REFRIGERANTS – Back to the future?

Don J. Cleland, HM.AIRAH, Richard J. Love Centre for Postharvest & Refrigeration Research, Massey University, Palmerston North, New Zealand

ABSTRACT

Choice of refrigerants has become ever more complex. Refrigeration and heat pump systems are essential parts of modern life and offer potential solutions to the global challenges of feeding the growing world population and reducing energy demand.

However, refrigerants are also perceived to degrade the environment through their ozone depletion and/or global warming potential. Further, there are concerns with some refrigerants in terms of safety; either flammability or toxicity. Lastly, there are technical and economic considerations in terms of cost, performance and availability. The ideal refrigerant remains elusive – inevitably there is a trade-off between one or more economic, technical, environmental and social factors.

This paper examines refrigerants in light of these constraints and identifies options for the future. While natural refrigerants offer many economic, technical and environmental advantages they do have significant safety constraints. New fluorocarbon refrigerants are being developed but there are significant uncertainties associated with their cost and performance and they are often flammable.

Despite the uncertainty, changes to refrigerant costs and availability driven by regulations and taxation regimes provide an opportunity to the refrigeration and air conditioning industry. Decisions need to be bold and visionary rather than defensive and evolutionary.

1. INTRODUCTION

Environmental concerns are becoming ever more important for human kind as we face growing populations, migrations to cities, depletion of key resources and increasing living standard expectations. The refrigeration industry worldwide can claim to be an exemplary case study in terms of how it has reacted to ozone depletion by anthropogenic chemicals including refrigerants. Within a generation of becoming aware of the problem in the early 1970s, a mechanism to overcome it, the Montreal Protocol (MP), was developed and has now been implemented globally to the extent that the planet is on track to eventually recover to safe levels of ozone depletion once the accumulated ozone-depleting-substances are destroyed or naturally dissipate.

Global warming (GW) is proving more difficult. A feature of the ozone debate was unambiguous evidence of a hole in the ozone layer. However, GW is more complex and no unequivocal evidence shows GW is occurring, or if it is, whether it is an anthropogenic or natural effect, and what the magnitude and time-frame of the impacts might be.

Although sceptics rightly challenge some of the circumstantial evidence in particular, scientific proof continues to grow and it is clear that if GW is real to even a small extent, the impacts on humankind will be huge. Therefore, most accept that the precautionary principle should be followed, and support taking action to minimise and mitigate ahead of definitive proof one way or the other.

The Kyoto Protocol (KP) is the current overarching agreement/treaty. It limits the emissions of a basket of 6 GW gases – carbon dioxide (CO_2) primarily due to fossil fuel use for energy; methane (CH_4) and nitrous oxide (N_2O) primarily as a result of decomposition of waste and agricultural activity; sulphur hexafluoride (SF_6) mainly used in electrical switchgear; perfluorocarbons (PFCs) mainly used in fire extinguishers and foams, and hydro-fluorocarbons (HFCs) primarily used as refrigerants and foam-blowing agents.

The specific contribution of a gas to GW relative to CO_2 can be quantified using global warming potentials (GWPs). The KP does not cover high GWP gases already being phased out under the ozone focussed MP. Each signatory has committed to stabilising its emissions of GW gases in 2008–2012 relative to 1990 levels. For Australia, the target is 108% of 1990 emissions. Unfortunately, the KP is known to be insufficient to make much impact on GW and there is variable commitment to it around the world.

Refrigeration technologies can influence GW emissions in two ways. There is the direct effect due to refrigerants released into the atmosphere. In particular, fluorocarbon refrigerants have extremely high GWPs, so small quantities can have a significant impact. For example, R134a has a GWP of 1,300 so emission of 1kg is equivalent to emission of 1.3 tonnes of CO_2. Also there is an indirect effect, primarily due to energy use by the refrigeration technologies. Worldwide refrigeration technologies account for about 15% of electricity use. In Australia, electricity generation accounts for about 40% of total GW emissions, which were 540 Mt CO_2 equivalent in 2010.

Australia depends heavily on refrigeration for food processing, storage and transport. A large fraction of export income comes from refrigerated food. In addition, there is an increasing demand for air conditioning and heat pump systems. Somewhat

Table 1: Evaluation of refrigerant classes against broad selection criteria.

Criteria	HCFCs	HFCs	HFOs	NRs
Refrigerant Cost (no levy)	low/medium	medium	high	low
System Cost	medium	medium	medium	high
Capacity	good	good	good	very good
Energy Efficiency	good	good	good	very good
ODP	yes	no	no	no
GWP (levy)	high	high	low	very low
Safety (e.g. flammability, toxicity, high pressure)	good	generally good	good except flammability	significant risks often
Oil Compatibility	traditional	synthetic	synthetic	wide

ironically, heat pumps offer higher energy efficiency (reduced energy-related GW emissions) than many alternative heating systems but often rely on high-GWP refrigerants.

Figure 1 shows the increase in GW impact of HFCs emissions in Australia by sectors since 1990 (DCCEE, 2010). Most HFC emissions come from commercial refrigeration (55%) followed by light vehicle air conditioning (16%). The bank (stocks) of HFCs in equipment (potential future emissions) is growing at about 8 to 10 times the emissions rate, suggesting refrigerant leakage rates average about 10% of charge per annum. The global emissions of HFCs are about 60 times that of Australia. Refrigeration currently accounts for about 7% of Australia's total GW emissions (1% direct and 6% indirect).

Australia has introduced legislation that puts a price on the GWP of KP refrigerants via a levy initially set at $23/tonne CO_2 equivalent. The purpose of this paper is to examine refrigerant options in light of this legislation.

2. THE PERFECT REFRIGERANT

The ideal properties of the perfect refrigerant are summarised in Figure 2 mapped against the three dimensions of sustainability: economic (prosperity), environmental (planet) and societal (people). Table 1 assesses the broad classes of refrigerants against these desirable properties while Table 2 lists the GWP, oil compatibility and some disadvantages of specific refrigerants.

Most refrigerant classes and individual refrigerants have at least one major disadvantage. Therefore the best refrigerant is a trade-off and, in part, depends on the extent that the weakness can be mitigated, which tends to be situation-specific. It should be noted that all refrigerants are asphyxiants and that most fluorocarbons result in cardiac sensitisation. In terms of material compatibility, the key aspects are the lubricants, metals and elastomers used in refrigeration systems. In terms of performance, the key aspects are favourable thermodynamic and transport properties across a wide temperature range of application. Normally the favourable properties include high values of pressure, critical point, latent heat, vapour density, heat capacity and thermal conductivity, and low values of boiling point, viscosity and surface tension.

These combinations lead to low volumetric flowrates, high heat transfer coefficients, low pressure drops and thereby compact, high capacity, high energy-efficiency equipment.

In general terms, pure substances are easier to use than blends. Azeotropic or low-glide blends are easier than blends with significant glides except when the glide can be closely matched with the cooling of the process fluid (e.g. water chilling concurrently with R407C). Non-azeotropic blends are generally not suitable for flooded systems due to differential distillation leading to composition changes throughout the system.

3. ALTERNATIVE REFRIGERANTS AND TECHNOLOGIES

Table 2 summaries some of the key properties of common refrigerants used in the past, presently and potentially in the future. Calm & Hourahan (2011)

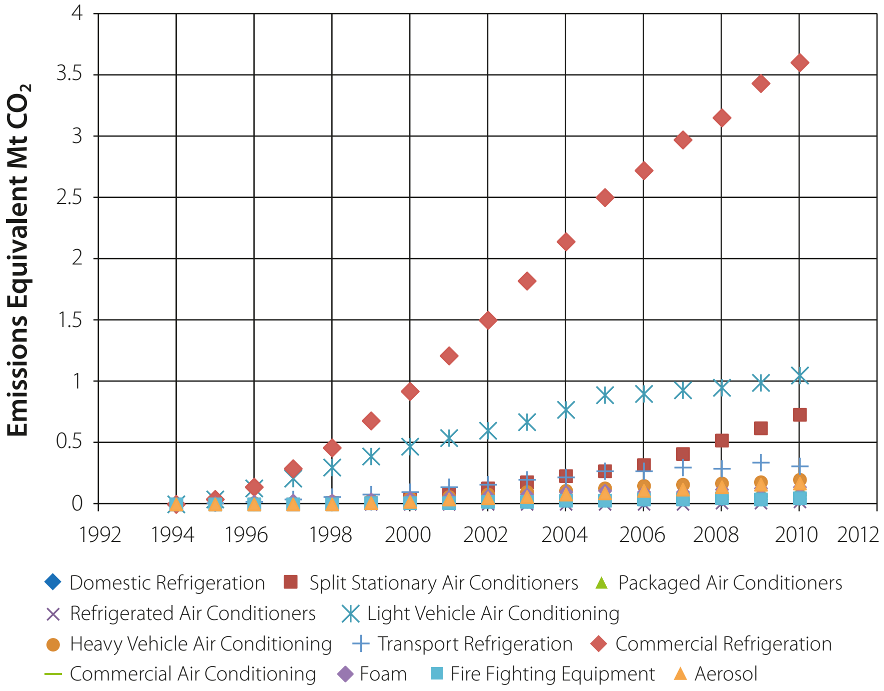


Figure 1: Australian emissions of HFCs by sector in CO_2 equivalents (DCCEE, 2010)

Table 2: Key properties of selected past, present and future refrigerants.

Number – Names	Formula	ODP	GWP	Oil Compatibility[1]	Levy ($/kg)	Other Weaknesses
CFCs						
R11 – trichlorofluoromethane	CCl_3F	1.0	4000	M	–	MP phase-out
R12 – dichlorodifluoromethane	CCl_2F_2	1.0	8500	M	–	MP phase-out
R502 – CFC blend	115 (51%), 22 (49%)	0.23	5590	M	–	MP phase-out
HCFCs						
R22 – chlorodifluoromethane	$CH\ Cl\ F_2$	0.055	1700	M,AB	–	MP phase-out
R123 – dichlorotrifluoroethane	$C_2H\ Cl_2F_3$	0.02	93	M,AB,POE	–	MP phase-out
HFCs						
R32 – difluoromethane	CH_2F_2	0.0	650	POE	15	A2L
R125 – pentafluoroethane	C_2HF_5	0.0	2800		64	
R134a – tetrafluoroethane	$C_2H_2F_4$	0.0	1300	POE,PAG	30	
R143a – trifluoroethane	$C_2H_3F_3$	0.0	3800		87	A2L
R152a – difluoroethane	$C_2H_4F_2$	0.0	140		3	A2L
R245ca	$C_3H_3F_5$	0.0	560		13	
R404A – HP62, FX70	125 (44%), 134a (4%), 143a (52%)	0.0	3260	POE	75	
R407C – Klea-66, Suva-9000	32 (23%), 125 (25%), 134a (52%)	0.0	1530	POE	35	High glide
R410A – AZ-20	32 (50%), 125 (50%)	0.0	1730	POE	40	High P
R417A – Isceon MO59	125 (46.6%), 134a (50%), 600 (3.4%)	0.0	1960	M,AB,POE	45	Medium glide
R422D – Isceon MO29	125 (65.1%), 134a (31.5%), 600a (3.4%)	0.0	2620	M,POE	60	Medium glide
R507 – AZ-50	125 (50%), 143a (50%)	0.0	3300	POE	76	
HFOs						
R1234yf	$C_3H_2F_4$	0.0	4	POE	0.1	A2L, high cost
R1234ze	$C_3H_2F_4$	0.0	6	POE	0.1	High cost
Perfluorocarbons (PFs)						
R218 – perfluoropropane	C_3F_8	0.0	7000		161	Long EAL
Natural Refrigerants (NRs)						
R170 – ethane	C_2H_6	0.0	~5	M,AB,POE	–	A3
R290 – propane, Care 40	C_3H_8	0.0	~5	M,AB,POE	–	A3
R600a – isobutane, Care 10	C_4H_{10}	0.0	~5	M,AB,POE	–	A3
R717 – ammonia	NH_3	0.0	<1	M	–	B2L, low P, no copper
R718 – water	H_2O	0.0	<1			0°C limit, very low P
R744 – carbon dioxide	CO_2	0.0	1	M	–	Low critical temp., high P
R1270 – propylene	C_3H_6	0.0			–	A3

1: Refer to section 8 for definitions of oil types.

give more detailed data for a wider range of refrigerants. There are relatively few low-GWP refrigerants other than natural refrigerants (NRs) but hydro-fluoro-olefins (HFOs) and HFO blends are starting to appear. Figure 3 show the pathways for transition that have occurred due to ozone depletion potential (ODP) and the MP plus possible pathways for transition from HFCs.

Rather than alternative refrigerants, another possibility is the use of alternative technology to the currently dominant mechanical vapour recompression using the reverse Rankine cycle. Some possibilities include acoustic refrigeration, magnetic refrigeration, thermo-electric (Peltier effect) refrigeration, vortex tube compression, Brayton (air) cycle or the Stirling cycle. Currently, all of these systems suffer from very low energy efficiency, low capacity and/or high capital costs. Therefore they are unlikely to have wide application in the foreseeable future beyond niche situations that rely on other drivers (e.g. low noise for thermo-electric).

Absorption or adsorption systems have much lower energy efficiency than mechanical recompression, so they will generally only be preferred when thermal energy is very low cost relative to motive power.

However, there are likely to be significant developments and improvements to the reverse Rankin cycle to improve energy efficiency, especially for alternative refrigerants with different properties than the refrigerants they replace. Examples are likely to include: expanders to reduce throttling losses, greater use of multi-staging, heat-transfer enhancement of heat exchangers, wider use of variable speed technology, refrigerant cascades to ensure refrigerants are only used in their optimal temperature range, and transcritical cycles where gas cooling can be matched to process heating requirements. In some situations, hybrid absorption/compression cycles may be worthwhile. Cascade systems are also likely to be used to minimise and isolate charges of high-GWP, flammable or toxic refrigerants, while "safe" refrigerants are used in populated areas.

4. FUTURE OPTIONS

The significant increase in price for most HFC refrigerants due to the Australian Government's carbon-equivalent levy will provide incentives for both the following responses:

- Replacement with low-GWP refrigerants, and
- Reduction in leakages rates through improved design, installation and maintenance, and reduction of refrigerant charge irrespective of the refrigerant.

As Tables 1 and 2 and Figure 3 show, likely replacements for high-GWP refrigerants have performance (e.g. R744), cost (e.g. HFOs) or safety particularly flammability (e.g. R717, R290, R600a, R32, HFOs) concerns.

Table 3: Likely alternative refrigerants envisaged by the chemical industry in 1990 and 1994.

Application	Original	Replacements foreseen in 1990	Replacements foreseen in 1994
Automotive Air Conditioning	R12	HFC-134a, blends	HFC-134a
Domestic appliances	R12	HFC-134a, blends	HFC-134a, R290
Retail food – low temperature	R502	HCFC-22, HFC-125	HFC-507, HFC-404A
Retail food–medium temperature	R12, R22, R502	HCFC-22,HFC-134a HFC-125, blends	HFC-134a, HFC-507, HFC-404A
Chillers – centrifugal	R11	HCFC-123	Blends
Chillers – centrifugal	R12	HFC-134a, blends	HFC-134a
Chillers – reciprocating	R12	HFC-134a, HCFC-22, blends	HFC-134a
Insulating foams	R11, R12	HCFC-123,HCFC-22	various
Industrial refrigeration	R22, R502, NH3	HCFC-22, NH3	HFC-507, HFC-404A, NH3

Although HFO-1234yf looks to be a very promising replacement for R134a, and other HFOs may replace R407C and R410A in many applications, HFOs and other synthetic refrigerants seem likely to be least mildly flammable. Therefore whether NRs, HFCs, HFOs or other synthetic refrigerants are used, charge and leak reduction will be increasingly important. Cowan et al. (2011) provides information on refrigerant leakage rates for various applications. Across most sectors, average annual leakage rates are 5 to 20% of charge, so there are significant opportunities for improvement.

A new ASHRAE class, 2L, has been created to further differentiate between highly flammable and mildly flammable refrigerants. Refrigerants with flame speeds less than 10cm/s are designated 2L. Such a low flame speed means that if it ignites the refrigerant causes less significant explosive damage, hence despite still being flamable it is considered less dangerous than refrigerants with a high flame speed. This class includes R32, R143a, R152a and many HFOs (usually A2L as low toxicity) plus R717/ammonia (B2L due to its toxicity). Unfortunately, the rules and regulations for safe use of A2L refrigerants have yet to be fully developed. However, it is clear that in the future all designers, installers and service technicians will have to be competent with flammable refrigerants, whereas in the past such refrigerants could be avoided.

Figure 2: The properties of the perfect refrigerant mapped against the three dimensions of sustainability.

Performance of replacements must not be too inferior. A high-efficiency, high-GWP refrigerant with low leakage rate can have a lower total GW impact than an inefficient, low-GWP refrigerant because the higher energy-related emissions offset the direct refrigerant emissions. The key will be life-cycle costing and GW impact estimates. "Total equivalent warming impact" (TEWI) or "life-cycle climate performance" (LCCP) are often used to quantify GW impact:

$$\text{LCCP (kg CO}_2\text{)} = \text{TEWI} + \text{emissions due to manufacture}$$

$$\text{TEWI (kg CO}_2\text{)} = \text{direct refrigerant impact} + \text{indirect energy use impact}$$

$$= \text{GWP}\ M\ [x\ n + (1 - \alpha\alpha)] + E\ n\ \beta$$

where M = refrigerant charge (kg)

x = leakage rate (% per year)

n = equipment life (years)

E = energy consumption (kWh/year)

α = recovery factor (%)

β = electricity emissions factor (kg CO_2/kWh)

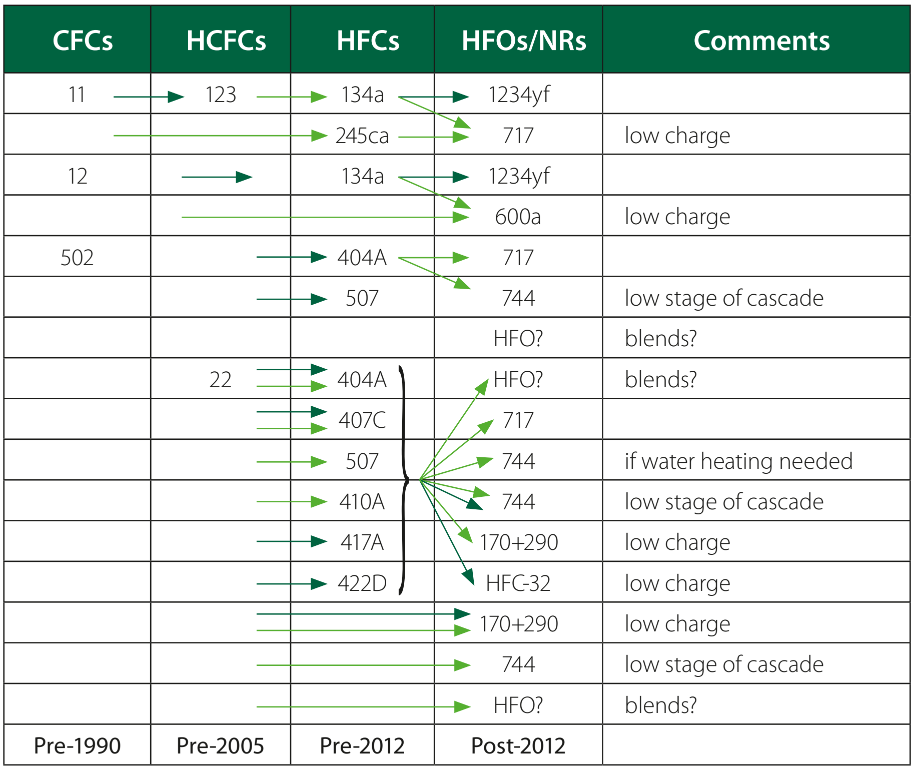
A problem with such approaches is that the leakage rate and energy consumption are seldom known accurately at the time of the refrigerant choice and investment decision. The advantage of the levy is that it converts this environmental consideration into a more purely economic one.

For example, compare R404A (GWP=3,260) in a system with a 5kg charge, 5% p.a. leakage rate and an annual energy consumption of 25,000kWh being replaced with a refrigerant with a GWP of 150 but 5% poorer energy efficiency after implementation of the levy. For both refrigerants the equipment life is 15 years, there is 90% refrigerant recovery, the electricity

Table 4: Manufacturers' recommendations for retrofit and new equipment replacement refrigerants in 2003 (Lommers, 2003)

Sector	Compressor Type	Refrigerant
Domestic Refrigerator	Sealed Unit	R134a, R401A, R409a, R413a
Commercial Equipment Medium Temperature	Sealed Unit	R134a, R22, R401A[1], R404A, R407A, R409A, R413A, R507
	Accessible Hermetic	R134a, R22, R401A[2], R404A, R407C, R413A, R507
	Reciprocating Open Drive	R134a, R22, R401A[2], R404A, R407C, R409A2, R413A, R507
Commercial Equipment Low Temperature	Sealed Unit	R22, R402A, R402B, R403A, R404A, R407B, R408A, R410A, R507
	Accessible Hermetic	R22, R402B, R403A, R404A, R407B, R408A, R410A, R507
	Reciprocating Open Drive	R22, R402A, R402B, R403A, R404A, R407B, R408A, R410A, R507
Large Commercial & Industrial	Reciprocating Open Drive	R22, R134a, R401A, R401B, R402A, R403A, R404A, R407B[4], R407C[4], R408A, R409A, R410A, R413A, R507, R717
	Centrifugal/Screw	R134a, R123, possibly R124[3] , R22, R407A[4], R401A[4], R717
Mobile Air Conditioning or Refrigeration	Reciprocating Open Drive	R22, R134a, R401C, R402A, R403A, R404A, R407C, R408A, R409A, R409B, R416A, R507, possibly R22
Air Conditioning	Reciprocating Open Drive	R22, R134a, R401A, R409A, R410A, R413A
	Centrifugal/Screw	R134a, R123, R22, R410A
	Accessible semi-Hermetic	R22, R123, R134a, R401B, R404A, R407C, R409B, R410A, R507

[1] R401A for evaporating temperatures between -23°C and 7°C. [2] R401A and R409A are not suitable for beverage coolers.
[3] Usually extensive modifications required. [4] Not for use with flooded evaporators.



CFCs	HCFCs	HFCs	HFOs/NRs	Comments
11	123	134a	1234yf	
		245ca	717	low charge
12		134a	1234yf	
			600a	low charge
502		404A	717	
		507	744	low stage of cascade
			HFO?	blends?
	22	404A	HFO?	blends?
		407C	717	
		507	744	if water heating needed
		410A	744	low stage of cascade
		417A	170+290	low charge
		422D	HFC-32	low charge
			170+290	low charge
			744	low stage of cascade
			HFO?	blends?
Pre-1990	Pre-2005	Pre-2012	Post-2012	

Figure 3: Pathways for refrigerant retrofit and replacement
(→, drop-in or retrofit with minimal change to equipment: →, new equipment).

emission factor is 1kg CO_2/kWh and the electricity cost is $0.1/kWh.

For R410A the TEWI is 388,855 kg CO_2 whereas for the alternative it is 394,388 kg CO_2 (1.4% higher). The marginal cost for the alternative (extra energy minus reduced levy) is $1213 over 15 years. The TEWI improves and there is a marginal savings in cost if the reduction in energy efficiency is less than 3.5% or 3.2% respectively for the low GWP alternative.

For this reason, when charges and leakage rates are low, then a case can be made for highly efficient but high-GWP refrigerants to be retained. Similarly, if the alternative energy efficiency is similar or higher then significant reductions in both cost and TEWI are possible.

Even with the levy, HFC refrigerant costs are still likely to be a relatively small fraction of the capital cost for many applications. The extra system cost with alternatives (e.g. to ensure safety with flammable alternatives) may more than off-set the savings in levy in many cases, unless there are also energy savings due to improved energy efficiency. Further, the before-levy cost for many low-GWP synthetics looks likely to be higher than for HFCs due to more complex manufacturing processes.

In general terms, there is considerable evidence that natural refrigerants such as ammonia, many hydrocarbons and CO_2 at low temperatures tend to be more energy efficient than HFCs (often by up to 10%). For example, while theoretical thermodynamic analysis suggests R290 is 1–2% less efficient than R22, Cleland et al. (2009) measured 5–10% improvements when HCs were used as drop-in replacements. Similarly, R32 and some HFOs have promising performance relative to R22 and R410A in high-temperature applications, while recent literature shows HFO1234yf is a close match to R134a across a wide temperature range.

Alternatives to R404a are a particular challenge due to its very high GWP and its wide use in low – temperature applications. In theory, R410A has potential as a lower GWP replacement for R404a at low temperatures with improved efficiency but equipment for such application is currently a constraint.

While use of cascades or safe secondary refrigerants have an inherent energy-efficiency penalty due to the extra heat exchanger temperature difference, the opportunity to use high-efficiency refrigerants in each of the high and/or low stages often more than compensates. Therefore, use of cascades and secondary refrigerants to enable low charges of and to isolate high-GWP, toxic or flammable refrigerants are likely to become even more common in medium and low-temperature applications. CO_2 is likely to become the most common low-stage or secondary refrigerant, especially now that suitable equipment is becoming more available and cost-effective, due to its safety in populated areas and attractive thermodynamic and transport properties well below its critical point e.g. low pumping power. A wide variety of refrigerants are likely to be used in the high stage of the cascades depending on specific circumstances (e.g. R1234yf, ammonia, HCs, HFCs). This trend is already evident in the supermarket sector and is likely to extend to larger scale low-temperature refrigeration and air conditioning applications.

5. LESSONS FROM THE PAST

In trying to ascertain the way forward in a low-GWP world, lessons from the past are worth noting. The current situation has many parallels to those faced in the 1990s as CFCs were phased out. Tables 3 and 4 summarise alternative refrigerants foreseen or suggested in 1990, 1994 and 2003.

Back then, there were concerns that retrofit alternatives such as R134a would have lower capacity and would be less efficient (lower COP) based on theoretical cycle analysis. In reality, the differences were small for a combination of reasons. Close capacity matches could be achieved in most cases (e.g. via blends) and there was usually sufficient spare capacity in the system design if there was a loss of capacity. Alternative refrigerants often had better heat-transfer properties so evaporator and condenser performance was enhanced, and the new synthetic oils were generally better lubricants than the mineral oils they replaced, although significantly more expensive. Furthermore, change in refrigerant was often an opportunity to upgrade to more modern and more efficient equipment. In many cases, the alternatives also provided the additional benefit of reduced discharge temperatures.

Initially, there were a large number of drop-in CFC replacements being used but this quickly stabilised to a manageable number of longer term replacements (Figure 3). R12 to R134a and R502 to R507 or R404A retrofits quickly became routine with oil changes, replacement of elastomer seals and replacement or adjustment of expansion devices. Initially there was little thermodynamic data available and virtually no equipment performance data for the new refrigerants. Often designers and technicians assumed similar performance to the refrigerants being replaced. This approach was generally adequate and the equipment performance data quickly arrived, as the new marketing opportunities the enforced changes created became obvious to manufacturers. Many found that material incompatibilities with the replacement refrigerants were not acute. Emergency retrofits could be done without full oil and elastomer replacements as long as these were undertaken in due course. R22 was used in many new installations, although it was due to be phased out, presumably because of familiarity with it and its perceived high performance.

There were concerns that the higher pressures with R410A would be a safety issue. While equipment designs with higher pressure ratings were needed, the basic installation and servicing techniques were very similar; 15 bar pressure with R22 at 40°C condensing is not necessarily significantly less dangerous than 24 bar pressure with R410A.

There were also concerns about cost of refrigerants and the likely negative impact on contracting and service businesses. Refrigerant prices were initially higher but they quickly reduced as manufacturing facilities came on line and the chemical companies competed against each other. Also, the extra refrigerant and retrofit costs were usually passed onto customers without too many complaints because there was reasonably wide awareness of ozone depletion and the MP.

In summary, the experience of the shift from CFC refrigerants was generally a case of technicians becoming familiar with the characteristics of the new refrigerants and slightly adjusting their practices rather than having to adopt entirely new practices. In general terms, we can expect similar trends to occur as the levy drives shift to lower GWP refrigerants. The big difference is that changes are driven by cost shifts rather than phase-out legislation and that most alternatives will be flammable so this will require new practices to be adopted by many who actively avoided flammable refrigerants in the past. Interestingly, Denmark and Norway introduced taxes similar to the levy in 2007. Rather than the taxes being deemed problematic, there are reports of the tax encouraging moves towards both low-GWP alternatives in large systems and a proliferation of low – charge systems (Cowan et al., 2011).

6. LEVY IMPACTS AND CHALLENGES

The levy will add costs to existing practice but these will be passed onto customers, and there is even potential for increased margins for contractors and service providers, if the levy is included in the wholesale price before mark-up. The levy should provide financial incentives for both providers and customers in a number of areas:

- Good practice in terms of reducing charge size and reducing leakage.
- Greater consideration of life-cycle costs and impacts.

- Rewards for innovative design and service practice.
- Early replacement of older, less efficient plant.
- Development of skills to work with flammable refrigerants.

However, some potential disadvantages are:

- Significantly higher refrigerant inventory costs.
- Added security costs due to higher risk of refrigerant theft (c.f. theft of copper when prices rise).
- Higher business risk if ignorant about environmental issues and developments in alternative refrigerants.
- Incentives to delay R22 replacement as it is not subject to the levy and is therefore lower cost (although reducing in availability due to MP phase-out).
- Uncertainty about availability and cost of HFOs in the short term.
- Poor customer relations due to lack of understanding of the levy and reasons for prices increases.
- A greater number of refrigerants in common use until the best alternatives become more obvious as experience is gained.

Burhenne & Chasserot (2011) and Colbourne (2011) summarise barriers to change of refrigerant and possible solutions to these barriers based on surveys of industry representatives in both developing and developed countries. Knowledge levels, technology availability, safety concerns and related psychological factors, and too-restrictive regulations and standards were all important barriers.

7. CONCLUSIONS AND RECOMMENDATIONS

The levy on refrigerants will increase costs for the refrigeration industry but will provide incentives for best practice and will provide enhanced commercial opportunities for well-informed and proactive customers and service providers. The levy will increase consideration of natural refrigerant options but the chemical industry has strong motivation to develop efficient and safe synthetic alternatives and is already having some success with R134a.

It is recommended that businesses:

- Focus on reducing refrigerant charges in new systems and increasing gas tightness on existing systems.
- Train staff to work with flammable refrigerants as they are likely to be part of the future for most applications.
- Keep engaged and informed about environmental issues and refrigerant options and performance.
- Use a life-cycle costing approach so decisions have a long-term focus.
- Shift to lower GWP refrigerants when significant system changes are needed, e.g. equipment becoming unreliable or demonstratively inefficient.
- Carefully plan and schedule replacement of existing large-scale R22 systems (short-term delay, until synthetic options become clearer and/or NR options become more mainstream, may be astute if stockpiles can be accumulated).
- Try to use NRs if safety issues can be addressed cost-effectively.

Ultimately, the levy introduction provides an opportunity for the refrigeration industry to lift its performance, as was the case when MP legislation was introduced, and should not be considered a threat. ▮

8. DEFINITIONS

AB	alkylbenzene oil
CFC	choro-fluoro-carbon
COP	coefficient of performance
EAL	estimated atmospheric life
HC	hydro-carbon
HCFC	hydro-choro-fluoro-carbon
HFC	hydro-fluoro-carbon
HFO	hydro-fluoro-olefin
Glide	evaporation/condensation temperature range for a blend at constant pressure
GWP	global warming potential
KP	Kyoto Protocol
M	mineral oil
MP	Montreal Protocol
NR	natural refrigerant
ODP	ozone depletion potential
P	pressure
POE	polyol-ester

9. REFERENCES

Burhenne, N., Chasserot, M. (2011) Natural refrigerants in the HVAC&R industry – a study of global market and policy trends. Proceedings International Congress of Refrigeration, Prague, Czech Republic, August 2011, paper 147.

Calm, J.M., Hourahan, G.C. (2011) Physical, safety and environmental data for current and alternative refrigerants. Proceedings International Congress of Refrigeration, Prague, Czech Republic, August 2011, paper 915.

Cleland, D.J., Keedwell, R.W., Adams, S.R. (2009) Use of hydrocarbons as drop-in replacements for HCFC-22 in on-farm milk cooling equipment, International Journal of Refrigeration 32: 1403-1411.

Colbourne, D. (2011) Barriers to the uptake of low GWP alternatives to HCFC refrigerants in developing countries. Proceedings International Congress of Refrigeration, Prague, Czech Republic, August 2011, paper 628.

Cowan, D., Lundqvist, P., Maidment, G., Chaer, I. (2011) Refrigerant leakage and containment – overview of the activities of the IIR working party on mitigation of direct emissions of greenhouse gases in refrigeration. Proceedings International Congress of Refrigeration, Prague, Czech Republic, August 2011, paper 856.

DCCEE (2012), Australian National Greenhouse Accounts: National Inventory Report 2010, Department of Climate Change and Energy Efficiency, Canberra, http://www.climatechange.gov.au/emissions

Lommers, C.A. (2003). Air-Conditioning and Refrigeration Refrigerant Selection Guide – 2003, AIRAH, Melbourne.

About the authors

Professor Cleland is Head of the School of Engineering and Advanced Technology at Massey University, New Zealand. His research interests are industrial refrigeration, energy efficiency and food processing.

Dr Love is a lecturer in the Institute of Food Nutrition and Human Health at Massey University. His research interests are industrial refrigeration, education in industry and fluid flow-in processing.