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Unscrambling The Refrigerant Clutter For The Future

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Why you should attend:

- To hear a critical evaluation of existing refrigerant classification frameworks, with particular emphasis on safety metrics and environmental impact criteria.
- To get an analysis of the technological, regulatory, and market-driven factors that will shape the selection of viable next-generation refrigerants.
- To find out which refrigerants are most likely to meet future performance, safety, and sustainability requirements.

Abstract

Recently the formal list of refrigerants in ISO 817 exceeded 240 and new refrigerants are being added at a rate of about 7 or 8 per year. 41 of these cannot be used due to prohibitions under the Montreal Protocol, leaving about 45 pure refrigerants and 155 blends to choose from. However, there are various technical, environmental, economic and safety drivers, including regulatory and market-orientated, that make many of these remaining refrigerant options unsuitable or not viable. Environmental concerns and associated legislation are evolving and in parallel, investigations and analysis of new molecules and blends of these and existing substances proceeds, along with consideration of historical perspectives on flammability, toxicity and chemical stability. Considering all these factors, it raises the question: what might we expect to see as the refrigerant landscape in the decades to come?

1. Introduction

Since the commercialisation of mechanical refrigeration in the late 1800s to early 1900s, there have been continuous discussions and lively debates on refrigerant selection (Colbourne, 2021) and this increased significantly with the advent of the Montreal Protocol in the late 1980s/early 1990s. Even prior to the introduction of halogenated refrigerants in 1930s, there were vigorous debates on the topic of refrigerant choice. With the recent publication of the European F-gas regulation (2024) and the even more recent proposed GB F-gas phase-down schedule (2025), the conversation is as energetic as ever.

The application of alternative refrigerants also dominates discussions within European and international safety standards; what and how much should be permitted in which situations, what are the appropriate mitigation measures and so on. This is despite the most significant hazards being related to aspects such as pressure safety and electrical safety, which are largely unrelated to refrigerant choice.

In the wider literature, the subject of refrigerants is highly pertinent, with an increasing number of books and other publications handling the topic. In the Fridoc database of the International Institute of Refrigeration (IIR, 2026), there are some 34,000 documents – being more than a third of all entries – on the topic of refrigerants. As long as vapour compression systems are in use, this confabulation will persist.

Parallel to this, chemical producers and other stakeholders are registering more and more refrigerants, largely driven by the various legislation and perceptions related to environmental impact and increasingly, tolerability of known (and emerging) hazards. The commercial drivers related to the introduction of new refrigerants, as well as the economic implications of applying alternatives, whether it is necessity to minimise leakage, avoid internal reactions, use gas or leak detection or redesigns to avoid potential ignition sources, lead to lively and excitable debates on the topic, across many different fora.

As of 2026, the formal list of refrigerants in ISO 817 exceeded 240, almost tripling in number over the past two decades; see Figure 1. In addition to those registered within ISO 817, the technical and patent literature reveals many other (hundreds of) proposed alternative refrigerants, most of which are blends.

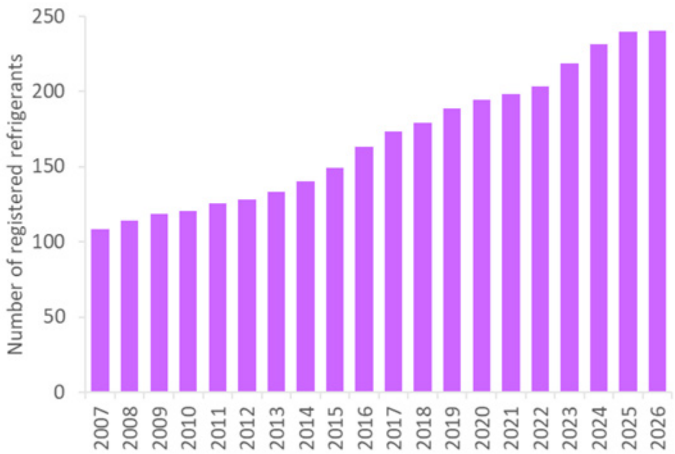

Figure 1: Number of refrigerants registered under ISO 817 since 2006

Whilst interesting and sometimes entertaining, this almost-perpetual refrigerant transition causes consternation and frustration to system producers (manufacturers, installers, assemblers), who ultimately only want to sell reliable systems that simply give and/or take heat, preferably with as low a purchase and running cost as possible – regardless of the refrigerant type. The ever-expanding clutter of alternative refrigerants seldom helps this objective. System producers in general would prefer an insight into what the most viable alternative refrigerants will be over the next decade and beyond. To tackle this objective, it is useful to consider certain aspects related to refrigerants and their selection. First, it is important to understand the various classification schemes, as this often dictates the onerousness of system design, construction and lifetime treatment obligations. Second, the drivers for refrigerant selection are laid out, which helps give insight into what affects the popularity of some substances and obsolescence of others. By understanding the motivating forces within the industry, some suggestions can be made as to the most likely options for the future.

Since the RACHP market is global, any discussion on refrigerant options should reflect the situation internationally. Due to the extreme diversity of national and regional regulations, standards, handling practices, not to mention legal frameworks and cultural orientations, the subject is comprehensively challenging.[1]

2. Classifications

2.1. General

A first step to mapping out refrigerant options and subsequently gauging the drivers for selecting alternatives, is to consider established refrigerant classifications. There are various means of classifying refrigerants, including those related to chemical substance and composition, health and safety hazards and environmental impact. These classifications are often used as key parameters for indicating acceptance or even determining legal acceptability and can be used, directly or indirectly, in legislation.

2.2. Composition

The first type of classification of refrigerants can be that of the bulk fluid composition. There are two types of refrigerant composition: a single component refrigerant and a blend, being composed of two or more substances. A single component refrigerant is a pure substance (single molecule), thus the behaviour in a refrigeration system is simple and well understood. Blends may be divided into two classes related to their bulk behaviour, being zeotropic and azeotropic mixtures. A zoetrope is where the refrigerant components' equilibrium vapour and liquid phase compositions are not the same at any point below the critical pressure. Conversely, an azeotrope is where the components have equilibrium at their vapour and liquid phase compositions that are the same at a specific pressure, although can be different at other conditions; essentially their behaviour is close to that of a single component.

Zeotropic refrigerant blends can offer a means of gaining favourable properties and characteristics of certain components to yield overall desirable result, such as achieving lower flammability, lower GWP and better oil solubility. They can also exhibit certain characteristics that potentially impact negatively on system function and performance, such as fractionation or component separation and large temperature glides, which can be detrimental to system performance especially when the system is not designed specifically to handle it. For application in most types of systems, rules-of-thumb are to avoid blends with temperatures glides of more than a few Kelvin, i.e., exceeding about 3 or 4 K.

2.3. Chemical structure

For single molecule (or "pure") refrigerants, ISO 817: 2024 and ASHRAE Standard 34 (2024) classifies fluids according to chemical structure. This classification uses an initialism for the chemical structure, for instance PFC

1. In this article, where feasible the treatment is as global as possible, but reluctantly constrained to the European or even national contexts in some places.

for perfluorocarbons, HCFC for hydrochlorofluorocarbons, or HFO for hydrofluoroolefin. The term olefin is one used for carbon chains with a double bond (conventionally referred to as an alkene). This chemical classification system is used for halogenated greenhouse gases and also elsewhere, for instance in legislation and in Intergovernmental Panel on Climate Change (IPCC) reports.

Within the RACHP industry, each refrigerant is given a unique designation known as an R-number. For single molecule refrigerants, this designation is based on the molecular structure and for most compounds, this structure can be derived from the designation. This designation can be used with the chemical classification as a prefix, or simply with an R-, for instance R-134a can also be written as HFC-134a to indicate that belongs to class of hydrofluorocarbons.[2]

For refrigerant mixtures, each refrigerant is assigned a number in the 400-series, 4100-series or 500-series depending on whether the mixture is an azeotrope (500-series) or not (400- and 4100-series). The numbers are assigned in the order that new R-numbers are applied for. After R-499A was assigned in amendment 'f' of 2025, new numbers for non-azeotropic mixtures are assigned in the 4100-series. If a new mixture has the same components as an existing R-number, it is assigned the same number, but with a different post fixed letter, for instance, R-407A, R407B, and R-407C all consists of R-32, R-134a, and R125, but in different proportions.

Refrigerants will almost always be mixed with oil in a refrigeration system, but in principle the refrigerant can also be mixed with low concentration of odorants or chemical stabilisers. Odorants can reduce health and safety risks in the event of refrigerant releases, but they are very seldom used largely due to reactivity. Chemical stabilisers are also rarely used, but they can potentially allow usage of unstable refrigerant molecules, such as R-13I1, R-1123, or R-1132(E).

There is a widely used term, "natural refrigerants" and the antithesis being "synthetic refrigerants". Natural refrigerants are so-called because they naturally occur in the earth's biosphere, in absence of man-made processes; synthetic refrigerants are essentially all those that are not natural refrigerants.

2.4 Safety class

ISO 817 and ASHRAE Standard 34 classify refrigerants on toxicity and flammability. For toxicity the classes are A for lower toxicity and B for higher toxicity. For flammability they are 1 for non-flammable, 2L for lower flammability, 2 for flammable, and 3 for higher flammability. The safety classification is the combination of these classes, for instance R-744 is classified as A1 (low toxicity and non-flammable); see Table 3.

Table 1: Safety classification in ISO 817 and ASHRAE Standard 34

	Low Toxicity	High Toxicity
Non-flammable	A1: e.g., HFC-134a, R-410A, R-744	B1: e.g., HCFC-123, HFC-245fa
Lower flammability	A2L: e.g., HFC-32, HFO-1234yf	B2L e.g., R-717
Flammable	A2: e.g., HFC-152a, HFO-1132a	B2: e.g., HFO-1132(E)
Higher flammability	A3: e.g., HC-290, HC-600a, HC-1270 and in ISO 817: HC-1150	B3 e.g., in ASHRAE Standard 34: HC-1150

[12] Hereafter, when referring to a refrigerant, the chemical initialism is used for pure substances (CFC-, HFC-, etc.) to help qualify the context of the discussions and R- for blends, since they may be composed of a variety of different types of substances, and similarly R- for inorganic compounds such as ammonia (R-717) and carbon dioxide (R-744).

Traditionally the toxicity classification has been based on chronic toxicity, but in ISO 817:2024 this was changed to also account for acute toxicity in recognition of the fact that in modern times most exposure to refrigerants occurs during refrigerant handling activities. The result is that a few fluids now have different toxicity in ISO 817 from that in ASHRAE 34, for instance R-11, R-245fa, and R-1150 and in ISO 817, some fluids have nevertheless changed from class A to class B.

ISO 817 and ASHRAE Standard 34 use almost the same criteria for flammability classification and the difference has no practical implications (at least not yet). What is different however is that for refrigerant blends, ISO 817 classifies both the worst-case formulation (WCF) and worst-case fractionated formulation (WCFF). The details will be skipped here, but the result is that ISO 817 has two flammability classes for each blend whilst ASHRAE Standard 34 only has one. For instance, in ISO 817, R-410A is A1/A1 and 403A is A1/A2, while in ASHRAE Standard 34 they are classified A1 and A2 respectively.

There are also safety concerns related to chemical stability for a number of newer molecules, specifically the halogenated members of the 1100-series and FIC-13I1, but in principle the same concern will apply to other molecules which have previously been deselected as potential refrigerants due to their unstable nature. The primary concern with the 1100-series is that if sufficiently high initiation energy is provided, they can disproportionate in an exothermic reaction, creating a very high pressure inside the refrigeration system similar to an explosion e.g., HFO-1123: $C_2HF_3 \rightarrow 0.5\ CF_4 + 1.5\ C + HF + 250$ kJ/mol (Zhang, 2023). For FIC-13I1 the concern is related to the carbon-iodine bond being significantly weaker than a carbon-hydrogen bond and this creates a risk of propagating exothermic free radical reactions. In refrigerant mixtures, stability issues can be mitigated by adding fluids to help stop these reactions from propagating. These fluids are also known as stabilisers. Another option is to avoid using these as pure fluids.

To address this safety concern, ISO TC86/SC8 has established a new working group, “Test Method for Refrigerant Reactivity”. This group is tasked with developing a new standard, ISO 26490 “Stability Test Method and Criteria”. The draft ISO 26490 defines 3 stability classes:

- Stability Class α: Refrigerant is stable enough to be used in conventional refrigeration systems.
- Stability Class β: Refrigerant is stable to be used with certain restriction of operating conditions in refrigeration systems.
- Stability Class γ: Refrigerant is not stable to be used in conventional refrigeration systems.

It remains to be seen how this classification will be integrated into ISO 817 – and other systems safety standards – but a possibility could be to have an extension to the current safety classification. E.g., R-410A would have safety class A1α (more likely the extension would be optional for Stability Class α, so as to create as small a change as possible).

2.5 Global harmonised system

Under the UN Global Harmonised System (GHS) (UNECE, 2026), as well as that for the UN model regulations for the transportation of dangerous goods and the European Classification, Labelling and Packaging of Chemicals (CLP) regulation in Europe, there is a classification system for hazardous substances. This is based on criteria for classifying chemicals according to their health, environmental and physical hazards and hazard communication requirements for labelling and safety data sheets (SDS). Non-flammable and non-toxic gases are assigned a hazard category of class 2.2 along with a hazard statement code “H280” referring to “gas under pressure; may explode if heated”. Concerning substances commonly used as flammable refrigerants, they are assigned a hazard category of class 2.1, 1A or 1B along with the additional hazard statement codes “H220” or “H221”, respectively, broadly for higher or lower flammability. In all cases, the hazard pictogram (red diamond with flames) applies. Higher toxicity gases under pressure (such as R-717) are categorised class 2.3 and require further hazard statement codes "H314" (severe skin burns and eye damage) and "H331" (toxic if inhaled). In most countries, these represent the minimum regulatory safety classifications and are used for overriding legal obligations where applicable. For example, building fire regulations typically rely on GHS classes. As there is no link to the ISO 817 safety classification system and in fact some substances' safety classifications differ, confusion can arise.

2.6. Global Warming Potential

Global warming potential (GWP) is a measure of a refrigerants ability to contribute to climate warming, relative to carbon dioxide and is being used as a determinant for permitted refrigerants in certain legislation. To facilitate the discussion on GWP of refrigerants, the Refrigeration, Air-Conditioning and Heat Pumps Technical Options Committee (RTOC) under the Montreal Protocol has published a classification of GWP levels based on the absolute value of the 100 year GWP, see Table 2 (UNEP, 2019; UNEP, 2022).

Table 2: UNEP RTOC classification of 100-year GWP levels

100-year GWP	Classification
< 30	Ultra-low or Negligible
< 100	Very low
< 300	Low
300 – 1000	Medium
> 1000	High
> 3000	Very high
> 10000	Ultra-high

Despite the GWP classification shown in Table 2, most legislation has instead set other boundaries. For example, from the EU F-gas regulations (EU, 2014; EU, 2024) it may be inferred that GWP above 2,500 is "high" (or "very high"), 750 is the upper boundary of medium GWP and 150 being the threshold between low and medium GWP. Rather than being derived using mathematical incrementation (as is the case with Table 2), these divisions are based on rounded-up values of certain refrigerants; specifically, HFC-152a for 150, HFC-32 for 750 and R-410A for 2500.

3. Current drivers for refrigerant selection

3.1. General

There are numerous factors that affect the choice of refrigerant. Some are technical, some legislative and many are predominantly subjective, where three broad levels may be identified:

- Soft drivers, which are primarily subjective and based on "feelings" rather than tangible values, changing fluidly with time;
- Medium drivers, usually affected by cost impacts and complexity, but can be addressed by various means;
- Hard drivers are mainly those that are dictated by legislation, yielding a definitive acceptance or rejection.

The term "current collective industry perspective" (CCIP) broadly describes the prevailing opinion of the wider industry with regards to what is acceptable for the sector and what is not; the amplitude of casual or unconstrained conversation on the subject involving details that are not confirmed. It is a combination of subjective views that are invariably affected by personal experience, financial interests, personal philosophical principles, volume of other voices, effectiveness of corporate marketing and so on. Opinions and perspectives may be applied to the handling on any individual drivers or overall, focussing on any one or any group of refrigerants. The impact of CCIP is perhaps one of the most dominant forces when it comes to refrigerant selection.

3.2. Ozone depletion

Ozone Depletion Potential (ODP) of substances is the primary factor for guiding the trajectory of refrigerant selection over the past four decades. Under the Montreal Protocol, all ozone-depleting CFCs (high ODP) were phased out globally by 2010 and HCFC (lower ODP) use and consumption will be phased out by 2030 (except for a small “service tail” until 2040, although GB and EU regulations banned all HCFC consumption in 2015. Essentially, no ozone depleting CFC and HCFC can be considered for refrigerants in new or existing systems; this eliminates nine of the single substance refrigerants and 26 of the blends. It is clear that refrigerants controlled under the Montreal Protocol cannot and will not be used, irrespective of any dissenting views.

It is noted that some of the substances recently added to ISO 817 do in fact exhibit a ODP. These include FIC-13I1, HFO-1224yd(Z), HCFO-1233zd E) and HFO-1130(E). However, these molecules easily breakdown soon after being emitted to the environment, resulting in a short atmospheric lifetime and because of this they are mostly expected to degrade before reaching the stratosphere and therefore not generally considered a threat to the ozone layer.

3.3. Climate change implications and GWP

Whilst at the earlier times of ODS phase-out, GWP was not often considered, but the implication of refrigerant emissions on climate change has escalated and is presently perhaps one of the strongest drivers.

Internationally, the Kigali Amendment to the Montreal Protocol (UN, 2016), which entered into force on 1st January 2019, set out to control the production and emissions of refrigerants (mainly HFCs) on a tonne of CO_2-equivalent basis. For those countries that have ratified the Amendment, corresponding national legislation comes into force, with some introducing more stringent phase-down schedules. At European level, there is the F-gas regulation, with the current version being from 2024 (EU, 2024). Within the United Kingdom, there has been no update since the 2014 F-gas regulation, although recently a consultation document was issued, based primarily on phase-down schedules similar to those of the 2024 EU F-gas regulation, albeit without any of the supplementary rules such as mandatory competence and placing on the market (POM) bans.

To illustrate the various phase-down schedules, Figure 2 compares values from the Montreal Protocol Kigali Amendment (MP-KA) the EU F-Gas (2024) and proposed GB F-gas (2025) regulations. The likely reason why the EU and GB F-Gas Regulations go beyond the Montreal Protocol is that the marginal abatement cost is considered to be low for refrigerant transition, compared with alternatives on the CO_2 marginal abatement cost curve. This makes refrigerants an attractive area to target for climate policies. The resulting national and regional regulations are currently perhaps the strongest drivers for refrigerant development and selection, whereby producers and end users are targeting “low GWP”, according to one definition or another.

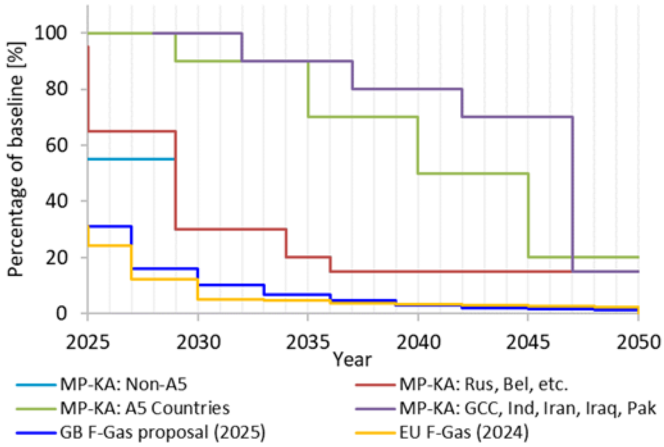

Figure 2: Phase down schedules as percentage of baseline for the Kigali Amendment to the Montreal Protocol (UN, 2016) and the EU F-Gas regulation (EU F-Gas, 2014; EU F-Gas, 2024)

Figure 3 is an illustration of how the average available GWP for refrigerants will develop if refrigerant consumption and market growth is put on top of the phase down schedule. For the EU, average GWP is about 50 in 2035 and 15 in 2050, whereas under GB proposal, it would be about 50 in 2035 and 10 in 2050. The average GWP is not the GWP of a specific refrigerant used in a specific application, but an average covering the use of ultra-low GWP in some segments and somewhat higher GWP in others. An important effect being ignored in this picture is that the consumption of refrigerant can be reduced dramatically with better system design and service practices, i.e., minimising system charges, reducing leakage and high recovery/recycling rates.

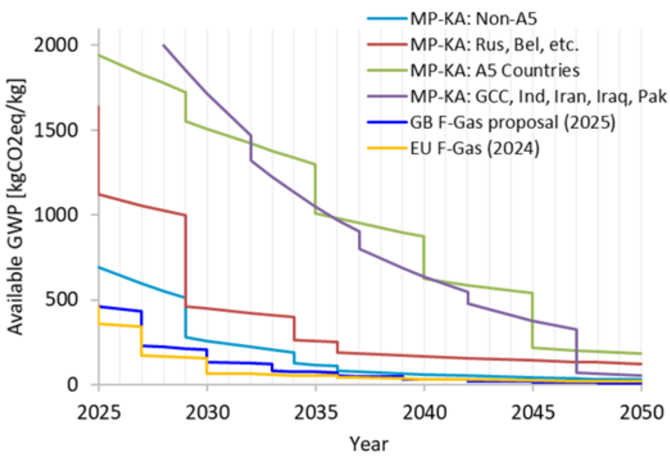

Figure 3: Illustration of average GWP with market growth (assuming 8% for A5 countries including GCC, India, etc. and 3% for the rest)

What the average GWP does imply is that for the major market segments, the refrigerant will have to be low GWP. Medium or high GWP may be used in niche applications, but the refrigerant becomes a low quantity material and the supply chain inevitably becomes narrower and more costly. This implies that medium GWP and high GWP refrigerants overtime will become less practical to use, acceptable for niche applications where cost is less of an issue, but not acceptable for the mass market. Moreover, it is uncertain whether the refrigerant market is large enough to support production of medium GWP and high GWP fluids in the long term, unless they are also manufactured for other purposes or as a by-product from the production of other substances. An example of the effect on the supply chain is that a commonly used refrigerant like HFC-134a currently has vendors in almost every city globally, while a niche refrigerant like HFC-152a is much more difficult to find and is only manufactured because it has other applications.

3.4. Per- and polyfluoroalkyl substances (PFAS)

PFAS is a very large group of substances, receiving a lot of media attention. The definition of PFAS is however not fixed. One example is OECD (2022), which categorises molecules with CF_2 or CF_3 groups as PFAS; under this definition, most fluorinated refrigerants can be classified as PFAS. Another example is the Toxic Substances Control Act of the USA (TSCA, 2023), which categorises PFAS as a molecule with one of 3 specific structures, leading to a requirement that there are at least two fluorinated carbons. In this case fluorinated refrigerants are not PFAS.

From a technical point of view, it is not interesting whether refrigerants are PFAS or not, since they have a limited atmospheric lifetime, but what is relevant is the nature of their breakdown products. The majority of atmospheric breakdown products from fluorinated refrigerants are inorganic compounds such as HF, CO_2, H_2O, but there are cases where they include trifluoroacetic acid (TFA) (CF3COOH). Noteworthy is that the breakdown of HFO-1234yf has 100% yield of TFA, while HFO-1234ze(E) is assumed to be 0% yield, even though the molecules are otherwise very similar. TFA is classified as PFAS under OECD (2022), but not under TSCA (2023). Whilst TFA can also originate from numerous sources, including pesticides and pharmaceuticals it was estimated (about 8 years ago) that some 50% of the precipitation-induced TFA originates from refrigerants; the rapid growth in consumption of HFC-1234yf and associated blends suggest a greater proportion going forwards (Behringer et al., 2021).

TFA is water soluble, unlike the long-chained PFAS molecules and this makes the environmental toxicity very different. For instance, TFA does not bioaccumulate in the traditional sense, but it seems to accumulate in the leaves and fruits of plants. It has been found in numerous liquid foods and the majority of drinking water samples (tap and bottled) as well as drinking water sources (reservoirs, rivers, etc.) throughout Europe (e.g., Burtscher-Schaden et al., 2024; Affricano et al., 2026). More so, concentrations in cereal crops have been found to be orders of magnitudes higher than has been observed in liquids (e.g., Taylor-Smith, 2026). Thus, it is increasingly recognised to be a significant environmental contaminant with rising levels in water, food and humans. Recent studies have found the rapid increase in concentrations to be attributable to “CFC replacements” (Hart et al., 2026).

Recognising that TFA does bioaccumulate, the key question is whether concentrations of TFA in plants and animals can present threats to health and infrastructure. While traditionally considered to have low to moderate toxicity, recent studies suggest it poses potential long-term risks, including reproductive and developmental harm. There are indications from toxicity studies in mammals that TFA is toxic to reproduction and that it exhibits liver toxicity (Arp et al., 2024).

As there are no known natural breakdown processes for TFA, this makes it a target for legislative action. There is currently a proposal in the EU to ban all PFAS chemicals under the EU REACH Regulation (ECHA, 2025). This proposal uses the PFAS definition from OECD (2022) and would ban most fluorinated refrigerants with the exceptions being HFC-23 (ultra-high GWP), HFC-32 (medium GWP), and the R-1100-series (low GWP). This is still just a proposal, but as it is moves through the pre-decision procedure, it is clear that it will eventually result in some restrictions on PFAS chemicals and refrigerants are clearly on the agenda of the expert committees preparing the details. This could end with a ban of most fluorinated refrigerants, but, since technically it is only the breakdown products that are important, it could also end with a narrower limitation on substances with

TFA as a breakdown product. It is noted that the 2024 EU F-Gas Regulation (EU, 2024) already contains sectorial bans for all fluorinated refrigerants in certain systems. This does not apply to the GB F-gas proposal. Outside Europe there is also an increasing focus on PFAS, but it is unclear whether this will extend to refrigerants and if so, it is most likely going to focus on breakdown products, hence more likely to hit HFO-1234yf than HFO-1234ze(E). All this implies that three scenarios need to be considered when forecasting the long-term refrigerant options:

i) Restrictions on refrigerants related to PFAS will only be regional, with EU being most restrictive;
ii) Fluids which decompose to TFA will be restricted in use across most of the world, thus limiting HFO-1234yf but not HFO-1234ze(E);
iii) All fluids with CF_2 or CF_3 groups will be restricted across most of the world, as is the current PFAS proposal in the EU.

A fourth scenario is that all fluids with halogens will be restricted in most of the world. This is the approach used in the 2024 EU F-Gas Regulation for small appliances, but globally it is highly improbable. For the time-being, omission of TFA-producing refrigerants will only be driven by CCIP.

3.5. Refrigerant safety – flammability

For Europe and many other parts of the world, safe application of refrigerants is governed at a legislative level by general building safety, mechanical and fire and explosion regulations (as opposed to specific regulations on refrigerating systems). For example, within Europe these include the Machinery Regulation, ATEX directives (equipment and workplace) and the equivalent dangerous substances and explosive atmosphere regulations (DSEAR) in the UK. None of these deal with refrigerants or refrigerating systems specifically, but they cover the application of flammable gases in general. The general principle in this legislation is not to limit or restrict quantities of flammable substance, or indeed quantities per unit volume of space, but instead to apply the necessary measures – which invariably incurs some cost penalty – to ensure that the flammability risk to persons and property is limited to a tolerable level. The exceptions are some national buildings (fire) safety regulations, which specifically address the use of flammable refrigerants in certain types of buildings. Since this only applies to a small number of countries and specific types of buildings and for which the European Commission is requesting resolution of within the context of the F-gas regulation (e.g., DG Clima, 2016), they will not be considered further.

Conversely, safety standards such as EN 378, ISO 5149, EN 60335-2-40 and EN 60335-2-89, do impose limitations on quantities of flammable refrigerant (both absolute and in terms of mass per space volume), according to a variety of parameters such as equipment type, application, occupancy and refrigerant characteristics. These standards are continually being revised, usually with improvements, although the approach for flammable refrigerant quantity limits is disparate, as is the philosophy underlining their derivation (Colbourne et al., 2020). Nevertheless, these safety standards do not represent any legal obligation with regards to limitation of refrigerant quantities, rather they represent an industry recommendation. Having said that, many system producers do opt to adhere to the requirements of such safety standards in the hope that they provide them some form of legal protection in the event of an accident.

When it comes to CCIP within the context of flammability, some interesting observations can be made. Historically – since the Montreal Protocol – the issue of refrigerant flammability was held with significant disdain (Colbourne, 2021). For example, during the 1990s there were extremely ferocious debates over whether hydrocarbon refrigerants could be used in domestic refrigerators, yet today, there are billions in the market (including in the kitchens of those who argued against their use). The requiescence of attitudes to flammable refrigerants have been helped by the widespread introduction of lower flammability refrigerants, such as HFC-32 and HFO-1234yf. Currently, more and more applications are being satisfied also with higher flammability refrigerants, such as HC-290 and HC-1270, including large air conditioning, display cabinets, train and bus air conditioning, domestic and industrial heat pumps and so on. The transition takes about a generation to become comfortable with such a change; waiting for those with entrenched views, such as "you'll never get a fridge working properly without CFCs" - type mindsets to retire before substantial changes become normality.

In principle, any flammable refrigerant can be applied in any reasonable quantity, but safety standards impose (often subjective) non-legally binding constraints on certain refrigerants.

'Refrigerant safety' – flammability and toxicity – should not be regarded as the only parameters detrimental to human life. The environmental impacts associated with the refrigerant can have a significant impact on human mortality in general; see for example, Colbourne and Kuijpers (2025) which shows that emissions of 150,000 to 200,000 tCO_2-eq of refrigerant will be responsible for one fatality due to climate impacts. Or, the GWP of HFCs needs to be in single figures to avoid leading to greater mortality risk to humans than when using a negligible GWP class A3 refrigerant.

3.6. Refrigerant safety – toxicity

Both within safety standards and national/regional legislation, application of higher toxicity refrigerants is seldom treated binarily, instead permitted quantities are based on toxicity values for individual substances.

The ISO 817 safety classification (class A or B) applies a broadly arbitrary threshold for dividing the classes, originally selected according to a natural gap between the clusters of the refrigerants being used at the time.

Despite all refrigerants being toxic to some extent (apart from R-729, air), over time, the CCIP has evolved into a general acceptance of class A, whilst broadly rejecting class B; the exception being for R-717 in industrial, process and other applications where it has traditionally been used. Nevertheless, actual obligations are essentially the same as with flammability safety: legislation tends to allow anything to be used, provided that appropriate mitigations are implemented and demonstrated by risk assessment. Safety standards can limit quantities but again, these are guidelines rather than legally binding. As mentioned elsewhere, given the constraints on options imposed by availability of molecules, it is foreseeable that more class B refrigerants will be developed and registered.

3.7. Refrigerant stability

Historically, only stable substances have been used as refrigerants – otherwise the system would cease to function, ultimately leading to financial detriment to producers; no one would consider using unstable refrigerants. Again, due to limited refrigerant options, refrigerant producers are increasingly considering mixtures with less stable molecules (see section 2.4 on safety classification). This matter is embryonic, but there is some experience with HFO-1234yf in car AC systems, where polymerised refrigerant has been found in systems. One application that is vulnerable to polymerisation is heat pumps (Figure 4), where testing has found evidence of polymerisation with the HFO-1234yf component of R-513A (Ignatowicz et al., 2026). This particular stability issue does not necessarily result in safety hazards, but other types of instability issues can do.

Figure 4: Discharged polymerised HFO-1234yf (originating as R-513A) (Ignatowicz et al., 2026)

In terms of CCIP status, there is minimal discussion and at present, any anticipation of poor refrigerant stability has negligible impact on choice of refrigerant. If and when more unstable refrigerants are introduced, cumulative experience will start generating opinions.

3.8. Availability of refrigerant, components and competence

Local availability of particular refrigerants and system components for those refrigerants is simply dependent upon market demand. As more and more manufacturers test, trial and produce systems with a particular alternative refrigerant, the refrigerant and system component suppliers and thus manufacturers respond to the request. Comprehensively reacting to the demand, especially in the case of a "new" refrigerant can take many years. With some fluids, there can be additional hurdles or barriers, such as where particular countries have national regulations concerning the handling or transportation of certain (hazardous) gases; either regulations need to be changed or the supply infrastructure needs modification (such as different capacity or types of refrigerant cylinders). Regardless, the process requires a critical quantity demand for a particular fluid, in order to justify the investment in development, infrastructure, materials, etc.

Crucially, there is an upper limit to the viable number of alternative refrigerant options. It is not economically feasible for system producers, component manufacturers, refrigerant distributors, etc., to invest in more than a few options. Thus, for the few that become commercialised, there must be compelling technical reasons and abundantly positive CCIP treatment of those fluids. Eventually too many options become commercially prohibitive.

For refrigerants with characteristics different to the conventional ones, competence of the workforce must be addressed, not only where it concerns safety aspects, but also thermodynamic characteristics such as temperature glide or material compatibility. Increasingly international awareness of competence of refrigeration technicians, system designers, etc. is leading to training schemes such as the so-called "refrigerant driving licence" (UNEP, 2026).

Ultimately, availability of hardware and knowledge does not represent an actual barrier to adoption of any one alternative refrigerant option, but does require a lot of time, effort and resources. For CCIP, it is significant as these are popular topics for open discussion in industry events and transactions.

3.9. New refrigerant market implementation

Developing a refrigerating system for a new refrigerant takes at least 1 – 2 years if the system components and design experience are readily available, otherwise up to 5 – 10 years. Non-negligible differences in thermodynamic and transport properties compared to established refrigerants means that new compressors may need to be developed or adapted. This is normally an optimisation task, but does require significant testing and certification, taking at least 2 – 3 years. Since testing and certification is expensive, it requires the compressor manufacture to be reasonably sure that the new refrigerant will reach a significant market share.

For fluids consisting of known molecules, where there is a production base, the time to market is dominated by getting the fluid accepted by the compressor manufactures and getting compressors available, so a total time to commercialisation of 5 years or more would be expected. Even if no new compressors are needed, it still takes time to convince the industry that the new fluid is worthwhile considering and this is also multi-year effort.

If the fluid contains a new molecule, which is not yet in industrial use, then new chemical production facilities are needed. This is a huge investment, and chemical manufactures will likely need to convince investors to gather the funds for such a project. This is likely a five- to 10-year project, with compressor and component manufactures working in parallel. With the current legislative uncertainty combined with the developing geopolitical deglobalisation, it is unclear whether the market for synthetic refrigerants is or will remain favourable enough to introduce a completely new molecule; also considering the possible changes that can occur over that period. That stated, the refrigerant market is very large and has strong growth.

3.10. Market segment refrigerant de/attachment

When a market segment is using a specific refrigerant, for instance AC has historically used HCFC-22, then it regards switching to another fluid as a huge change, due to, for instance:

- Components, especially compressors need to be verified for the new fluid (see section 3.8 and 3.9);
- System manufactures need to develop and optimise systems for the new fluid (see section 3.8 and 3.9);
- Supply chain needs to ensure wide availability for the service sector and appropriate service tools and equipment as well.

Each of these tasks depends on economy of scale and market players requires significant motivation to invest in such a change. This tendency to resist change implies that once a fluid is selected for a market segment, then it is unlikely to change unless there is legislative or very strong market pressure to do so. For instance, split AC changed from HCFC-22 to R-410A due to ODP legislation, but then to HFC-32 due to HFC phase down. There currently is an effort to switch from HFC-32 to HC-290 for small split AC systems, and if this is successful, then it is highly unlikely that this application will subsequently switch away from HC-290.

The implication of this is that there is a race to commercialisation: if new fluids manage to take market segments when legislative bans take effect, then these fluids are likely to prevail. If they do not make it to the market fast enough, then these segments are more likely to switch to natural refrigerants and thus become the long-term alternatives. Given the aggressive HFC phase-down in the EU, it is likely that many applications will switch to natural refrigerants due to the lack of more conventional alternatives. Most of these will lock-in to natural refrigerants for the long-term.

There is however also a fragmentation of the global market, where the refrigerant options in the EU might not be acceptable in other regions, especially in North America. This points towards a transition where there will be different refrigerants for a given application depending on the region for the medium term, and the long-term winner will depend on which of the two options perform best economically, environmentally, etc.

3.11. Refrigeration system energy efficiency and costs

Refrigerants do not have an efficiency as such, rather it is the system that uses the refrigerant that exhibits an efficiency. This system efficiency results from cumulative effects of system components, circuitry, ancillary parts and the refrigerant's thermophysical properties under the operating temperatures. Instead, refrigerant "potential efficiency" can be regarded as some form of expression to indicate the impact of a refrigerant's properties on a systems performance. Across most commonly used refrigerants, this is within the range of around ±15%. System design, however, can affect efficiency far more, by a factor of 5 to 10 times depending upon the conditions and starting point.

At present, there are increasingly more "minimum efficiency" (including maximum energy consumption) rules being established around the world, applying to an ever-widening range of different classes of RACHP systems and applications. Such minimum efficiency rules are usually coupled with energy labelling, where equipment exceeding the minimum efficiency levels are designated with "low" to "high" labels; analysis of published data shows clustering of systems' efficiency very close to those incremental efficiency levels. This highlights the direct link between system efficiency and cost, for example, where a refrigerant exhibiting poor system efficiency can be remedied by increasing the size of heat exchangers. At least where minimum efficiency rules exist or where there are efficiency bands (so that a system designer targets a given system efficiency), the impact of thermophysical properties translates as differences in component sizes (and thus costs) rather than actual system efficiency.

Applying flammable and/or higher toxicity refrigerants can have cost implications, such as for special components, controllers, detectors and so on. Often, such components are small and low cost, so any major cost implications tend to arise at the earlier stages of refrigerant implementation, diminishing as the market enlarges.

Due to energy consumption usually dominating both lifetime costs and CO_2-eq emission of most RACHP systems, all industry stakeholders have an interest and often express strong opinions as to which refrigerant outperforms another; CCIP can have a strong weighting in this area. Although ultimately, system producers and end users – who are all seeking the lowest expenditure for their cold or hot – will use testing, trials and analysis to find the options that yield the most cost-effective results. Moreover, after adopting a new refrigerant, gaining of experience, understanding and "learning" the refrigerant usually leads to design refinements that minimise costs.

4. Refrigerant landscape in forthcoming decades

4.1. General

The various drivers from section 3 are summarised in Table 3, indicating the obligatory limitations under the legislation column and the softer, more subjective and flexible considerations under the CCIP column. Identification of the various drivers in this way helps to filter refrigerants with regards to future options.

Table 3: Summary of drivers

Driver	Legislation	CCIP
Ozone depletion	Bans all CFCs, HCFCs	No discussion
Climate change implications and GWP	Kigali Amendment and F-gas regulations limit tCO_2-eq production and consumption	Medium and high GWP increasingly regarded as unacceptable, especially by end users/operators
Per- and polyfluoroalkyl substances (PFAS)	None to date	Perceived as future restriction, but awareness if currently emerging
Refrigerant safety – flammability	Generally, regulations only control risk, some national regulations prohibit some flammables	Historically, vehemently against their use, but becoming increasingly accepted
Refrigerant safety – toxicity	Not widely controlled	Currently 'disliked' by large portion of (non-industrial) industry
Refrigerant stability	No direct prohibitions	Concerns likely to increase if issue becomes more prevalent
Availability of refrigerant, components and competence	No direct prohibitions	Popular discussion points and can strongly affect refrigerant selections
New refrigerant market implementation	No direct prohibitions	Needs a compelling reason to justify investment in facilities and infrastructure
Market segment refrigerant de/attachment	No direct prohibitions	Needs a compelling reason to justify expenditure and resources to switch
Refrigeration system energy efficiency and costs	No direct prohibitions, only minimum efficiency regulations	Strong opinions, but factual testing should identify best options for the system

Consideration of these drivers helps to carry out a filtering exercise on the entire set of ISO 817 listed refrigerants, using quantitative values as the basis.

4.2. Filtering

Table 4 shows the results of the filtering exercise, where headers correspond to the following descriptions:

- With R-number – those substances that are listed in the latest ISO 817 or ASHRAE 34, along with an assigned safety classification.
- Not MP controlled – not prohibited under the Montreal Protocol
- GWP < 150 – with a GWP (100-year ITH) below 150, according to the IPCC 5th assessment report
- -80 < NBP < +25°C – with a normal boiling point above -80°C and below +25°C, i.e., suitable for the majority of RACHP operating conditions.
- No TFA – substance does not degrade into TFA under normal atmospheric conditions; this gives HFO-1234ze, HFO-1336mzz(E), HFO-1336mzz(Z), and five blends containing HFO-1234ze the benefit of the doubt
- Not PFAS – substance is not classified as a PFAS according to the ECHA definition
- Non-halogenated – molecule contains no fluorine, chlorine or iodine; being the natural refrigerants plus dimethyl ether (R-E170)
- Synthetic non-PFAS – a synthetic molecule with GWP < 150, but which is not classed as PFAS or yielding TFA in decomposition

Of the total number of substances included in each category, the number with a particular safety classification is given, along with those conforming to selected ranges of temperature glide (dTg).

Table 4: Filtering of listed refrigerants

	With R-number	Not MP controlled	GWP < 150	-80 < NBP < +25°C	No TFA	Not PFAS	Non-halogen	Synthetic non-PFAS
Pure fluids	57	45	33	17	16	12	8	4
400/4000 series	166	143	58	56	35	31	21	10
500-series	18	12	4	3	2	2	2	0
Total	241	200	95	76	53	45	31	14
that are A1	134	99	17	10	6	2	1 (R-744)	1 (R-13I1)
that are A2L	43	43	23	23	6	2	0	2
that are A2	13	10	8	7	5	5	0	5
that are A3	40	40	40	33	33	33	28	5
that are B1	8	5	4	1 (R-764)	1 (R-764)	1 (R-764)	1 (R-764)	0
that are B2L	1 (R-717)	1 (R-717)	1 (R-717)	1 (R-717)	1 (R-717)	1 (R-717)	1 (R-717)	0
that are B2	2	2	2	1 (R-40)	1 (R-40)	1 (R-40)	0	1 (R-40)
that are B3	0	0	0	0	0	0	0	0
Total	241	200	95	76	53	45	31	14
with dTg < 10 K	210	171	78	61	40	38	27	11
With dTg < 5K	143	112	56	39	27	25	17	8

From the initial 241 listed fluids and after being subject to the filtering exercise, there remain about 25 which are broadly applicable to most RACHP applications and may be regarded as approximately “future proof-ish”. Of the 18 which are not halogenated, many are HC blends and which show minimal technical advantage (usually disadvantages) over the pure HCs (R290, R1270, R600a, etc). The eight "synthetic non-PFAS" with small temperature glide comprises four pure substances and four blends, being R-429A, R-430A, R-431A, R-435A. All of these are blends of HFC-152a and hydrocarbons and/or DME. Synthetic refrigerants remaining that have a temperature glide between 5 K and 10 K are R-491A, R-497A and R-4101A. R-491A comprises R-1132(E) and 152a, and R-497A and R-4101A both include FIC-13I1 and thus have unresolved stability issues. These three blends all have a NBP of between -40°C and -30°C and all are flammable (one is class A2L and two are A2). Being a little more flexible with temperature glide (to 10.2 K) then enables inclusion of R-485A, which contains HFO-1132a, R-744 and HFC-32 and would in fact be the only non-flammable blend in this category. Those with a temperature glide well in excess of 10 K are R-494A, R-494B and R-498A, all of which include FIC-13I1.

Within such an analysis, it is appropriate to also mention that across the vast range of different RACHP applications, there can be more or less flexibility assigned to the various filtering parameters. For instance, certain types of systems may be less tolerant of temperature glide, whilst others can be designed to exploit this characteristic. Similarly, in some types of systems or applications application of flammable refrigerants may be prohibited or at least use will incur high costs to configure systems in an acceptable manner. Particular niche systems and applications may have very specific boundaries that means that many of the drivers discussed previously might not apply in the usual way. Taking this into consideration implies that at least some of the alternatives otherwise discounted, may actually have a place.

4.3. Particular developments

In principle, it is possible that a new molecule is discovered, which will be suitable as refrigerant. To address this possibility McLinden et. al, (2017) screened a database consisting of more than 60 million chemical structures and summarised that there were only 27 low GWP compounds which can potentially be used in a replacement for traditional HFC-refrigerants. Of these 27 compounds only 6 had not previously been discussed for use as refrigerants, and none of them are particularly compelling from a performance standpoint. A follow-up paper (Domanski and McLinden, 2025) reviewed the latest data, and two of the previously reviewed chemicals were highlighted as potentially promising. The first of these is 3,3,3-trifluoropropyne ($CF_3C{\equiv}CH$) with a GWP of 11, a boiling point estimated to be -51.4 °C and is flammable, possibly class 2 flammability. The second is HFO-1132(Z) (cis-CFH=CFH) with a boiling point of -26 °C, similar to that of HFC-134a, the GWP is <<1, but not much data is available on this fluid and there are some indications that HFO-1132(Z) may be of higher toxicity. The flammability and toxicity characteristics of 3,3,3-trifluoropropyne ($CF_3C{\equiv}CH$) are not fully known, the triple bond will likely make the molecule chemically unstable and additionally it falls under the proposed EU REACH PFAS ban, since it contains a CF_3-group (scenario 3 from the PFAS discussion) and depending on the breakdown products, it could also be not feasible under scenario 2. Note that both these molecules are in the category of new HFOs (if a triple bond is going to be considered as an olefin in a future ISO 817) with some flammability or toxicity and concerns about stability.

If the above is combined with the fact that a low boiling point is usually linked to a small molecule, it is highly unlikely that a "miracle molecule" will emerge as a perfect refrigerant. Instead, we may see molecules, which have previously been deselected for refrigerants due to flammability, toxicity, or lack of chemical stability. It may even be that any new molecules coming on the market will not be refrigerants themselves, but be to control the stability of the marginally un/stable HFO molecules discussed above

4.4. Less stable molecules

A number of molecules proposed as components for refrigerants are based on halogenated ethene, a backbone of two carbon atoms linked by a double bond. Currently these are HFO-1132a, HFO-1132(E) and HFO-1123.

These are produced in large quantities as precursors for halogenated plastics (PVC, PTFE, etc). In principle new molecules could also be based on longer carbon chains with double or even triple bonds, with a low number of halogen atoms attached. The advantage of this structure includes:

- Most of these fluids have relatively low boiling points due to the small molecular size, making them potentially suitable for alternatives to R-410A and HFC-32.
- Very short atmospheric lifetime due to the double bond, which gives very low GWP and ODP.
- Not classified as PFAS under any of the classification schemes, so will not be banned under any PFAS legislation.
- Simple degradation products when breaking down in the atmosphere, reducing the likelihood of concerns over unforeseen environmental impacts.

These substances are either flammable to some degree (class 2 or class 3) or have higher toxicity. There are also concerns related to poor chemical stability which potentially has stark safety implications (as discussed above), where the molecules might react with other compounds in the refrigeration system, such as lubricants or sealants. This can affect the lifetime of the compressor and other parts of the system and thus needs to be addressed by refrigerant and system component manufactures.

To handle the chemical instability, some kind of stabiliser is needed to be added. In blends that currently have an R-number, the stabiliser is often HFO-1234yf, but for scenario 2 and 3 from the PFAS discussion (section 3.4), a blend with long-term global reach will need a different stabiliser and it might not be a molecule currently used in refrigerants. With the increasing focus on PFAS, the chemical structure of any stabiliser and what breakdown products it forms will increasingly be under scrutiny.

Another unstable molecule is FIC-13I1 (CF_3I). The primary benefit of FIC-13I1 is its function as flame retardant. This is a component in several new mixtures, including R-466A, a non-flammable alternative to R-410A with a medium GWP where it turns an otherwise flammable mixture of R-32 and R-125 into a non-flammable mixture. Safety concerns related to propagating free radical reactions was discussed above, but other potential chemical reactions might lead to R-23 creation (which has ultra-high GWP) or the iodine might contribute to other chemical reactions, leading to formation of other unwanted chemicals in the system, for instance iodine acid (IH) which can easily etch holes in system piping. Again, these chemical processes can be suppressed with stabilisers, likely to be of a different nature than those for the 1100-series. Nevertheless, at the present time, companies previously endeavouring to develop systems for R-466A have reportedly abandoned it due to perpetual compatibility problems.

FIC-13I1 breaks down relatively quickly in the atmosphere, thus having minimal impact on the ozone layer (the ODP) from the iodine atom. The ODP varies depending on where the fluid is emitted (WMO, 2014). In North America and Europe, the ODP is very low since FIC-13I1 breaks down before reaching the ozone layer. In the latitudes of the Indian Subcontinent there are however strong up-winds, transporting emissions into the upper atmosphere, resulting in an ODP significantly above that of HCFC-22 (ODP of 0.055 in the Montreal Protocol). This makes FIC-13I1 unlikely to ever become a component in refrigerant mixtures with long-term global reach.

Another limitation of FIC-13I1 is that the global production capacity of iodine is not large enough to support the production of enough FIC-13I1 to support a consumption of a mainstream refrigerant.

4.5. “Semi-synthetic” blends

An alternative to looking at completely synthetic refrigerants is to consider mixtures of synthetic and natural fluids. In general, it is difficult to improve the safety classification of natural refrigerants by adding synthetic compounds. It only requires a small fraction of hydrocarbon for a mixture to become A3 and likewise it only requires a small amount of R-717 for a mixture to become toxicity class B. It is however possible to improve the thermodynamic properties of R-744 by adding small amounts of synthetic (or other natural refrigerant) components.

Examples of mixtures exploiting these features include:

- the high GWP mixture R-473A (R-1132a/23/744/125 [20%/10%/60%/10%]), where the bubble-and dew-point are -87.6 °C and -83.0 °C respectively, slightly lower than the triple point of R-744 (-78 °C), allowing for applications at very low temperatures, and
- the low GWP mixture R-485A (R-1132a/744/32 [10%/69%/21%]) where the critical temperature has been increased from 31 °C and to R744 to 40.6 °C for the mixture (Grundy et al. 2024). This can potentially give energy efficiency improvements over R-744 under higher ambient temperatures.

Especially R-485A and similar mixtures can potentially gain global importance by improving energy efficiency while only containing components with simple break down products and not containing any fluids categorised as PFAS under any current definitions.

5. Conclusions

Since the Montreal Protocol, there has been a continual discussion on alternative refrigerants, being both emotionally and technically effervescent. It has yielded thousands of research publications and forced the RACHP industry to understand refrigerant-related thermodynamics much more than would have happened otherwise, without refrigerant transitions being forced upon them. Moreover, it has led to numerous offshoots, such as better understanding and analysis of efficiency and energy consumption, system modelling, quantification methods for lifetime emissions (Total Equivalent Warming Impact, TEWI, Lifecycle Climate Performance, LCCP, etc.), improvements in controls, leak detection, safe design and risk assessment, characterisation of heat transfer and heat exchangers, application of safety standards and so on. Whilst some elements of the industry grumble about refrigerant transition, the overall result has surely been transformationally positive.

In parallel with this, the scope and extent of environmental legislation has also expanded and is likely to become increasingly stringent, whether this is inclusion of PFAS/TFA restrictions in forthcoming F-gas regulations, stricter and more inclusive Ecodesign regulations, minimum efficiency rules, etc. Indeed, continual improvement in energy efficiency, electrification and growth in renewables reduces the energy-related contribution of TEWI/LCCP calculations and thereby emphasises the importance of the refrigerant (GWP) weighting. As such, the pressure on acceptable refrigerant options is unlikely to ease off in the foreseeable future. Bearing in mind the time for research and development of new systems and components using alternative refrigerants, especially as they will be increasingly of higher toxicity and/or higher flammability and/or vulnerable to chemical stability issues, much further-forwards thinking is needed for refrigerant selection.

It is remarked that higher GWP refrigerant will become more costly, both due to quotas and because of their narrowing supply channels. This will likely create issues with existing systems, especially those older (higher charge, leakier) systems; whether perpetual topping-up, modifying for cheaper alternatives or scrapping and reinstalling new systems all infer significant cost. Considering the continual, rapid growth in registering new refrigerants – and the almost infinite number of possible blends based on the available components – one would expect continuing additions to the list of refrigerants at least at the average rate of 7 or 8 per year. It is reasonable to envisage more fluorinated fluid blends of flammability class 2 and even class 3 and similarly also with toxicity class B. This all leaves the following refrigerant options for the medium- to long-term future:

- The currently known natural refrigerants
- The currently known HFO and HCFO pure fluids, depending on the PFAS scenario:
  - 1: all HFO molecules currently available.
  - 2: only HFO molecules that do not degrade to TFA (e.g., HFO-1234ze(E) will be available, but HFO-1234yf will not).
  - 3: none of these molecules will be used as pure fluids.
- Low GWP mixtures of synthetic refrigerants, where the molecules are known today, but possibly not as refrigerants:
  - The currently known HFO and HCFO pure fluids, depending on the PFAS scenario (see above)
  - The 1100-series and other chemically unstable molecules, used together with stabilisers (and which stabilisers will be available will depend on the PFAS scenario)
  - Possibly small amounts of medium GWP fluids, especially fluids which are used in other industries, for instance as chemical precursors
- New mixtures containing a large fraction of R-744 together with the compounds used in low GWP mixtures of synthetic refrigerants

It is also appropriate to consider the other wider factors that may affect the future refrigerant demand. In particular, there is a desperate need to minimise thermal loads and it may be that governments eventually opt to tackle this by imposing rules on better insulation, natural ventilation and so on, which reduces the need for mechanical refrigeration and thus refrigerant. Similarly, there may even be significant breakthroughs and improvements in leak reduction and recovery and recycling of refrigerants, thereby reducing refrigerant demand. Perhaps further in the future, there will be rapid successful developments of so-called “not-in-kind” refrigeration technologies, where for example, magneto-caloric refrigeration and other such refrigerant-free concepts become widely commercialised and thereby eliminating the need for refrigerants.

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Daniel specialises in environmental, performance and safety aspects of alternative refrigerants and systems. He works on behalf of various organisations and companies, including implementing agencies, manufacturers and end users. He is a member of the UNEP Refrigeration Technical Options Committee and several BSI, CEN, ISO and IEC standardisation committees and working groups on refrigeration safety and is a member of the Institute of Refrigeration Technical Committee.

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