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WEIGHING THE CLIMATE MORTALITY RISK OF HFCS WITH THE FLAMMABILITY RISK OF NATURAL REFRIGERANTS

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ABSTRACT

Increasing temperatures lead to human mortality directly, by means of physiological response to extreme heat but also indirectly due to drought, flooding, famine, disease, wildfires, infrastructure disruption, conflict, etc. Numerous studies have attempted to quantify the mortality risk of the various individual consequences of climate change as well as the overall impact. Emissions of fluorinated refrigerants, as used in refrigeration, air conditioning and heat pump systems, make a notable contribution to current and future warming and therefore some proportion of the overall mortality can be attributed to those refrigerants. Alternative refrigerants include hydrocarbons, which have negligible global warming potentials and provided they are correctly selected, can provide lower energy consumption. However, their higher flammability introduces an additional hazard which can also lead to fatalities. This study compares the climate-related mortality risk of HFCs with the flammability fatality risk of hydrocarbon refrigerants in order to determine whether their adoption can benefit society.

Keywords: *climate, mortality, hydrocarbons, safety, flammability risk*

1 INTRODUCTION

Over the next decades, the likely lack of international mitigation and adaptation efforts to address climate change will present a significant global risk; changing climate and weather patterns are already causing concern. Increasingly severe weather events such as heat waves, floods, droughts, storms, etc. will escalate the spread of disease and pollution, which, coupled with inequities of health services, exacerbate various effects of climate change in many global regions and amongst social groups.

Natural refrigerants are considered to be viable options for the replacement of fluorinated refrigerants, such as hydrochlorofluorocarbons (HCFC) and hydrofluorocarbons (HFC), which typically have high global warming potentials (GWP). Under the Kigali Amendment to the Montreal Protocol, HFCs are scheduled to be phased down to (i) 15% of the developed country baseline consumption level by 2036, to (ii) 20% of the Group 1 developing country baseline consumption by 2045, and to (iii) 15% of the Group 2 developing country baseline consumption by 2047. All HFC baselines include a certain percentage of the HCFC baseline consumption, being 15% for developed and 65% for developing countries.

Fluorocarbon-based alternatives for HCFCs and HFCs are unsaturated HFCs (also known as hydrofluoroolefins, HFOs) which, whilst having comparatively low GWPs, are generally classified as polyfluoroalkyl substances (PFAS) and are linked to negative impacts on ecosystems and human health (Arp et al., 2024), not to mention harmful emissions arising from their manufacture. Due to the current lack of data, quantifying the effects are outside the scope of the current work.

Amongst the natural refrigerants, hydrocarbons (HCs) are known to be exceptionally good refrigerants in terms of performance and material compatibility. However, they are highly flammable and thus may pose an increased fire and explosion risk during use and handling. Accordingly, a frequent argument put forward

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by refrigeration, air conditioning and heat pump (RACHP) industry stakeholders is that wider use of HC refrigerants can be expected to result in additional damage to property and persons. Nevertheless, there is already a residual local risk with using non-flammable HFCs due to pressure explosions, asphyxiation, physiological toxicity effects, freeze burns and so on, which are widely known and reported (IIR, 2025). When it comes to refrigerant handling, there should be more incentive to reduce releases of flammable refrigerants than those of non-flammable ones provided the individual involved is aware of the potential direct and immediate detriment.

Anthropogenic greenhouse gas emissions, including those of fluorinated refrigerants, are leading to climate change and constitute a significant risk to property and persons through a variety of mechanisms. It has been argued (Pearce and Parncutt, 2023) that due to the mortality risk of these emissions, all efforts to reduce them should be considered "life-saving". However, if such efforts result in reduced availability of cold or heat for food preservation or human comfort, or result in increased fatalities from alternative refrigerant hazards, these arguments may not apply. The subsequent question is: would the widescale use of HC refrigerants result in an offset of the risk to property and persons, or would their use lead to a greater detriment than that generated by the continued emissions of fluorinated refrigerants?

The approach taken here is to compare the estimated mortality due to all global greenhouse gas emissions, adjusted for the proportion of temperature rise attributed to HFC refrigerants. This factor is then compared against the risk of fatality from the ignition of leaked HC refrigerants, multiplied by all RACHP systems globally, assumed to be produced with HC refrigerants instead of fluorinated refrigerants. Whilst not all RACHP systems use medium and high GWP HFCs, quantification of risk considers most systems that historically used fluorinated refrigerants can feasibly use natural refrigerants, specifically HC refrigerants.

It is recognised that the perceptibility of such a comparison is problematic. Attributing blame for a fatality directly caused by the ignition of leaked HC refrigerant is easy. Conversely, attributing the blame of a single death of a person involved in a flood or a wildfire, to a single or multiple releases of HFC refrigerant in a different country, years earlier is awkward; consequences of emissions on climate are far detached from the actual emission event. Those affected by the flammability risk are directly or at least closely linked to the emission event, whereas those affected by the climate risk could be of an entirely different population from those causing the HFC emission event. Moreover, within this context of climate mortality, a modest HFC emission event does not affect a single person or people locally but rather affects billions of people sometime in the future and each by just a little bit. Nevertheless, this perceived tenuousness can be rationalised: just as a doubling of global CO_2 emissions would approximately lead to a doubling of mortality, so would a doubling in HFC emissions. Similarly, a doubling of the number of RACHP systems using HCs would also increase the absolute fatality risk. Whilst quantification of the local and global consequences of an emission of gas are not easily appraised, from this perspective, gauging the separate hazards is reasonable.

2 CLIMATE RISK

2.1 General

There are a variety of impacts on property and persons caused by emissions of greenhouse gases. These include detrimental effects on human physiology from heat and cold extremes; human and animal disease; windstorms, water resources, drought, flooding; wildfires; flora and fauna habitat loss; damage and demands on infrastructure (agriculture, electricity production and supply, national health systems); and human conflict.

Here, for brevity, only mortality will be considered. It is reported in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (IPCC, 2022) that only about one-fifth of the cost of health impacts would be related to mortality issues; the majority due to long-term illness, disability, and other health conditions. In parallel, the ratio between costs of workplace fatal and non-fatal accidents are comparable

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(e.g., HSE, 2024), i.e., the use of fatality appears to be a reasonable proxy for the situation overall, yet still only represents fraction of the overall impact. Conversely, it has been observed that across the literature, techniques for quantification of disability-adjusted life years (DALY) attributed to climate change vary so results are incompatible (Pearce and Parncutt, 2023). Therefore, the use of mortality is a clearer and less ambiguous measure.

The IPCC (IPCC, 2022) presents various emissions and societal response scenarios and similarly crucial to the current work is the formulation of a specific scenario relevant for anticipated refrigerant usage; to give the work relevance, it is reliant upon assumptions that (presently) can be assigned a high level of confidence. The two scenarios to be considered are:

- Current legislation with minimum effort (CLME), where all countries achieve phase-down according to the Kigali schedule or national regulations (if more stringent) and this is done by applying HFCs and HFC blends with as high a CO_2-equivalent as possible within these constraints. (This is essentially the Velders et al. 2022 "KA-2022" scenario; see below.)

- Natural refrigerant maximum effort (NRME), where all countries switch to natural refrigerants in all RACHP applications, by 2050.

In principle, the mortality risk from climate impacts and fatality risk from flammable refrigerant use can be assessed after several years, once the shift has become established. However, 2050 is taken as the reference year since most climate-related studies quantify mortality for 2050. Moreover, it is reasonable to assume that the RACHP industry can entirely transition to natural refrigerants over a period of 20 – 25 years.

2.2 Mortality estimates

Throughout the recent literature, numerous studies aim at quantifying the excess deaths due to climate change. Some focus on the most direct impact, being the effect of extreme temperature on human physiology, others address secondary effects, such as those listed above, whilst some attempt to encompass all. Many studies focus on particular cities or regions, rather than the whole globe. Those that are global or cover larger regions and those that address most or all causes of fatality are adopted here.

Prediction of "extreme heat-related deaths" uses an empirical approach, where the number of historical excess deaths is correlated to a variety of temperature extremes. This correlation is then applied to projections for extreme temperatures under selected shared socioeconomic pathway (SSP)[1] and representative concentration pathways (RCP)[2] scenarios, as defined in the IPCC AR6 (Chen et al., 2021). Projections for most other causes require more elaborate assumptions. Deaths from extreme heat are thought to represent only about a tenth of the climate-related mortality (Eitelwein et al., 2023). Estimates from various studies are listed in Table 1 and range from around a quarter to 1 million per year in 2050, depending upon selected causes and related to the assumed RCP and SSP (where for example, SSP2 is the "middle-of-the-road" scenario). Most studies do not account for all causes (as mentioned in the

[1] SSPs are climate change scenarios that project how global socioeconomic conditions might change up to the year 2100. They are used to assess and quantify the challenges of climate change mitigation and adaptation in different socioeconomic contexts. There are five alternative scenarios that represent different combinations of challenges to climate change mitigation and include assumptions on adaptation, population, gross domestic product, urbanisation and other socio-economic developments. Generally, SSPs with higher numerical designation correspond to greater temperature rise.
[2] RCPs are climate change scenarios that project future greenhouse gas concentrations and radiative forcing. They are used to model future climate scenarios based on human activities that emit greenhouse gases and are designed to capture possible future trends, such as whether we continue to burn fossil fuels or shift to renewable energy.

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introduction). Generally, studies show that mortality increases exponentially with a greater temperature rise.

Table 1: Predicted mortality from climate change

Source	Cause	Location	Year(s)	Scenario	Global temp. rise	Mortality
Naumann et al. (2022)	Heat only	EU and UK *	To 2050	SSP2-6.0	1.5 K 2.0 K	500,000 per year 900,000 per year
Eitelwein et al. (2024)	Infrastructure	Global	To 2050	SSP2-6.0	2.2 K	14.5 m by 2050 = 500,000 per year
Hales et al. (2019)	Health impacts	Global	To 2030 2030 to 2050	SRES A1b	2.0 K 2.5 K	241,000 per year 250,000 per year
Gasparrini et al (2017)	Heat only	Global **	To 2100	RCP2.6 – 8.5	3.2 K	85 m ≈ 1 m per year
Carleton et al. (2022)	All	Global ***	By 2050 By 2100	SSP3/RCP6-8.5	1.6 K 4.5 K	About 1 m per year About 8 m per year

* Determined for Europe and UK only, extrapolated to global
** Only includes certain world regions, not all
*** Estimated using https://www.who.int/news-room/fact-sheets/detail/climate-change-heat-and-health

In addition to those in Table 1, other approaches have been reported. A "1000-tonne" rule (of thumb) says that the emission of 1000 tonnes of carbon – equivalent to 3670 tCO_2-eq – will cause the death of one future person (Parncutt, 2019); it is acknowledged that this is an "order of magnitude estimate". There are other comparable general methods of quantification (Pearce and Parncutt, 2023), such as the "temperature niche" approach and the "mortality cost of carbon (MCC)" (Bressler, 2023) which can be used to cross-check more specific assessments. The temperature niche expresses the number of fatalities per year caused by the emission of one additional tonne of CO_2-equivalent emissions in 2020. MCC values are given for two emissions scenarios, where the "optimal" (2.4 K by 2100) is 1.07×10^{-4} per tCO2eq.

2.3 HFC emissions contribution

Refrigerant emissions contribute directly to climate change and also through the impact of the RACHP system operation on energy consumption that – in most regions – has CO_2 emissions associated with the production of electricity used by the RACHP systems. Here, only the direct warming effect of HFCs is considered; it is broadly acknowledged (RTOC, 2022; McLinden et al., 2017; etc.) that provided the right natural refrigerant is used in the correct application, energy consumption will be no higher than with an equivalent system using HFCs and even lower in most cases. Nevertheless, across most regions and equipment types, minimum efficiency rules apply meaning that energy consumption becomes unaffected by refrigerant choice and therefore no differences in energy consumption are assumed. Moreover, the immediate impact of "equivalent" refrigerant emissions is more significant than energy-related CO_2 emissions due to the differences in decay/lifetimes (Colbourne and Suen, 2004).

Currently, warming from HFCs is estimated to represent around 1.5% of all anthropogenic warming, whilst the contribution of CFCs and HCFCs, due to their substantial atmospheric lifetimes, accounts for another 11% of the warming impact (NOAA, 2024). Annual anthropogenic emissions from now until 2050, are projected to be 55-65 $GtCO_2eq$ per year without interventions or declining to 10-20 $GtCO_2eq$ per year in 2050 if a 1.5 – 2°C target is to be achieved (IPCC, 2023). Across all scenarios evaluated by Velders et al. (2022), it is estimated that the contribution of HFCs is between 0.055 to 0.12 K by 2050 and 0.05 to 0.44 K by 2100; see Table 2. The "KA-2022" may be regarded as the most likely scenario since the KA has already been ratified by some 165 countries[3]; this is deemed to reflect the CLME scenario. HFCs include those used

[3] https://treaties.un.org/Pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVII-2-f&chapter=27&clang=_en

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for RACHP and other applications; foams, aerosol, fire extinguishers and solvents. From Velders et al. the average split in CO_2-equivalent emissions between RACHP and other applications between the years 2020 to 2050 is 85%:15%, so the temperature contribution is reduced by 15% to isolate the share for RACHP.

Table 2: Contribution of HFC emissions to temperature rise by 2050

By year	Baseline V-2015	Current K-I	CLME (≅ KA-2022)
	Velders et al. (2015) baseline scenario; incl. HFC phasedown policies in EU, USA and Japan; independent of KA	Kigali-independent; accounts for updated HFC policies as of end 2022	As Current K-I but incl. 2016 KA HFC phasedown schedule
2050	4.0 – 6.2 $GtCO_2$-eq	1.9 – 3.6 $GtCO_2$-eq	0.9-1.0 $GtCO_2$-eq
	0.12 K (0.10 K)*	0.07 K (0.06 K)*	0.055 K (0.047 K)*
2100	0.31 – 0 .44 K	0.14 – 0.31 K	0.04 K

* Adjusted to isolate contribution from RACHP only

2.4 Mortality-attributable HFC emissions

A basic approach is applied, where the mortality is deemed proportional to the contribution of average global temperature rise and therefore represents a reasonable approximation. The values for predicted mortality were normalised, expressed in terms of the number of fatalities per unit (K) of anthropogenic temperature rise, from the study reference year of the respective study. Results according to the different source studies and the CLME scenario are shown in Figure 1, where the annual mortality attributable to HFC emissions ranges from 10,000 to 25,000. Also shown are results for the "1000-tonne" rule, which more or less captures the range of values based on the detailed studies. In conclusion, the mortality risk due to HFC refrigerant emissions is taken as the average of those values given in Figure 1, being 16,000 per year.

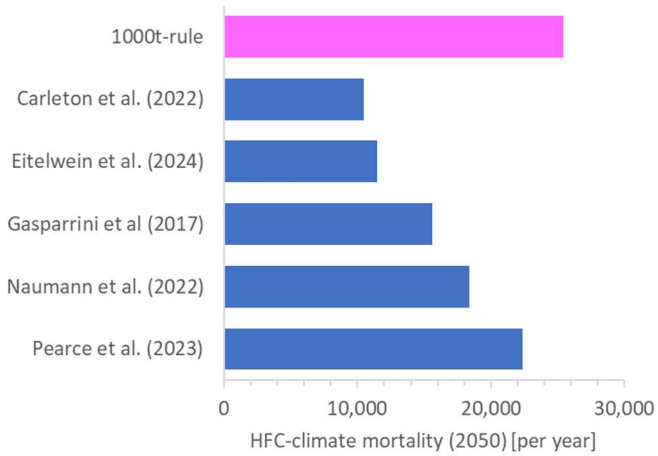

Figure 1: Results of estimated annual mortality attributed to HFC refrigerant emissions to the year 2050 assuming CLME scenario ("KA-2022" of Velders et al., 2022), based on overall mortality data from different studies

Due to the absence of HFC emissions under NRME and the negligible GWP of natural refrigerants, climate change related mortality is zero.

3 FLAMMABILITY RISK

3.1 General

RACHP equipment, as with almost any other machinery, poses a variety of hazards to people and property and injuries and fatalities are regularly reported globally, irrespective of refrigerant type. Shifting from non-

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flammable HFCs to flammable alternative refrigerants should not necessarily affect the level of safety except for the introduction of flammability risk. Nevertheless, most HFC refrigerants, whilst non-flammable, are combustible and the oils used within systems are similarly flammable, so it should be understood that there always remains a level of residual flammability risk. Perhaps the most common cause of fatalities from RACHP equipment is related to electrical faults, which then lead to building fires.

The objective is to estimate the overall risk of fatality under the NRME scenario, being the global replacement of HFCs with (mostly) HC refrigerants. This requires estimations of the likelihood of ignition, explosion and/or secondary fire and ultimately injury and fatality due to leakage or unintended release of the flammable refrigerant. The frequency of accidents is often estimated using quantitative risk assessment (QRA) for individual system designs and installation conditions. Within the current context, it needs to be extended to the global inventory of RACHP equipment.

3.2 Market discretisation

RACHP equipment comprises a wide variety of systems, ranging from small water dispensers or domestic refrigerators to large supermarket systems, industrial chillers and cold store complexes. The variety, size and arrangement of RACHP systems are extensive; a comprehensive overview of systems, within the context of refrigerant replacement, can be found in the UNEP Refrigeration Technical Options Committee Report (UNEP, 2023a). It is noted that not all RACHP equipment should, would or could use HC refrigerants, but it is assumed they are applied as widely as practicable, as reflected in the NRME scenario.

For brevity, RACHP equipment has been narrowed down to nine main groupings as Table 3, which is considered to represent the vast majority of global refrigerant use. The number of systems is obtained from a global database (GCI, 2025) and extracted for both 2025 and 2050; as may be expected, there is significant growth for certain groups (domestic refrigeration, small ACs and heat pumps (Navarro et al., 2024), whilst some categories remain fairly static.

Table 3: Grouping and characteristics of RACHP systems

Group	Description	No. systems, 2025 [mil]	No. F-gas systems, 2025 [mil]	No. systems, 2050 [mil]	HFC charge [kg]	HC charge [kg]
Domestic refrig.	Domestic fridge/freezers	2,131	1,144	3,786	<0.3	<0.15
Small comm. refrig.	Plug-in retail cabinets, etc.	71	50	86	<0.2 – 1.0	<0.1 – 0.5
Large commercial refrigeration and air conditioning chillers	Chillers for secondary systems, sub coolers in R744 systems, chillers for central air conditioning	7.4	6.2	8.1	20 – 100	10 – 50
Small air conditioning	Window and split air conditioners	1,315	1,049	3,675	0.4 – 2.0	0.2 – 1.0
Larger direct commercial air conditioning	Ducted systems, variable refrigerant flow systems	28	28	49	2.0 – 20	1.0 – 10
Coldrooms/ condensing units	Single or multi-cold room complexes	29	23	36	4.0 – 40	2.0 – 20
Vehicle air conditioning	Air conditioning for cars, buses, trains, etc.	1,260	1,247	1,959	1.0 – 6.0	0.3 – 1.5
Transport refrigeration	Trucks and others	3.1	2.2	3.5	0.5 – 10	0.2 – 5.0
Domestic heat pumps	Air or water-source heat pumps	21	17	58	0.4 – 6.0	0.2 – 3.0

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The difference between the number of systems and F-gas (mainly HFC but also HCFC and HFO) based-systems yields those that use natural refrigerants. Overall, assumptions for the number of systems and charge amounts have been cross-checked against the banks and emissions in Velders et al. (2022), where near-parity was found. In 2050, for purposes of methodological simplification, it is assumed that HCFCs have expired in all systems, despite the GCI data indicating a remnant of 0% to 8% HCFC depending upon the equipment type. HC refrigerant charge is also listed for reference.

Due to the wide variety of types of industrial refrigeration equipment and absence of QRAs in the literature, that it is the smallest of the estimated HFC bank segments in 2050 (GCI, 2025) and that it is a complicated category to tackle by means of the simplistic grouping approach, it has been neglected here. Throughout many parts of the world, industrial systems currently use natural refrigerants anyway, such as R744 (carbon dioxide) and R717 (ammonia) and it is likely that the remaining parts of the world will follow. There is no need to consider HC refrigerants for this application.

3.3 QRA values

There have been various studies which quantify the flammability risk of HC refrigerants in different equipment, providing predicted ignition and consequence frequencies. Table 4 summarises values for normal operation reported throughout the literature.

Outputs of the QRA studies differ in terms of consequences for which frequencies are expressed. Estimated ignition frequencies show a generally lower risk in more recent studies, due to improvements in calculation tools and data, meaning that less conservative assumptions are necessary. As the frequency of fatality is of interest, for those studies which do not provide it, frequencies in Table 4 have been adjusted pessimistically according to the following approximations: injury to fatality: ÷10; secondary fire to fatality: ÷100; ignition to fire/explosion to fatality: ÷100.

Table 4: Predicted HC refrigerant flammability risk frequencies for normal operation

Group	Description	Source	Frequency [/y]	Group ign. freq [/y]	Group fatal freq. [/y]
Domestic refrig.	Domestic fridge	Colbourne & Suen (2015)	Sec fire: $4×10^{-8}$	$1×10^{-9}$	$1×10^{-10}$
		Hou et al. (2024)	Sec. fire: $1.0×10^{-12}$ – $5.1×10^{-11}$		
Small comm refrig	Chest freezer	Ritter & Colbourne (1998)	Sec fire: $1.3×10^{-6}$	$1×10^{-9}$	$1×10^{-10}$
	Chiller cabinet	Ritter & Colbourne (1998)	Sec fire: $1.1×10^{-6}$		
	Beer cooler	Ritter & Colbourne (1998)	Sec fire: $9.7×10^{-6}$		
	Ice cream freezer	Colbourne & Espersen (2013)	Ignition: $1.6×10^{-9}$ to $1×10^{-13}$		
	Display cabinet	Colbourne (2015) [unpub. report]	Sec fire: $1×10^{-10}$ to $1×10^{-7}$		
Large comm refrig and AC chillers	Air cooled chiller	Colbourne (2012) [unpub report]	Ignition: $3×10^{-10}$ to $2×10^{-9}$	$1×10^{-9}$	$1×10^{-11}$
	Chiller	He et al. (2024)	Fire: $2.5×10^{-10}$ to $1.7×10^{-9}$		
Smaller AC	Split AC	Rajadhyaksha et al. (2015)	Ignition: $6.7×10^{-10}$ to $3.8×10^{-9}$	$1×10^{-9}$	$1×10^{-11}$
	Split AC	Colbourne & Suen (2015)	Ignition: $4×10^{-10}$		
	R22 split AC (R290 drop-in)	Colbourne et al. (2016a)	Sec fire: $7.2×10^{-12}$ to $9.8×10^{-7}$		
	Split AC	Colbourne et al. (2016a)	Sec fire: $6.0×10^{-13}$ to $2.2×10^{-9}$		
		JSRAE	Ignition: $1×10^{-12}$ – $2×10^{-8}$		
		He et al. (2024a)	Fire: $1×10^{-11}$ – $9×10^{-10}$		

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Group	Description	Source	Frequency [/y]	Group ign. freq [/y]	Group fatal freq. [/y]
	Cabinet AC	Guo et al., 2024	Ignition: 7×10^{-11} – 1.4×10^{-10}		
Larger direct comm AC	Ducted split AC, rooftop AC	Colbourne et al. (2018)	Ignition: 6×10^{-6}	1×10^{-8}	1×10^{-10}
		He et al. (2024b)	Fire: 1.7×10^{-9} to 2.5×10^{-10},		
Coldrooms/ condensing units	Coldroom	Ritter & Colbourne (1998)	Ignition 1.3×10^{-5}	1×10^{-6}	1×10^{-8}
		Colbourne (2018) [unpub. report]	Ignition 2.8×10^{-7}		
Transport refrig.	Reefer container	König and Bararu (2014)	Ignition: 1×10^{-6} to 3×10^{-19}	1×10^{-7}	1×10^{-9}
	Truck refrig.	Jansen & van Gerwen (1995)	Ignition: 1×10^{-6} to 3×10^{-6}		
	Truck refrig.	Colbourne et al. (2016b)	Ignition: 3.6×10^{-7}		
	Truck refrig.	Ritter & Colbourne (1998)	Fire, damage: 1.8×10^{-5}		
Vehicle AC	Cars	Dieckmann & Bentley (1991)	Injury: 3.5×10^{-7}	1×10^{-8}	1×10^{-10}
	Cars	Maclaine-cross & Leonardi (1995)	Ignition: 2×10^{-9} to 3×10^{-9}		
	Cars	Ritter & Colbourne (1998)	Injury 3.1×10^{-7}		
Domestic HPs	Indoor water, outdoor air	Elbers & Verwoerd (1997)	Occupant injury: 1.8×10^{-7} Public injury: 2.0×10^{-8}	1×10^{-8}	1×10^{-10}
	Indoor water	Colbourne (2020) [unpublished report]	Ignition: 5×10^{-9}		
Generic RACHP	"Other"	Colbourne & Suen (2008)	Ignition: 6×10^{-12} to 7×10^{-9}	1×10^{-10}	1×10^{-12}

Risk values for refrigerant handling activities, such as by technicians during service and maintenance, are less widely published, probably due to the difficulty in determining reliable values. Available ignition frequencies are shown in Table 5. For servicing, adjustment for ignition to fire/explosion to fatality in Table 7 is set at ÷50 on account of the technician more likely being localised to the event.

Table 5: Predicted risk values for refrigerant handling activities

Risk indicator	Source	Commercial refrig. unit		Split air conditioner		Domestic heat pump	
		Typical practice	Best practice	Typical practice	Best practice	Typical practice	Best practice
Total ignition frequency per visit	Colbourne (2011)	3.6×10^{-4}	2.4×10^{-5}	1.1×10^{-4}	6.6×10^{-6}	Not applicable	
Worker injury	Elbers and Verwoerd (1997)	Not applicable		Not applicable		3.8×10^{-7} per year	
"Ignition probability" *	JSARE (2016)	Not applicable		2.8×10^{-7} – 8.1×10^{-7}		Not applicable	

* Values are included for the purpose of completion, but the report does not provide a clear explanation of whether the values refer to the ignition per visit, ignitions per year, or during the entire unit lifetime.

Since many of the studies cited were produced before the widespread application of HCs, it is helpful to gauge QRA values against the amount and significance of anecdotal reports across the industry. Whilst this attempt cannot provide accurate quantitative values, it gives a "feeling" of whether the calculated values are reasonable. Specifically:

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- Over one million R290 split ACs – no reported fatalities (or injuries) during operation or servicing.
- One million R290 HPs – some fires reported and accidents during servicing, but no fatalities.
- Over 1,000 million domestic refrigerators using HC refrigerants, where deployment of such technologies began in the early 1990s (Colbourne, 2021). Apart from some tens of incidents arising from manufacturing faults (subject to product recalls), there have been no public reports of fatal accidents. Similarly, technician burn injuries due to technician work procedure errors are occasionally reported, but no verified fatalities have been reported to be found in the public domain.
- For vehicle air conditioners, primarily cars, it is known that tens of millions, probably over 100 million vehicles have been retrofitted with HC refrigerant blends. No reported incidents have been found for in-use, although a small number (tens) of technician injuries have been highlighted in the trade literature.

It is impossible to source accurate data for most countries, let alone globally. It is likely that more incidents have occurred than have been reported in the trade literature. For example, some manufacturers are probably aware of ignition events involving their products and installations but are not forthcoming with such information for commercial reasons. Nevertheless, widespread accidents would become apparent.

Accordingly, the values in Table 4 and Table 5 may be considered to be pessimistic representations of the actual risk. One further consideration is that were the use of HC refrigerants to become ubiquitous, manufacturing, design, technician training, competence and familiarity with practices will reduce the further likelihood of accidents.

3.4 Global risk values

Based on the values in Table 4, representative frequencies have been determined for each grouping and these are listed in Table 6. "Compliant" refers to products produced according to good design practice, i.e., they follow the applicable safety standard or equivalent, whereas "non-compliant" refers to products manufactured and installed without any consideration of the appropriate safety rules. The non-compliant equipment have frequencies two orders of magnitude higher, consistent with the "drop-in" cases determined by Colbourne et al. (2016a). It is assumed that the majority of RACHP systems broadly comply with applicable safety standards since manufacturers prefer to avoid repercussions that may be detrimental to their business. It is further assumed that 10% of systems do not sufficiently comply with safety standards.

Flammability hazards are present throughout the lifetime of the equipment, from manufacture to storage, transportation, installation to decommissioning. However, previous QRAs have found that the flammability risk across all these stages represents less than 0.1% of that for normal operations; given that RACHP equipment is usually in storage or being transported for a few days of its entire one to two decades-long lifetime, the near-negligible contribution to lifetime risk is intuitive. Therefore, only the risk during normal operation and refrigerant handling are considered.

Results of global flammability risk are given in Table 6, where the system population data is for 2050. The total number of fatalities is estimated to be just below 10 per year.

Table 7 provides frequencies for refrigerant handling activities (during service and maintenance), based on the data in Table 5, along with assumptions for service visit rates and the likelihood of refrigerant handling tasks during a visit. Values for service frequency (number of repair visits per system) and frequency of refrigerant handlings (fraction of repairs that require intervention of the refrigerant circuit) are approximate values, based on informal discussions with manufacturers and technicians. Some indicative data are available in the literature (e.g., Salman et al., 2024; Elmouatamid et al., 2023).

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Table 6: Fatality risk for normal operation assuming 90% of systems compliant (from Table 4)

Group	Number of systems [mil]	Weighted ignition risk [/y]	Weighted fatality risk [/y]	Total fatalities [/y]
Domestic refrig.	3,786	1.0×10^{-7}	1.0×10^{-9}	3.8
Small comm. refrig.	86	1.0×10^{-6}	1.0×10^{-8}	0.9
Large comm refrig./AC chillers	8.1	1.1×10^{-8}	1.1×10^{-10}	0.001
Smaller AC	3,675	1.1×10^{-8}	1.1×10^{-10}	0.4
Larger direct commercial AC	49	1.1×10^{-7}	1.1×10^{-9}	0.1
Coldrooms/ cond units	36	1.1×10^{-5}	1.1×10^{-7}	4.0
Vehicle AC	1,959	1.1×10^{-8}	1.1×10^{-10}	0.2
Transport refrig.	3.5	1.1×10^{-6}	1.1×10^{-8}	0.04
Domestic HPs	58	1.1×10^{-7}	1.1×10^{-9}	0.1

Because technicians should be equipped with personal protective equipment (PPE), suitable tools and equipment and should be aware of appropriate precautions, it is expected that the ratio of fatality per incident is deemed to be half that for members of the public (i.e., 1 in 10). Crucially, the base ignition frequency accounts for a proportion of technicians being "competent" or not. This split varies widely by equipment type and geographic region, moreover, whilst technician training is being proliferated globally, it does not necessarily guarantee "competence". A pessimistic assumption of 75% being "flammable-competent" is used here. Overall, it can be observed that the risk of fatality for refrigerant handling activities is about ten times greater than for normal operation, which is considered to be a reliable representation.

Overall, including normal operations and refrigerant handling activities, the estimation results in 146 fatalities per year for the NRME scenario. By comparison, these should be considered with respect to the number of fires caused by electrical and similar faults. For example, using empirical fire frequency data under normal operation (Colbourne and Suen, 2015), for domestic fridges, approximately 38,000 fires leading to 380 deaths and for air conditioners, approximately 75,000 fires leading to 750 deaths per year. Data for fires and fatalities during servicing activities are not known. Overall, the risk from external (building fires) is substantially greater still (di Fillipio et al., 2025).

Table 7: Fatality risk for refrigerant handling assuming 75% of technicians are flammable-competent

Group	Ignition freq. [/visit]	Service freq. [/y]	Reft handlings [/visit]	Risk of fatality [/y]	Total fatality risk [/y]
Domestic refrig.	2.7×10^{-5}	0.01	0.1	5.4×10^{-7}	2.0
Small comm. refrig.	2.7×10^{-5}	0.02	0.1	5.4×10^{-7}	0.1
Large comm. refrig/AC chillers	3.0×10^{-5}	2.0	0.1	6.1×10^{-7}	1.0
Small AC	3.2×10^{-5}	0.1	0.3	6.5×10^{-7}	72
Larger direct comm. AC	3.2×10^{-5}	2.0	0.3	6.5×10^{-7}	19
Coldrooms/ cond units	8.1×10^{-5}	0.1	0.2	1.6×10^{-6}	1.2
Transport refrig.	3.2×10^{-5}	0.2	0.2	6.5×10^{-7}	51
Vehicle AC	3.2×10^{-5}	0.2	0.2	6.5×10^{-7}	0.1
Domestic HPs	2.7×10^{-5}	0.1	0.1	5.4×10^{-7}	0.3

4 CONCLUDING REMARKS

Under the NRME scenario, it is estimated that some 150 fatalities could arise annually from the widespread use of HC refrigerants across all applicable RACHP equipment. By comparison, the CLME scenario with

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emissions of HFCs would be responsible for an annual mortality of between 10,000 to 25,000, being two orders of magnitude greater. Cumulatively, the difference that arises over one or more decades would be considerable, in the order of hundreds of thousands. Based on the current estimates, where the assumptions for the flammability risk from HC refrigerant employ broadly pessimistic assumptions, the number of HFC-attributable deaths vastly outweighs the number of HC-refrigerant-related fatalities.

A consequential question arising from this analysis is whether it is possible to approximate a "tolerable" average GWP for alternative refrigerants so that the mortality does not exceed the one related to the flammability risk? Using the ratio of annual mortality from HFC emissions and the flammability fatality risk, the average GWP of emitted refrigerants should be about 100 times lower than that needed to comply with the Kigali Amendment, i.e., about a factor of 5. Another perspective is that an additional death will occur for every 365 tonnes of refrigerant emitted with a GWP of 500.

Considering the list of viable alternative refrigerants (UNEP, 2023a), this would mean that using almost any HFC would result in higher mortality than due to the HC flammability fatality risk. This may lead one to the conclusion that the most viable alternatives are therefore HFOs. However, concerns over the health and potential fatality impacts of decomposition products (e.g., TFA) are absent, and it would not be prudent to attempt to make such quantitative estimations. Furthermore, experience to date has shown that while lower flammability refrigerants (such as some HFOs) should present a lower flammability risk, severe explosion accidents involving ignition inside RACHP systems suggest the flammability hazard can actually be worse than for HCs, especially when servicing the equipment (Higashi et al., 2017; Saitoh et al., 2020; Colbourne, 2021).

Across the wider literature, a comparison of the climate risks of HFC refrigerants and the flammability risks of natural refrigerants is absent. This preliminary study, however, shows that the overall differences in mortality from HFC emissions compared to the potential flammability fatality risk from HC refrigerants are stark. Of course, due to the numerous assumptions for both aspects of the work, there are significant uncertainties, however, given the magnitude of differences between HFC mortality and HC flammability risk, there is strong confidence in the overall outcome.

NOMENCLATURE

AC	Air conditioner	MCC	Mortality Cost of Carbon
CLME	Current legislation with minimum effort	NRME	Natural refrigerant maximum effort
DALY	Disability-Adjusted Life Years	PFAS	Poly-Fluoroalkyl Substances
EU	European Union	PPE	Personal Protective Equipment
GWP	Global Warming Potential	QRA	Quantitative Risk Assessment
HC	Hydrocarbon	RACHP	Refrigeration, Air Conditioning and Heat Pumps
HCFC	Hydrochlorofluorocarbon	RCP	Representative Concentration Pathways
HFC	Hydrofluorocarbon	SSP	Shared Socioeconomic Pathway
HFO	Hydrofluoroolefin	TFA	Trifluoroacetic acid
HP	Heat pump	UK	United Kingdom
IPCC	Intergovernmental Panel on Climate Change	UNEP	United Nations Environment Programme
KA	Kigali Amendment		

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