carried out. In the worst case the detection of leakage is by the annual calculation of the refrigerant top-up quantities as a percentage of system charge, and leaks must in general be repaired within 30 days of discovery.

USA – California

If the US Federal Law and the trigger leak rates appear to be generous by European standards, then the State of California has tightened up and its state legislation California Assembly Bill (AB) 32 – Global Warming Solutions Act of 2006 - covers all ODS and high-global warming refrigerants with a GWP >150 [8]. They have further introduced a Refrigerant Management Program (RMP) enforced through their Air Resources Board (ARB). All facilities/systems in California must from January 1, 2011:

a) Conduct periodic leak inspections
b) Repair leaks within 14 days of detection.
c) Follow required service practices.
d) Ensure proper refrigerant sale, use and disposal.
e) Facilities must be registered, reported, and annual fees submitted (up to $370 per site) to ARB.

Leak Inspections must be carried out:

a) For Large Facilities (>2,000 lbs. charge). A continuous Automatic Leak Detection (ALD) system must be installed – annual calibration is required.
b) For Medium Facilities (>200 to 1,999 lbs. charge). Quarterly inspection required, unless ALD installed.
c) For Small Facilities (>50 to 199 lbs. charge). Annual inspection required, unless ALD installed.
d) If 5 lbs. of refrigerant, or 1% of total charge (whichever is larger) is added to any system.

China

It is very difficult to identify specific regulations in China aimed at prohibiting the intentional venting of refrigerant gases to the atmosphere. At this stage refrigerant gases are treated as is any other form of pollutant. The current focus (and headlines) in China relate to air pollution in large cities (smog) and the health effects on the population.

Emissions of refrigerant gases are covered by the environmental protection law – *'Emission standards for odour pollutants (GB14554-93 1993-07-19)'*, and an obligation to repair leaks, with fines and penalties being applied for non-compliance; but there appears to be no specific regulations relating to refrigerant containment.

Chinese industry has invested heavily in R410a as the small AC system replacement for R22, but with the relatively high GWP (2088) of R410a, the developed countries may look now to carry out a regulatory phase down of this gas. This may be a reason for the reluctance of China to make firm commitments to HFC phase down? On a more positive note however, China and the US have recently jointly signed the following pledge: *Regarding HFC's, the United States and China agreed to work together and with other countries through multilateral approaches that include using the expertise and institutions of the Montreal Protocol to phase down the production and consumption of HFC's, while continuing to include HFC's within the scope of UNFCCC and its Kyoto Protocol provisions for accounting and reporting of emissions* [9]. China's heavy use of coal-fired power stations (see Table 3), and the high stock of high GWP refrigerants, with no (apparently) clear refrigerant emissions regulations will result in very high CO_2 (equivalent) emissions, and this is of course a major cause for concern.

The situation for India is very similar to China, although they are perhaps 'less proactive' than China in regard to HFC and CO_2 emissions.

European Union

End users of refrigeration, air conditioning or heat pump (RAC) equipment, are responsible for complying with the Fluorinated Gas (F Gas) Regulations being the designated 'operator' of the system. The aim of the F Gas Regulations (EC 842/2006) is to reduce leakage of HFC type refrigerants. In brief, the regulations require that:

a) Leak test systems with between 3 and 30 kg of refrigerant charge at least once a year, and systems with more than 30 kg twice a year.
b) Fit permanent leak detection to systems with more than 300 kg of charge.
c) Log leak tests and refrigerant usage.
d) Use engineers qualified to the F Gas Regulations standard to carry out this work. (The company they work for must also be registered and certified)

The updated ODS (Ozone Depleting Substances) Regulations (EC 1005/2009) cover the phase out of HCFC refrigerants and place broadly similar obligations on end users.

Minimum leak test frequency is covered by the Fluorinated Gas (F Gas) and Ozone Depleting Substances (ODS) Regulations:

a) Systems containing between 3 and 30 kg of HFC or HCFC refrigerant (or between 6 and 30kg for hermetic systems1) must be leak tested every 12 months;
b) Systems containing more than 30 kg of HFC or HCFC refrigerant must be leak tested every 6 months
c) Systems containing over 300 kg of HFC refrigerant must have permanent fixed leak detection.
d) Systems containing over 300kg of HCFC refrigerant must be leak tested every 3 months
e) If a leak is found it must be fixed as soon as possible (within 14 days maximum for systems containing HCFC refrigerants) and the system re-tested at the point of repair within one month.

The F-Gas Regulations are of course currently under review, with many possibly significant implications for the use of synthetic refrigerants. It now appears very likely that a limit on a maximum GWP will be imposed, with a phase out and service ban similar to that seen for R22. The current prediction (only the author's opinion) on this GWP limit will be certainly no higher than 2500, and possibly lower.

Government Taxes on HFC's

A number of countries (Denmark, Norway, Spain, Australia and possibly France very soon amongst others) have introduced taxes on the purchase of HFC's of up to £65 per kg. This is intended to encourage the use of alternate, natural refrigerants, and in many cases a tax rebate is offered for quantities of HFC correctly destroyed to also encourage the proper method of disposal of 'waste' gas from dismantled systems.

What is the Importance of Refrigerant Containment?

Human activity is causing global warming. A further basic assumption is that the need and demand for refrigeration and air-conditioning will continue to grow. RAC equipment is electrically driven in most cases. Generation of electricity adds to the global warming problem because we emit CO_2 (a key GHG) from power stations. More refrigeration equals more CO_2 into the atmosphere. So if we want to do the best for the environment we must reduce CO_2 emissions (or their equivalent). The total emissions from a refrigeration system into the environment are made up from two items:

1. Direct emissions of refrigerant fluid which is calculated as the equivalent amount of CO_2 and is expressed as the gases Global Warming Potential (GWP) number. R404a has a GWP of 3922. CO_2 as the reference gas has a GWP of 1.
2. Indirect emissions are the result of all the electrical power consumed to drive all components within a refrigeration system.

A high leak rate of a high GWP refrigerant will mean a significant increase of the total CO_2 emissions resulting from the use of the refrigeration system.

We can measure our total impact on the environment using a variety of methods. The method that the author has adopted for this paper is the Total Equivalent Warming Impact (TEWI) [10]

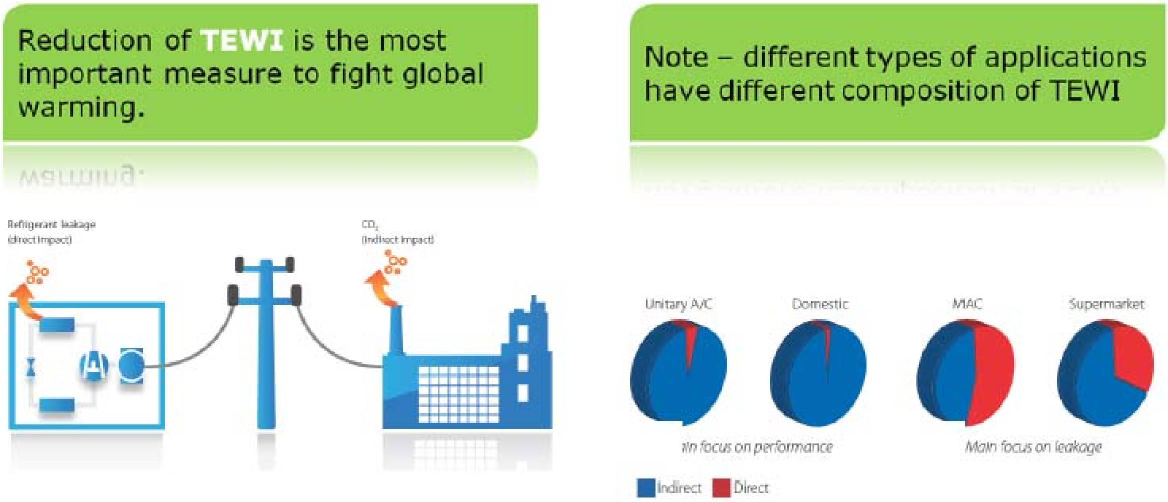

Figure 2 – TEWI and Direct/Indirect Emissions Measure Environmental Impact [Courtesy of Danfoss]

The ‘Environmental Lobby’ would explain that synthetic refrigerants used up to now, have all had some bad side effect on the environment, and the newly developed synthetics will be no different [11]. The only ‘safe’ solution is to use a natural refrigerant where the side effects are clearly understood and are ‘minimal’. They may be right. We are now talking about the fourth generation of synthetic refrigerants. Each time, with each ‘next generation’, we discover some new unforeseen effect that these ‘new’ gases have on the environment. Replacing all current RAC applications with natural refrigerants is however, likely to have the reverse effect on our long-term goal of reducing direct and indirect CO_2 emissions. So can we demonstrate that we can contain any type of gas for these applications, and are there any other reasons why refrigerant containment may be a ‘good thing’?

To answer those questions we must first determine what are the ‘drivers’ in the decision making processes of the owners, end users, and operators who ultimately pay for the purchase (Capex) and running costs (Opex) for RAC equipment. Many large end users quote a ‘triangle of priorities’ in the order Safety, Reliability and Efficiency, but in a more general scope what are the key drivers.

a) Regulations – this is mandatory, so no choice (assuming they are enforced).
b) Safety – a priority and often embedded in a)
c) Money (this includes Reliability and Efficiency)
d) Environment (actually includes Efficiency as a factor).
e) Short term Capex minimisation or long term Opex investment and payback?

What is the order of priority for this list? This is probably (in more general real and practical terms):

1. Safety.
2. Money (Reliability with short –term capital cost)
3. Environment.

So if the environment comes at the bottom of the priority list (unless Regulations alter it!), how can we ensure that we do the ‘right thing’ to reduce global warming. Figure 2 shows an example of the choices that can be made for commercial and retail refrigeration systems depending on the chosen priority order. In this example an R404a DX system is taken as the baseline reference, and safety is assumed as equal in all cases, although it can be argued that for R290 (propane) and R744 (CO_2) there are higher risks relating to the degree of flammability and higher system pressures that commercial/retail service engineers may be unfamiliar with (even if correctly trained – they may lack practical experience).

Case		1	2	3	4	5	6	7	8	9	10	11	12	13	14
System		Direct Expansion				Direct Expansion Distributed		Cascade				Secondary			Booster
Refrigerant Medium Temperature		R404A	R404A	R134a	R407A	R404A	R407A	R404A	R407A	R134a	R134a	R410A chiller	R290 chiller	HFO chiller	R744
Refrigerant Low Temperature		R404A	R404A	R404A	R407A	R404A	R407A	R744	R744	R744	R744	R744	R744	R744	R744
Compressor technology Medium & Low Temp.		Scroll	Recip.	Recip.	Scroll	Scroll	Scroll	Scroll	Scroll	Recip.	Scroll	Scroll	Scroll	Scroll	Scr/ Recip.
Normalised Score	Power	**Base**	12%	5%	**-3%**	0%	**-3%**	7%	4%	12%	9%	7%	9%	12%	12%
	TEWI	Base	6%	-18%	-24%	-24%	-36%	-2%	-23%	-27%	-28%	**-42%**	**-43%**	**-41%**	**-42%**
	Investment Cost	**Base**	3%	11%	0%	**-14%**	**-13%**	13%	13%	25%	21%	17%	18%	32%	48%

-3% Best Option 0% Second Best Option 4% Third Best Option

Figure 3 – Refrigerant and Technology Choices for Commercial and Retail Refrigeration [12] Courtesy of Emerson

If we are totally committed to minimising our environmental impact, then we would choose case 11, 12, 13 or 14; but the short term investment costs would range from 17% to 48% higher. We would also pay penalty for increased running costs of 7% to 12%. Lowest short term investment would select case 5 or 6, but the environment will suffer from our short term focus.

The choice of course depends on our priorities.

The Real Cost of Refrigerant Leaks
When a leak occurs from a refrigeration system, there are a number of consequences. Figure 4 shows these major factors and effects.

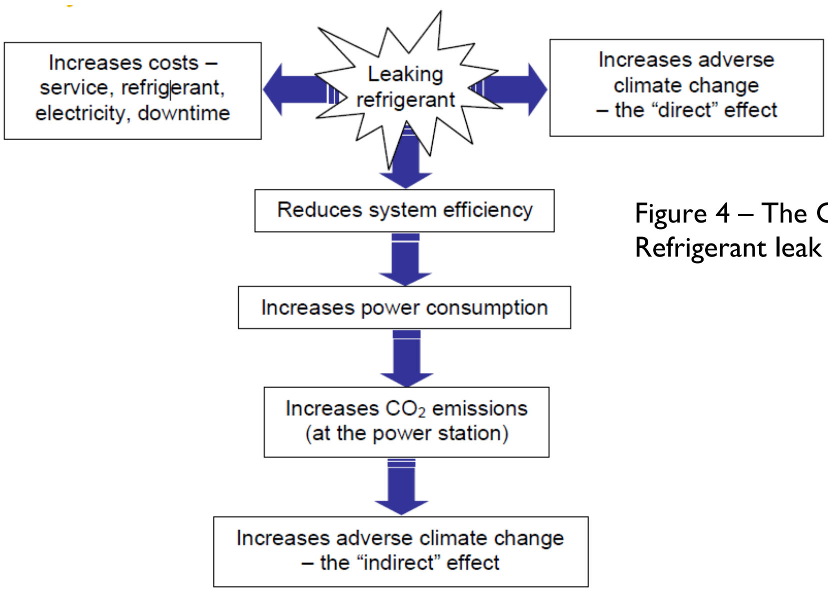

Figure 4 – The Consequences of a Refrigerant leak [13]

Cost of refrigerant gas – this depends of course on the gas being used in the system. From experience with R22 systems, any HFC which may be identified for phase out (based on a probable maximum GWP limit of 2500 from the F-Gas Review process), will experience significant price increases in the coming years. Those end users who have delayed replacing R22 in their systems have a seen a 1000% increase in gas price since 2004, and *have 'paid –the-price'* for their hesitation. The relative prices for refrigerants are

Refrigerant	% R134a cost
R134a	100%
R22R	426%
R404a	96%
R422D	240%
R407F	227%
R290	50%
R717	26%
R744	20%

Table 2 – Refrigerant Cost Relative to R134a

shown in Table 2. This does not include any additional taxes which as previously mentioned are now applied in many countries (but not yet in the UK).

Cost of the repair – the Carbon Trust [14] uses a typical cost for the labour time to repair a leak as £700. This is of course a cost per leak, and the labour cost is not likely to be significantly higher for most commercial sized systems, unless the location is particularly difficult to isolate from the rest of the system, or the reason for the leak requires replacement of a high cost component.

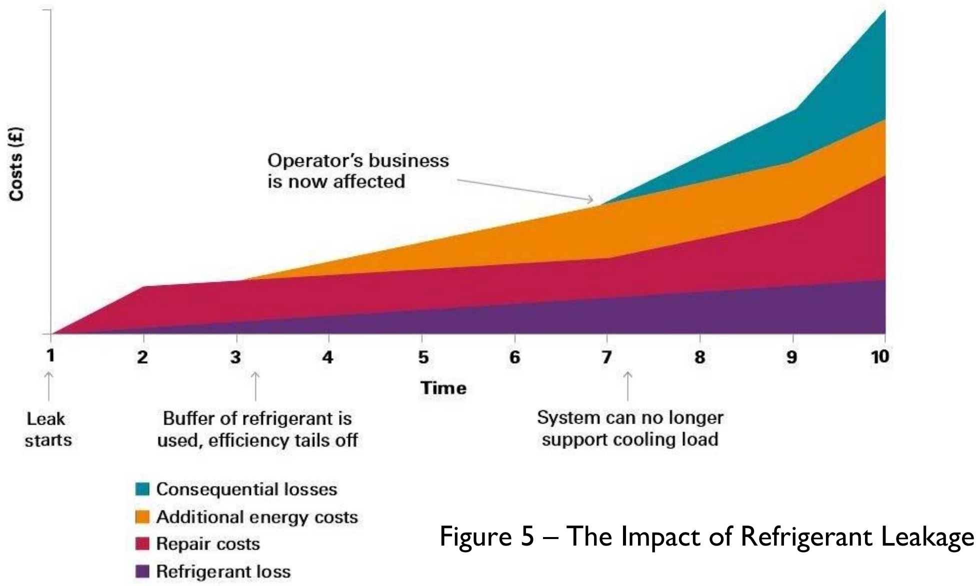

Figure 5 – The Impact of Refrigerant Leakage

Cost of increased energy consumption (reduced efficiency) - during the period of the leak. This factor is very difficult to assess as there are a large number of variables to consider. If the system has a receiver installed (buffer of refrigerant charge), then of course the system could leak up to 30% (or more) of its initial charge before there is any measurable impact on system cooling capacity or efficiency. The relationship between the loss of performance (capacity and efficiency) is very difficult to predict but in results derived from experimental measurements taken by Woohyun Kim [15] shown in Figure 6, it can be seen that when the effective refrigerant charge is reduced to 85% of the correct amount, then annual running costs are increased by 10%. This annual running cost penalty increases in a non-linear manner so that at 60% correct charge, the running cost penalty is +45%.

Take the case that a typical system costs £60,000 per year in electricity costs to run, then if the system charge is reduced to 80% (20% annual leakage rates still being typical in some applications), the operator incur a 15% annual running cost penalty. Assuming a linear leakage rate of 5% per 3 month period, then the running costs annualised amount to £4800 (see Table 2).

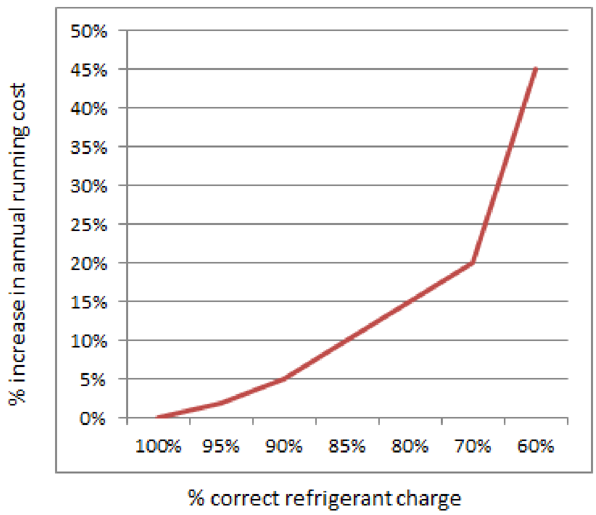

Figure 6 – Relationship between annual running costs and refrigerant leakage for small air-conditioning and commercial systems

annual run cost = £60,000	12 month period				
	Q1	Q2	Q3	Q4	Total
% correct charge	95%	90%	85%	80%	-
% run cost penalty	2%	5%	10%	15%	-
actual penalty cost per Q	£ 300	£ 750	£ 1,500	£ 2,250	£ 4,800

Table 3 Annual Running Cost Increase for a 20% Annual Leakage Rate

Using the Carbon Trust typical repair cost of £700, the operator could better invest this cost to preventative leak detection (and repair on the same day); and could then visit twice per year (cost £1400 total) and limit the annual leakage rate to 5%, and therefore save £3400. This saving could even be invested in Automatic Leak Detection Equipment. The beneficial side effect is that we also reduce both direct and indirect emissions of CO_2 (equivalent). The amount would of course depend on the refrigerant gas and the emission rate of the power source (see Table 3).
There are other methods of leak detection that could be used, and for example by installing instrumentation it is possible monitor and data log the running conditions of the plant, and with a pre-defined 'baseline', abnormal conditions (which would result in a loss of performance and efficiency) can be detected and an alarm could be raised. The problem with this approach is the large variance in the running conditions and load, ambient conditions etc. that would make establishing a practical baseline very difficult to achieve. For smaller systems, the cost of the necessary instrumentation may add 30% to 50% to the cost of the system. There is also the option to add a *'stenching agent'* to any gas (that does not have a natural, strong smell). This is of course done with natural gas that is piped into our homes, to give us an ALD in the form of the human nose. Would such a thing be possible for refrigerant gases?

Cost of the lost productivity - of the end users process (downtime). This of course depends entirely on the end users actual process, but can vary from mere inconvenience for a comfort cooling system; to truly staggering costs for high value factory production processes. A good example is in the storage of pharmaceuticals. Very small commercial sized cold stores can hold millions of £'s worth of pills and tablets in a very small space. It is very common for temperature sensitive products (like pharmaceuticals) to be stored within very strict temperature ranges. Even a 2K increase in storage temperature may require the product to be thrown away.

The impact on the climate of a leak – this is a combination of the direct emission effect of the amount of refrigerant leaked to the atmosphere and of course the GWP value of the gas. Refrigerant gases with a lower GWP will of course have a lower direct equivalent CO2 impact on the environment. The direct emissions amount is however usually (in the UK) dwarfed by the impact of the indirect emissions. The indirect effect is the amount of the additional energy consumed due to inefficient running with the system refrigerant charge at less than correct design level. In the UK, 74% of the electrical power generated comes from thermal (fossil fuel) power station with a very high rate of CO_2 emitted per kWh of electrical power generated. In France by contrast only 8% of their electrical power comes from a fossil fuel thermal station (77% comes from nuclear power). Clearly the environmental impact of reduced efficiency resulting from leaks is much lower in France, where the direct emission effects (from a GHG perspective) will be a much higher proportion of the total environmental impact.

Country	**Energy Mix**				Average CO_2 emissions rate
	Thermal	**Hydro**	**Nuclear**	**Renewables**	kg CO_2/kWh
UK	**74%**	**1%**	**24%**	**2%**	0.64
France	**8%**	**14%**	**77%**	**1%**	0.09
Germany	**62%**	**4%**	**30%**	**4%**	0.61
USA	**71%**	**6%**	**21%**	**2%**	0.66
China	**82%**	**17%**	**1%**	**0%**	0.77

Table 4 – Average CO_2 Emissions Rate for Electrical Power generation in Major Economies [16]

How do we reduce these costs (this was our target)? I really mean 'reduce in total' and not just 'relocate' cost to someone else!

a) Planned Preventative Maintenance.
b) Upgrading the specification and quality of equipment and installation
c) Upgrading the 'specification and quality' (training and awareness) of the people to enable a) and b).

These means that we need to focus on the long-term issues – the Total Cost of Ownership (TCO), rather than the short-term capital costs. Figure 7 shows a typical split between the 3 major elements of TCO (there is a fourth item – disposal costs, but we will not discuss that issue in this paper). In most applications the cost of the energy to run the refrigeration system can be up to 90% of the TCO. It is clear long-term benefit to invest upfront in more efficient, higher quality (leak tight), easy to maintain systems, with planned preventative maintenance programmes in order to reduce TCO and the Lifetime CO_2 emissions of the system.

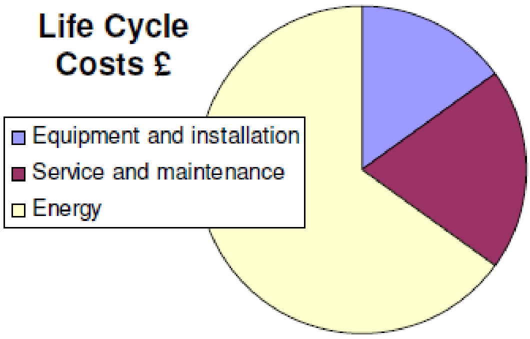

Figure 7 Total Cost of Ownership [17]

For the cases shown earlier in Figure 3, we can clearly see from Figure 8 impact of leakage on the overall lifetime Co2 emissions or TEWI number. An annual leakage rate of 10-15% dependant on the system type has been assumed. Improved leakage reduction programmes would of course reduce the TEWI value for the systems using higher GWP refrigerant gases such as R404a.

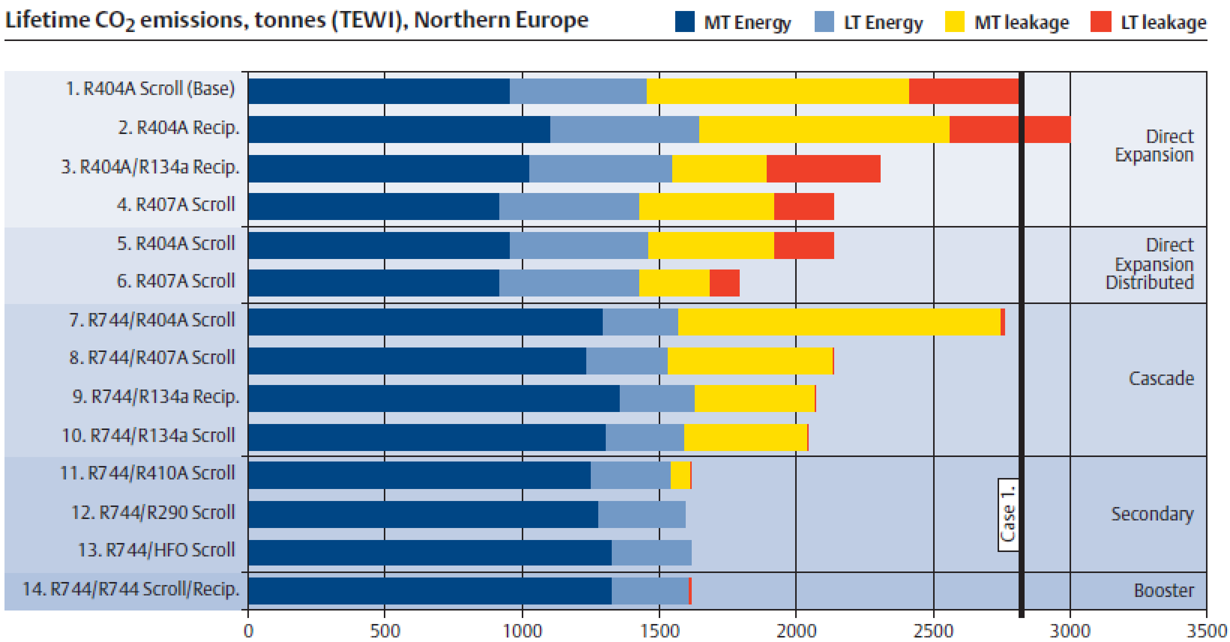

Figure 8 – Commercial and Retail Refrigeration Systems Lifetime Emissions – Courtesy of Emerson

Best Practices – a Global Perspective

From the author's personal experience (mostly in industrial refrigeration) it has been observed that the best practices to solve particular problems are very similar regardless of local geographic location. Different geographic locations however have very different priorities based on local conditions. They all follow the same principles as described above, but implement them in different priority sequences. Large organisations (Nestle, Coca-Cola, Unilever, Tesco, Walmart, Huure, JCI, GEA, Bitzer, Daikin, Carrier etc. tend to transmit best practices between their organisations in different countries. The information then spreads within a country, usually accelerated by contractors and equipment manufacturers following large end-user best practices and specifications, and local organisations and institutions such as the IoR, ASHRAE etc. Local regulations, climate conditions, industry and market norms all set different driving forces behind local decision makers and the paths they follow.

For industrial refrigeration for example, the Russian market has a preference for screw compressor based technologies, considering the design more 'modern' than piston compressors, even though in many applications piston compressors are more efficient than screw compressors

High ambient conditions make CO_2 transcritical less attractive compared to HFC based solutions.

Single stage ammonia piston compressor chillers for sub-zero secondary fluid cooling applications, popular in Northern Europe, as a highly efficient natural refrigerant solution, are not suitable for hotter climates.

Air-conditioning systems are becoming more and more common in large cities in India and China, where income levels are rising and cost of AC systems is reducing. Window mounted systems cover the sides of many old buildings and these systems are unlikely to be properly maintained. Population and income growth in Asia and Africa will lead to a huge increase in the number of such systems installed, and these (in the author's opinion) are likely to become a major source of refrigerant leakage in the future. Only economic effects (high prices) or legislation will prevent this happening.

Conclusion

Whatever the refrigerant in a system is, it is good practice to keep the fluid contained within the pressure system. This helps us achieve our long term vision – protecting our environment.

It is the authors opinion that there is a place for synthetic refrigerants in applications where there is no better alternative, assuming we can minimise leaks to a 'sustainable level' for the environment. Perhaps we should stop debating the natural versus synthetic refrigerant fluid argument, and focus on the best long term SUSTAINABLE refrigerant fluid, that achieves the best result for our overall target of carbon emissions reduction. Ensuring a practical minimum fluid leakage – refrigerant containment – is a key element in achieving this long term goal, as well as our own personal short term goals– so refrigerant containment is certainly a 'good thing' for everyone.

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