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Critical Literature Review of Low Global Warming Potential (GWP) Refrigerants and their Environmental Impact

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September 2024

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OAK RIDGE National Laboratory

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

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Environmental Sciences Division

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REFRIGERANT AND DEGRADATION PRODUCT ABBREVIATIONS

CFC	chlorofluorocarbon
CTC	carbon tetrachloride
HC	hydrocarbon
HCFC	hydrochlorofluorocarbon
HCFO	hydrochlorofluoroolefin
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
R-11	CFC-11; trichlorofluoromethane
R-1224yd(Z)	HCFO-1224yd(Z); (Z)-1-chloro-2,3,3,3-tetrafluoropropane
R-1233zd(E)	HCFO-1233zd(E); trans-1-chloro-3,3,3-trifluoropropene
R-1234yf	HFO-1234yf; 2,3,3,3-tetrafluoropropene
R-1234ze(E)	HFO-1234ze(E); trans-1,3,3,3-tetrafluoropropene
R-125	HFC-125; pentafluoroethane
R-1336mzz(E)	HFO-1336mzz(E); trans-1,1,1,4,4,4-hexafluoro-2-butene
R-1336mzz(Z)	HFO-1336mzz(Z); trans-1,1,1,4,4,4-hexafluoro-2 butane
R-134a	HFC-134a; 1,1,1, 2-tetrafluoroethane
R-143a	HFC-143a; 1,1,1-trifluoroethane
R-152a	HFC-152a; 1,1-difluoroethane
R-227ea	HFC-227ea; 1,1,1,2,3,3,3-heptafluoropropane
R-245fa	HFC-245fa; 1,1,1,3,3-pentafluoropropane
R-290	propane; C_3H_8
R-32	HFC-32; difluoromethane
R-717	ammonia; NH3
R-744	Carbon dioxide; CO_2
TFA	trifluoroacetic acid or trifluoroacetate

ABBREVIATIONS

ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATEL	acute-toxicity exposure limit
CAS	Chemical Abstracts Service
ECHA	European Chemicals Agency
EPA	US Environmental Protection Agency
EC50	effective inhibition rate at 50%
EU	European Union
F-gas	fluorinated gas
GEOS-Chem	Goddard Earth Observing System with Chemistry
GHG	greenhouse gas
GWP	global warming potential
IDHL	immediately dangerous to life or health
IUPAC	International Union of Pure and Applied Chemistry
LC50	lethal concentration at 50%
LFL	lower flammability limit
LOEL	lowest observed effect level
MAC	mobile air conditioning
NIOSH	National Institute for Occupational Safety and Health
ODP	ozone depletion potential
ODS	ozone-depleting substance
OECD	Organisation for Economic Co-operation and Development
OEL	occupational exposure limit
OH	hydroxyl
PFAA	perfluoroalkyl acid
PFAS	polyfluoroalkyl substances
PFCA	perfluoroalkyl carboxylic acids
PTR-ToF-MS	proton transfer reaction time-of-flight mass spectrometer
RAC	refrigeration and air conditioning
RCL	refrigerant concentration limit
SNAP	Significant New Alternatives Policy
TSCA	Toxic Substances Control Act
UNEP	United Nations Environment Programme
VOC	volatile organic compound
WEEL	workplace environmental exposure level
WRF-Chem	Weather Research and Forecast with Chemistry
WWTP	wastewater treatment plants

EXECUTIVE SUMMARY

Refrigeration and air conditioning currently account for ~20% of the total electricity consumption in buildings around the world. Over the next three decades as global temperatures are projected to increase, urbanization and economic growth will lead to an increased demand for refrigeration and cooling. Most commonly used refrigerants belong to the five following classes: (i) chlorofluorocarbons, (ii) hydrochlorofluorocarbons, (iii) hydrofluorocarbons (HFCs), (iv) hydrofluoroolefins (HFOs), and (v) natural refrigerants. Over the past century, there have been shifts in which compounds were used for refrigeration to improve safety and durability, allow for ozone protection, and, most recently, to reduce global warming potential (GWP). Although technological advances have led to increased cooling capacity and safer refrigerants, emissions from refrigeration systems can affect the environment by contributing to greenhouse gas emissions or by depleting the ozone layer, depending on the gas emitted. The focus is increasingly on adopting compounds that are both efficient at cooling and effective for reducing emissions and other adverse environmental impacts. Because of policy and regulatory changes to avert ozone depletion and global climate change, much discussion has centered on the environmental impacts of next-generation refrigerants. Of particular interest are the fluorinated refrigerants, HFCs and HFOs, most of which are defined as per- and polyfluoroalkyl substances (PFAS) and their breakdown products (especially trifluoroacetic acid). The US Environmental Protection Agency in 2021 drafted a Strategic Roadmap for PFAS, which has already resulted in an increase in investment in research on these compounds and has restricted the release of PFAS into the environment through the implementation of monitoring and reporting requirements. A critical evaluation of fluorinated refrigerants and their breakdown products with respect to persistence, biodegradation and toxicity, and global warming potential is needed to guide environmental regulations. This document aims to perform a critical review of the relevant scientific data on the most common refrigerants currently used, their degradation products, and their alternatives. Where available, estimates of precursor production quantities and existing environmental regulatory information are reviewed. Key data of interest for the evaluation include physicochemical properties, environmental fate parameters, ecological or human health toxicity/risk information, and GWP for compounds of interest.

1. INTRODUCTION

Refrigerants are working fluids used in vapor compression systems in which they go through thermodynamic processes known as evaporation, compression, condensation, and expansion. Based on their chemical characteristics, most of the refrigerants can be assembled in five groups: (i) chlorofluorocarbons (CFCs), (ii) hydrochlorofluorocarbons (HCFCs), (iii) hydrofluorocarbons (HFCs), (iv) hydrofluoroolefins (HFOs), and (v) hydrocarbons (HCs) (Figure 1.1). HCs, commonly called "natural refrigerants," were the most widely used refrigerants before the introduction of chlorinated fluorocarbon refrigerants in the 1930s; they are now being reconsidered as options due to their favorable environmental characteristics and cost-effectiveness. All these refrigerants are heavily regulated because of concerns about safety in the workplace (flammability), toxicity due to potential exposures, and their contribution to climate change (i.e., their global warming potential [GWP]) and atmospheric degradation (i.e., their ozone depletion potential [ODP]). Over the past few decades, progress has been made toward using safer, more effective refrigerants with lower environmental impacts. This progression has been prompted by several international policies and regulations (e.g., Montreal Protocol, Kyoto Protocol, Kigali Amendment, US Environmental Protection Agency [EPA] Significant New Alternatives Policy [SNAP], European Chemicals Agency [ECHA]; see Section 4.3). An additional issue has appeared recently: the formation of pollutants during the breakdown of refrigerants that could affect the environment. Of particular interest is the formation of trifluoroacetic acid (TFA), which has the potential to significantly increase in concentration in the near future owing to shifts in the global use of HFOs as refrigerants, thus highlighting a critical need for better quantification of TFA in the environment and a better understanding of the long-term environmental impacts (i.e., bioaccumulation, toxicity, and fate and transport) of this compound.

The present report is intended to provide a critical review of the environmental impact of some of the refrigerants currently being used most widely and their degradation products.

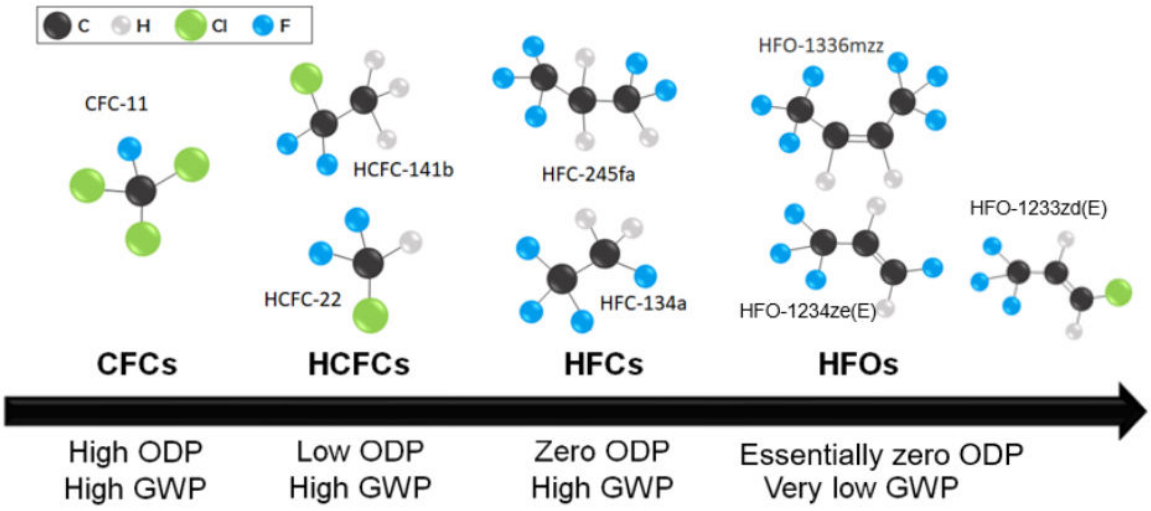

Figure 1.1. Evolution of refrigerant classes and their environmental impacts (Park et al. 2023).

2. REFRIGERANT CHARACTERISTICS

2.1 NOMENCLATURE

The American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) has developed a refrigerant designation system (the ASHRAE Standard 34 codes) to standardize the categorization of these chemicals. Single refrigerants are identified using a letter (where "R-" stands for refrigerant) followed by a number, which is systematically assigned according to molecular structure. The first ASHRAE digit is the number of carbon atoms minus 1, the second digit is the number of hydrogen atoms plus 1, the third digit is the number of fluorine atoms, and any remaining spaces are chlorine atoms (e.g., R-134a has two carbon, two hydrogen, and four fluorine atoms; the "a" designates this as an isomer of $C_2H_2F_4$, specifically 1,1,1,2-tetrafluoroethane rather than 1,1,2,2-tetrafluorethane) (ASHRAE 2013, ISO-817 2014, 2017, ASHRAE 2019).

Blended refrigerants can be classified as either zeotropic or azeotropic blends, depending on whether the components evaporate and condense at a constant temperature acting like a single refrigerant (i.e., azeotrophic) or have a gliding evaporation and condensing temperature (i.e., zeotropic). Zeotropic blends are assigned numbers in the 400 series (e.g., R-448A), whereas azeotropic blends are assigned numbers in the 500 series (e.g., R-513A), following the ASHRAE refrigerant designation (ASHRAE 2013, 2019).

In this critical review, we have selected 12 single-component fluorocarbon refrigerants [R-32, R-125, R-134a, R-152a, R-227ea, R-245fa, R-1224yd(Z), R-1233zd(E), R-1234yf, R-1234ze(E), R-1336mzz(E), and R-1336mzz(Z)], 3 natural refrigerants (R-290, R-744, and R-717), 12 zeotropic blend refrigerants (R-448A, R-449A, R-449B, R-449C, R-450A, R-452A, R-454B, R-454C, R-455A, R-456C, R-471A, and R-476A), and 3 azeotropic blend refrigerants (R-513A, R-515B, and R-516A). Descriptions of chemical structures, specifications, compositions, International Union of Pure and Applied Chemistry (IUPAC) chemical names, and Chemical Abstracts Service (CAS) designations for these compounds can be found in Tables A1–A3 in the Appendix.

2.2 DESIGNATION AND CLASSIFICATION

ASHRAE Standard 34 and ISO 817 deal with the designation and safety classification of refrigerants. These standards have developed classifications based on toxicity and flammability characteristics. Figure 2.1 depicts the safety and toxicity classes, which will be described in detail later in this section.

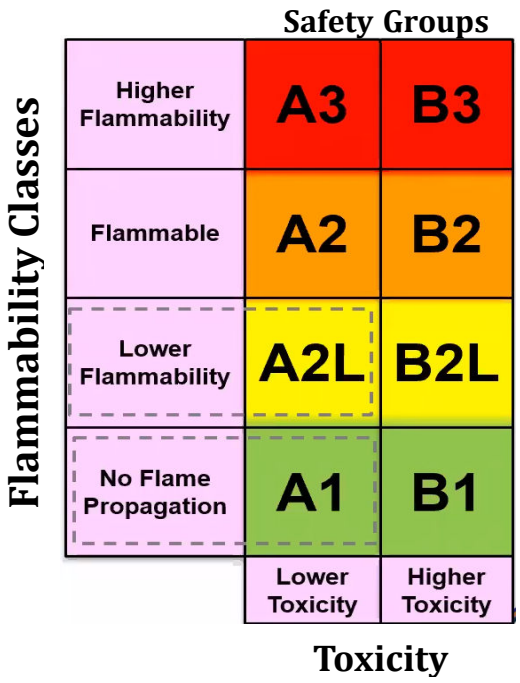

Figure 2.1. Refrigerant safety groups.

2.2.1 Workplace Exposure and Toxicity

Among the major safety hazards identified for refrigerants are workplace exposure and toxicity. Workplace exposure refers to the occupational conditions of workers that may lead to exposure to chemical stressors and at different concentrations, whereas toxicity specifies acute and/or chronic adverse health effects as a result of exposure (e.g., workplace) to the chemical stressors through different routes (e.g., contact, inhalation, or ingestion) (ASHRAE 2013, WEEL 2023). To address these safety hazards, ASHRAE, the American National Standards Institute (ANSI), and the National Institute for Occupational Safety and Health (NIOSH) have developed specific nomenclature as well as health- and safety-based guideline values for chemical stressors, including refrigerant chemicals (ASHRAE 2013). In the refrigerant industry, the Safety Group Classification System from ANSI and ASHRAE is commonly used to communicate health and safety risks from exposure to chemical refrigerants (ASHRAE 2013, 2018, 2019). Refrigerants can then be classified (Figure 2.1) based upon their flammability (Class 1, 2L, 2, or 3) and their toxicity (Class A or B) (ASHRAE 2013, 2018, 2019).

The two toxicity classes are based on toxicological data in accordance with the ANSI/ASHRAE 34 Safety Group 2013, ANSI/ASHRAE 34 Safety Group 2019, and subsequent addenda. Toxicity concerns of refrigerants have been assessed in short- (i.e., acute) and long-term (i.e., chronic) studies using animal models (e.g., rats, rabbits, dogs), occupational accident release, and volunteer data. In terms of the workplace, the occupational exposure limit (OEL) was developed to estimate workers' exposure conditions and frequency based on a normal 8 h workday and a 40 h workweek. Refrigerants are classified by ASHRAE Standard 34 based on long-term exposure for OEL. Class A (lower toxicity) is assigned when the OEL is higher than 400 ppm. Class B (higher toxicity) is for refrigerants with OEL lower than 400 ppm (ASHRAE 2013).

Other toxicity and health-based nomenclature includes the refrigerant concentration limit (RCL), the acute-toxicity exposure limit (ATEL), the immediately dangerous to life or health (IDLH) concentrations, oxygen deprivation limit, and flammable concentration limit. The RCL values, measured as refrigerant

concentration by volume in the air, are used to determine the risk of toxicity of refrigerants in accordance with ASHRAE standards. The RCL is intended to reduce the risks of acute toxicity, asphyxiation, and flammability hazards in normally occupied, enclosed spaces. These values are used to communicate toxic effects for refrigerant chemicals. The RCL values are derived from the ATEL values, also determined in accordance with ASHRAE standards for normally occupied, enclosed spaces. The ATEL values are equivalent to the IDLH concentrations set by NIOSH. Note that ATEL values include additional adverse effects (e.g., cardiac sensitization, anesthetic or central nervous system effects, other escape-impairing effects, and permanent injury), oxygen deprivation limits, and flammable concentration limits (ASHRAE 2013).

In addition to the ANSI/ASHRAE designation and safety classification for refrigerants, the Workplace Environmental Exposure Level (WEEL) values, established by the Occupational Alliance for Risk Science, are used as health-based guideline values for chemical stressors (e.g., refrigerants) to communicate safety in the workplace (WEEL 2023). The WEEL values represent air concentrations considered "safe" or "relatively safe." These concentrations aim to safeguard workers from potential adverse health effects resulting from occupational chemical exposure throughout their working lifetime, irrespective of the industry (WEEL 2023). The WEEL values are derived from potential exposure to refrigerants in the workplace from accidental releases (e.g., spill or rupture), service operations, and repeated or sustained exposures in a lifetime in machinery rooms. The workplace exposure scenarios were established according to the American Industrial Hygiene Association, using an 8 h total weight-average concentration for a 40 h workweek and measured in the worker's breathing zone (ASHRAE 2013).

2.2.2 Flammability

The flammability or flame propagation classification includes four classes (Class 1, 2L, 2, or 3) based on flammability data in accordance with the ANSI/ASHRAE Standards 34-2013 and 34-2019 and subsequent addenda. Each classification has specific criteria applicable to both individual refrigerants and blends. The criteria applied to these categories are defined by lower flammability limit (LFL), upper flammability limit, and the flammable concentrations in air for all flammables and vapors. Class 1 is for refrigerants that do not exhibit propagation. Class 2 refrigerants are considered "lower flammability" because they exhibit flame propagation and have an LFL of more than 0.10 kg/m^3 and a heat of combustion less than 19 MJ/kg. Class 2L is for lower flammability refrigerants with a maximum burning velocity of less than 10 cm/s. Class 3 is for "higher flammability" refrigerants that exhibit flame propagation with an LFL of less than 0.10 kg/m^3 or a heat of combustion greater than 19 MJ/kg (ASHRAE 2013, McLinden and Huber 2020).

3. ENVIRONMENTAL CONSIDERATIONS

3.1 OZONE DEPLETION POTENTIAL

ODP is a measure of how much damage a chemical can cause to the ozone layer compared with a similar mass of the CFC trichlorofluoromethane (R-11), which is assigned an ODP of 1.0. ODP values are based on models that simulate their reactivity under "normal" atmospheric conditions and according to their chemical structure and makeup. For blended refrigerants, ODP values are created by looking at the proportion of each individual component blended refrigerant, multiplying their ODP by their proportion of the mixture, and then adding the proportional ODP of each substance to get the blended ODP sum. For example, R-401A contains R-22 (53%), R-152a (13%), and R-124 (34%), with ODPs of the individual components of 0.055, 0.0, and 0.022, respectively. When multiplying each ODP value by its proportion of the overall blend and summing them, the overall ODP of the blend is 0.036 (UNEP 2023). Most of the refrigerants in use today have negligible (close to zero) ODP values (Table 3.1) because of international agreements to phase out ozone-depleting substances (ODSs) (Section 1.3).

ODP is an essential parameter considered for refrigerants, specifically for compounds containing halogen (i.e., chlorine, iodine, and bromine). The ODP parameter assesses the expected influence of a species on globally averaged total columnar ozone per unit mass emission, compared with the effect of trichlorofluoromethane (R-11) over a given period (Solomon et al. 2007, Zhang et al. 2020). Among the single refrigerants, R-1233zd(E) and R-1224yd(Z) are the only refrigerants containing a chlorine atom. The ODPs of R-1233zd(E) and R-1224yd(Z) are 0.00034 and 0.00023, respectively, which are significantly lower than unity (e.g., reference value). The emissions of such refrigerants do not cause substantial destructive effects on stratospheric ozone compared with R-11 owing to their low ODPs. The atmospheric lifetimes of 0.071 years for R-1233zd(E) and 0.054 years for R-1224yd(Z) are the main drivers of the ODPs of such refrigerants, in which the removal time of gases in the atmosphere is inversely proportional to ODP (Rodriguez 2007).

3.2 GLOBAL WARMING POTENTIAL

The GWP of a refrigerant is a measure of how much infrared thermal radiation a ton of greenhouse gas added to the atmosphere would absorb over a defined period, as a multiple of the same amount of radiation that would be absorbed by 1 ton of carbon dioxide (CO_2) emissions, which is assigned a value of 1. GWP values are often used to define effects of greenhouse gases (GHGs) over periods of 20, 100, or 500 years. The larger the GWP value, the more that a given gas warms the Earth's atmosphere compared with CO_2 over the same timescale. Blended refrigerants' GWP values, like their ODP values, are calculated based on the proportion of each individual component of the blend. For example, the blend R-499C contains the following single refrigerants at different proportions, given in parentheses: R-32 (0.250), R-125 (0.243), R-134a (0.273), and R-1234yf (0.232), with 100 year GWPs of 771, 3,740, 1,530 and 0.501 for each of the constituents, respectively. The GWP of the blend is calculated by summing the product of the GWP with the proportion of each constituent in the blend, giving a 100-GWP of 1,519.37 for R-499C (UNEP 2023).

Note that the GWP of a refrigerant chemical does not include the energy required for its use in an operating system or over its operating lifespan. GWP includes only the modeled effect the refrigerant would have if released into the atmosphere based on the chemical characteristics (e.g., chemical structure) and its total lifespan within the atmosphere. Depending on the reactivity of the chemical in question, the GWP of a greenhouse gas can be analyzed using different timescales (e.g., 20, 100, or 500 years). For chemicals with a short lifespan (i.e., ranging in days), shorter GWP time periods (e.g., 20 years) could be used when considering overall environmental impact. Still, global regulations use the GWP over a 100 year period because it allows for comparisons of refrigerants with a variety of lifespans.

3.3 ATMOSPHERIC LIFETIME

The definition and quantification of an atmospheric residence time or lifetime for a gas emitted at the earth's surface are fundamental to understanding the relationship between the inventory of the gas in the atmosphere and its potential to contribute to GWP, ODP, deposition of breakdown products, and bioaccumulation or toxicity in the environment. The measurement of OH radical kinetics is one way to estimate the atmospheric lifetime of refrigerants. Like other chemicals emitted to the atmosphere, refrigerants undergo oxidation and transformation, which influence their lifetime, global warming, and ozone-depleting potential. Atmospheric degradation of HFC and HFO refrigerants starts with initiation, in which free radicals react with the refrigerants. The process generates highly reactive molecules that proceed to the propagation step, in which alkyl radicals ($R\cdot$) react with oxygen to form peroxyradicals ($RO_2\cdot$). RO_2 radicals subsequently react with other molecules such as nitric oxide (NO_x), RO_2, and HO_2 to form other products, such as aldehydes, ketones, peroxides, acids, and nitrates (Seinfield and Pandis 2006).

Atmospheric degradation of HFC and HFO refrigerants occurs primarily through the reaction with OH radicals, which takes place during the daytime. A typical reaction proceeds by OH addition or hydrogen abstraction to the refrigerant molecule. The OH reactivity of the HFC and HFO refrigerants, dictated by the reaction coefficients, controls the atmospheric lifetime of refrigerants. Slower reactions make refrigerants atmospherically persistent molecules. Conversely, swift reactions ($>10^{-13}$ cm^3 $molecule^{-1}$ s^{-1}) significantly reduce the lifetime of the HFC and HFO refrigerants in the atmosphere. Figure 3.1 shows the trends of HFC and HCFC refrigerants in terms of OH reactivity and the number of carbon and chlorine atoms (Burkholder et al. 2015).

Typically, longer carbon-fluorine chains and saturated structures in the molecular formula of refrigerants can lead to increased refrigerant atmospheric lifetimes.

For comparison purposes, R-1234yf has a reaction rate constant of 1.1 10^{-13} cm^3 $molecule^{-1}$ s^{-1}, which is at least 10 times faster than the HFC and HCFC refrigerants' rates presented in Figure 3.1. The presence of a double bond in its structure significantly enhanced the OH addition during the oxidation process. The calculated atmospheric lifetime of R-1234yf is close to 10.5 days upon the emission of the refrigerant. At such a lifetime, the persistence of R-1234yf is limited, with degradation products of OH reaction more likely to be observed, compared with that of the parent refrigerant.

Figure 3.2 shows the atmospheric lifetime of the focal and natural refrigerants reviewed here, primarily based on the reaction with OH radicals/daytime oxidation process. In general, refrigerants with the shortest atmospheric lifetime (<0.1 years) are compounds with double bonds (i.e., C=C) in their structure [e.g., R-1234yd(Z) and R-1336mzz(Z)], with the exceptions of R-717 (ammonia) and R-290 (propane). The relative instability and electron-rich profile of the unsaturated refrigerants increase their reactivity, and thus the likelihood of participating in OH addition compared with the saturated fluorinated compounds, reducing their lifetime in the atmosphere. For example, R-717 (ammonia) has a reduced lifetime owing to the immediate reaction of NH_3 with SO_2 and NO_x, which are dominant acidic pollutants in urban environments (Wang et al. 2015). Conversely, R-227ea, a highly fluorinated saturated refrigerant, is the most atmospherically persistent molecule owing to the combination of stability of the alkene backbone and the number of fluorine atoms bonded to the carbon chain. The two longest-lived refrigerants under consideration, R-227ea and R-125, have only one available hydrogen for abstraction during the OH oxidation process, which most likely slows the oxidation process.

Figure 3.2 also shows the relationship between atmospheric lifetime and GWP of the refrigerants in this study. While both radiative efficiency and atmospheric lifetime of refrigerants are used to calculate GWP, Figure 3.2 shows that two refrigerants (R-227ea and R-245fa, which have similar radiative efficiencies of ~0.24 W/m/ppm; Table 3.1) can have very different GWPs owing to differing atmospheric lifetimes. In contrast, highly reactive HFO refrigerants such as R-1234yf and R-1234ze(E) have less capacity to warm the atmosphere compared with CO_2 owing to their rapid transformation in the atmosphere.

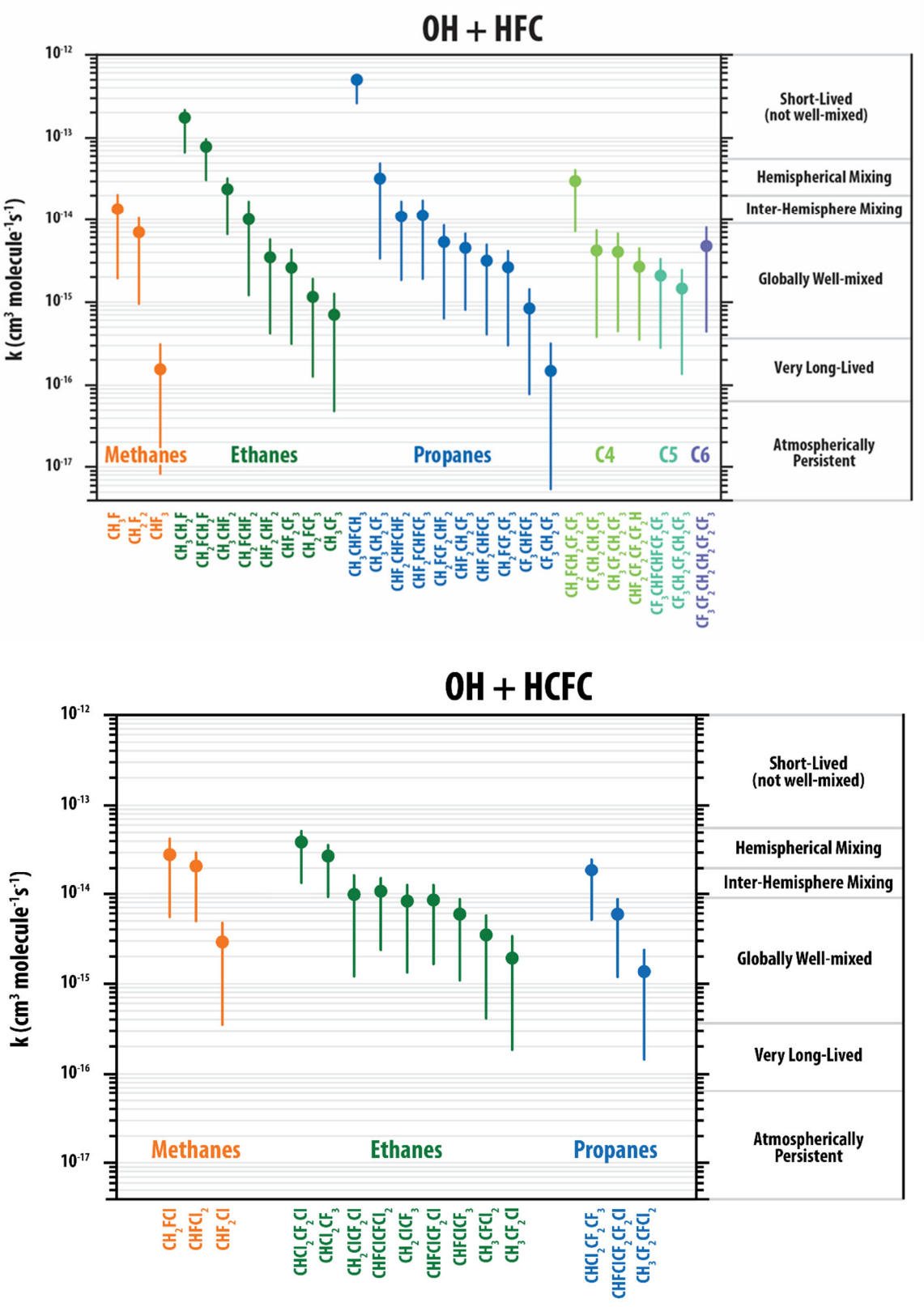

Figure 3.1. The reaction rates (k) of HFC (top) and HCFC (bottom) refrigerants with hydroxy radicals. Adapted from: J. B. Burkholder, R. A. Cox, and A. R. Ravishankara, *Chemical Reviews*, 2015, 115, 3704–3759. (Burkholder et al. 2015)

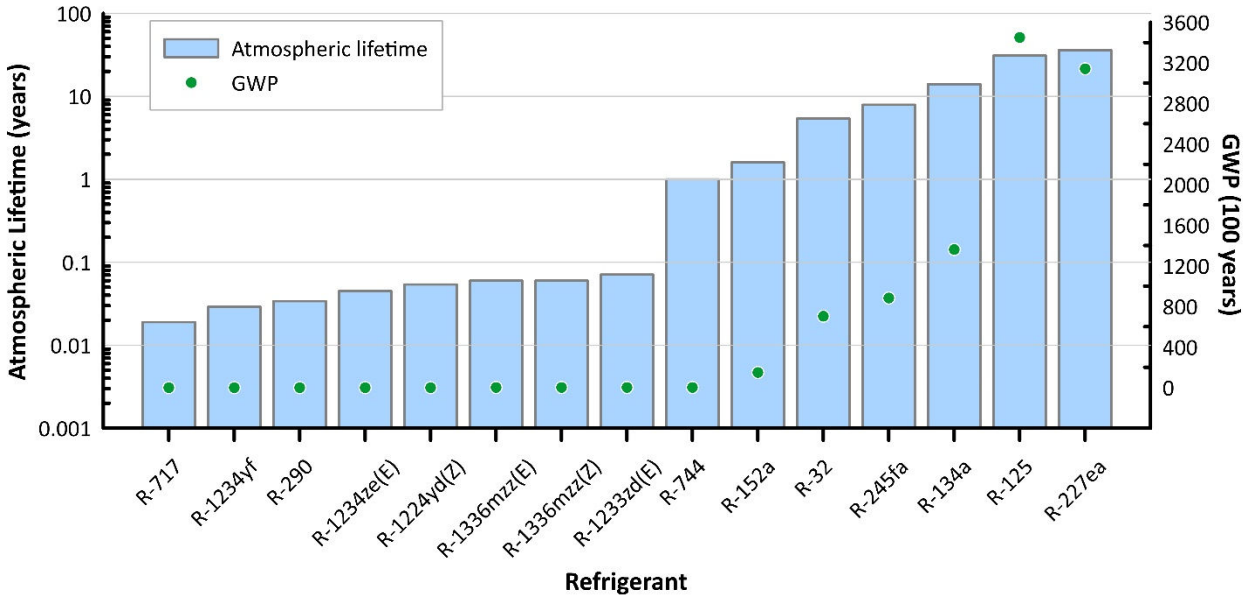

Figure 3.2. Atmospheric lifetime (in years; left axis on log scale) and global warming potential (GWP; right axis) of the single refrigerants. GWP values represent the effects of greenhouse gases over a 100 year period.

3.4 TOXICITY

Because refrigerants are gaseous, the major route of exposure to an organism is through inhalation. The toxicity of refrigerants has been assessed in short-term (i.e., acute) and long-term (i.e., chronic) studies using animal models (e.g., rats, rabbits, dogs), occupational accident release, and volunteer data; most of these studies were done to address human occupational exposure and health. Table 3.1 shows a summary of available mammalian inhalation toxicity data for the refrigerants in this study. The LC50 (lethal concentration at 50%, or the concentration of a chemical that kills 50% of study animals) is a commonly used metric to assess lethality. For all the refrigerants considered in this study except for R-1233zd, even the highest concentrations considered in experimental studies did not cause 50% mortality in test organisms (denoted by the *greater than* signs in the LC50 column in Table 3.1). Although LC50s are commonly used metrics in toxicological studies, they are considered less environmentally relevant than sublethal metrics that can be used toward the protection of populations, rather than of individual organisms (Stark 2005). Also reported in Table 3.1 are the LOEL (Lowest Observed Effect levels) the lowest concentration to elicit an effect in test organisms. The LOEL concentrations listed in Table 3.1 are orders of magnitude higher than those of environmentally relevant concentrations, which is another indication of relatively low toxicity. Indeed, except for R-245fa, the HFO and HFC refrigerants considered in this study are classified as Class A (lower toxicity; OEL >400 ppm). To elicit a response, subjects must be exposed to elevated concentrations that are not likely to be environmentally relevant (except in the case of an accident). (However, note that ASHRAE is currently reconsidering the use of the class system for toxicity shown in Figure 2.1.)

While the concentrations of parent refrigerants in the atmosphere are too low to be an environmental concern, toxicity data are available only for single refrigerants because refrigerants are assumed not to interact with one another in the environment. From a toxicological standpoint, response to mixtures may not be a simple linear or additive function related to the proportions of individual compounds found in refrigerant blends. Further, toxicity and safety data discussed in Tables 3.1 and 5.1 provide a given exposure concentration to a given single refrigerant compound but don't necessarily consider the toxicity of blends or degradation products from refrigerant breakdown in the environment (See Sections 3.5 and 7 for more discussion of degradation products).

Table 3.1. Toxicity of single refrigerants reported in mammalian inhalation studies. Concentrations are reported as volume of refrigerant in air (ppm v/v).

Class	Identifier	Chemical Formula	Chemical Name	Mammalian Studies		
				4 h LC50 or ALC (ppmv)	Lowest Observed Effect (ppmv)	Toxic Effect for LOEL
HFC	R-32	CH_2F_2	Difluoromethane	>760,000	86,000	Reduced breathing rate and salivation
	R-125	CF_3CHF_2	Pentafluoroethane	>800,000	50,000	Slightly lower food consumption and weight gain
	R-134a	CH_2FCF_3	1,1,1,2-tetrafluoroethane	>500,000	50,000	Slight focal interstitial pneumonia
	R-152a	$C_2H_4F_2$	1,1-difluoroethane	>400,000	100,000	Mild chronic irritation in the lung
	R227ea	C_3HF_7	1,1,1,2,3,3,3-heptafluoropropane	>800,000	105,000	Cardiac sensitization
	R245fa	$C_3H_3F_5$	1,1,1,3,3-pentafluoropropane	>203,000	2,000	Increased urinary fluoride levels
Halogenated Olefins	R-1234yf	$CF_3CF=CH_2$	2,3,3,3-tetrafluoro-1-propene	>400,000	1,500	Myocardial inflammation and skeletal muscle necrosis
	R-1234ze(E)	$CF_3CH=CHF$	trans-1,3,3,3-tetrafluoro-1-propene	>207,000	4,000	Transient reduced pregnancy rate
	R-1336mzz(E)	$CF_3CH=CHCF_3$	trans-1,1,1,4,4,4-hexafluoro-2-butene	>17,000	15,000	Restlessness, blepharospasm, and myoclonic jerks
	R1336mzz(Z)	$CF_3CH=CHCF_3$	cis-1,1,1,4,4,4-hexafluoro-2-butene	>102,000	1,500	Reduced maternal body weight gain
	R-1233zd(E)	$CF_3CH=CHC1$	trans-1-chloro-3,3,3-trifluoro-1-propene	120,000	1,994	Increase in cholesterol levels
	R-1224yd(Z)	$CF_3CF=CHC1$	(Z)-1-chloro-2,3,3,3-tetrafluoropropene	>213,000	50,000	Transient repetitive movement of mouth/jaws
Natural Refrigerant	R-290	$CH_3CH_2CH_3$	Propane	>200,000	50,000	Cardiac sensitization
	R-717	NH_3	Ammonia	>2,000	400	Severe damage to the eyes, nose, throat, and respiratory tract
	R-744	CO_2	Carbon dioxide	>400,000	50,000	Respiratory arrest and unconsciousness

4 h LC50 = median lethal concentration at 4 h; ALC = approximate lethal concentration; LOEL = lowest observed effect level; TWA = time-weighted average; AIHA = American Industrial Hygiene Association; OARS = Occupational Alliance for Risk Science; WEEL = Workplace Environmental Exposure Levels; ASHRAE = American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Sources: (NRL 2015, Honeywell Inc 2017, NRL 2017c, a, b, ASHRAE 2018, NRL 2018b, c, a, Rusch 2018, Honeywell Inc 2019, NRL 2019b, a, WEEL 2019b, a, Honeywell Inc 2022, AGC Inc 2023, Honeywell Inc 2023, NCBI 2023a, b, d, c)

3.5 DEGRADATION PRODUCTS OF FLUORINATED REFRIGERANTS

While HFO refrigerants are generally considered environmentally friendly and short-lived in the environment (Figure 1.1), they can undergo photooxidation to TFA. The reaction of HFOs and HFCs with OH radicals in the atmosphere yields degradation products of varying persistence and toxicity. HFOs are environmentally friendly in part because the carbon double bond in HFOs is highly reactive with atmospheric hydroxyl (OH) radicals, which leads to their short atmospheric lifetimes and low GWP. However, because these compounds degrade quickly, they have the potential to create significant yields of varying degradation products. One of the most well-known degradation products, particularly from HFCs and HFOs, is TFA, whose classification as an ultra-short per- and polyfluoroalkyl substance (PFAS) is under considerable debate, which has policy implications as both the European Commission and the EPA have signaled their commitments to systematically decreasing the use of PFAS compounds (Glüge et al. 2020). See Section 4.3 for a more detailed discussion of regulatory issues related to PFAS. Regardless of classifications, TFA is generally regarded to be highly persistent in the environment, and long-term effects from environmental exposures are uncertain. Section 7 of this report includes a more detailed discussion of the formation, quantification, and environmental impacts of degradation products.

4. REGULATORY CONSIDERATIONS

4.1 ODP-RELEVANT REGULATIONS

The Montreal Protocol, also known as the Montreal Protocol on Substances that Deplete the Ozone Layer, is a landmark multilateral agreement signed in 1987, aiming to protect the ozone layer by phasing out the production and consumption of ODSs, which includes CFC refrigerants, known as the first generation of widely manufactured refrigerants [Figure 1.1; (Molina and Rowland 1974, Tsai 2014, NOAA 2023)]. The Montreal Protocol phased down the consumption and production of different ODS compounds in a stepwise manner, with different timetables for developed and developing countries (i.e., “Article 5 countries”). Since 1989, over 98% of the world’s ODS consumption has been phased out; in 1990, an amendment was approved to call for the elimination of production of CFCs (UNEP 1990).

CFCs release chlorine atoms in the stratosphere that can destroy ozone in catalytic reactions at a ratio of 100,000 molecules of ozone destroyed per chlorine atom; CFCs have high ODPs, ranging between 0.1 and 1.0. To lessen the effects on the atmospheric ozone, the carbon-chlorine bonds of CFC refrigerants were partially replaced by carbon-hydrogen bonds in the chemical structures of the second generation of refrigerants designated as HCFC refrigerants [Figure 1.1; (NOAA 2023)]. The HCFCs had a significant lower ODP (e.g., 0.001–0.52) and shorter atmospheric lifetimes (e.g., 1.7–17.2 years) than those of CFC refrigerants (USEPA 2023d).

In the United States, ODP substances are divided into two classes: Class-1 ODP substances are chemicals with an ODP $\geq$0.2, and Class-2 ODP substances are chemicals with an ODP <0.2, which include HCFC refrigerants. Class-1 ODP substances (e.g., such as CFC refrigerants, halons, carbon tetrachloride, methyl chloroform, and hydrobromofluorocarbons) were completely phased out for end usage in refrigerant operating units and foam blowers in 1996 (USEPA 2023d). Another Class 1 ODP substance, methyl bromide, was completely phased out in the United States in 2005 as required by US regulations. Class-2 refrigerants (e.g., HCFC refrigerants and other chemicals with an ODP < 0.2) are currently being phased down globally. The most recent phasedown step in 2020 required (1) the cessation of production and import of chemicals such as R-142b and R-22 refrigerants and (2) the absolute reduction in use and production of HCFC refrigerants more broadly at 99.5%, compared with baseline levels. The final phasedown of Class-2 ODP substances is scheduled in 2030, in which the import and production of any HCFC substance will be banned. As shown in Table 3.1, most of the refrigerants currently in use have

ODP values of zero. Of the refrigerants under consideration for this study, only R-1233zd(E) and R-1224yd(Z) have ODP values > 0, though the values are very low (Table 3.1).

4.2 GWP-RELEVANT REGULATIONS

The third generation of fluorinated refrigerants, HFCs, involved the replacement of all carbon-chlorine bonds with carbon-hydrogen and carbon-fluorine bonds (Ravishankara et al. 1994). This action helped eliminate the effect chlorine atoms have on atmospheric ozone (e.g., ODP of zero) (Ravishankara et al. 1994, WMO 2019). However, the introduction of this generation of refrigerants raised concerns because they can last in the atmosphere tens or hundreds of years and act as potent GHGs (e.g., high GWP), thus contributing to climate change (USEPA 2023b).

The Kyoto Protocol, adopted in 1997, is an international treaty under the 1992 United Nations Framework Convention on Climate Change (UN 1992) that aims to reduce GHG emissions. The emissions of HFCs were regulated under the Kyoto Protocol because of concern over their high GWP (Table 3.1). HFC refrigerant use and production were further regulated in 2016 with the Kigali Amendment to the Montreal Protocol (UNEP 2016), which, similar to the original Montreal Protocol, sets different timetables for developed and developing countries for the phaseout of HFCs. Most developed countries began phasedowns in 2019 and must achieve an 85% cut from their baseline by 2036 (UNEP 2016). Although the US did not initially sign the Kigali Amendment, the American Innovation and Manufacturing Act of 2020, enforced by the EPA, set similar phasedowns of HFC refrigerants by 85% from historic baseline levels by 2036 (Federal Register 2023a) to align with the Kigali Amendment. Unlike the previous transition from R-22 to R-410A—both nonflammable (A1) refrigerants—the available alternatives are of lower flammability (A2L), which has required changes to mechanical codes and standards. The EPA Technology Transition Program (EPA, October 2023) facilitates the transition to next-generation technologies through sector-based restrictions. The objective is to reduce the production and consumption of HFCs by 60% by the end of 2024 and 70% by 2029.

In addition, regulations such as the US Clean Air Act and European Commission F-Gas Legislation have pushed the refrigerant industry to develop alternative refrigerant chemicals that have a GWP <150 to combat the threat of rapid climate change. A fourth generation of refrigerants, the HFOs and hydrochlorofluoroolefins (HCFOs), is under development (Booten et al. 2020, Sicard and Baker 2020). They are categorized as having zero ODP and a low GWP (<30 for 100 year GWP; Table 3.1) and are therefore considered an environmentally friendly alternative to CFC, HCFC, and HFC refrigerants. In contrast, CFC, HFC, and HCFC refrigerants are sometimes called high-GWP gases because they have GWP values ranging from a high of ~15,000 to the high hundreds over a 100 year timescale.

Whereas HFCs are saturated organic compounds, HFOs are unsaturated but contain at least one C=C double bond, which provides a chemical reactivity to the refrigerant's chemical structure, reducing their atmospheric lifetime (e.g., a few weeks) and, therefore, avoiding significant build-up over time (Nair 2021, European Commission 2023). Many refrigerants in the HFO class are chemically stable and inert, nontoxic, and nonflammable or mildly flammable (Table 3.1). For this reason, these compounds are being considered as alternatives to HFCs by the EPA's Significant New Alternative Policy (SNAP) Program and are currently in use by automobile manufacturers (USEPA 2024c). This generation also includes hydrochloroolefin isomers of chlorotrifluoro-propylene (HCFOs), which are currently used as blowing agents. In the European Union (EU), the fluorinated gas (F-gas) regulations set schedules for phasedowns of HFCs and other F-gases, some beginning as early as 2027, with a complete ban by 2050 (European Commission 2014, Oltersdorf et al. 2021, ECHA 2023, European Commission 2024).

The EU F-Gas Legislation, passed in 2006 and updated in 2014, aims to identify climate-friendly alternatives for F-gases in accordance with the Kyoto Protocol guidance on reducing overall GHG

emissions. In its first iteration, this legislation focused primarily on minimizing fugitive emissions from refrigerant units and the proper disposal of refrigerant chemicals at the end of an operating systems lifespan. The revised F-gas legislation that was passed in 2014 was put into effect starting in 2015. Building off the earlier successes of minimizing fugitive emissions, F-gas regulations have now been used to meet the goals of the Montreal Protocol by specifically reducing overall HFC usage by two-thirds by 2030, stopping the illegal trade of high GWP and ODP refrigerants, and increasing the monitoring of use of all F-gases, including HFOs and HCFOs. Owing to this legislation, HFC use and emissions in the European community have fallen year over year as alternatives such as HFOs, HCFOs, and natural refrigerants have become viable. In April 2022, the EU commission started a review of the F-gas legislation successes and limitations with the goal of modifying the legislation to ensure commitments made under the Montreal Protocol and Kigali Amendment are met. As a result, the European Commission proposed (but has not yet finalized) a 150 GWP limit that applies to plug-in air conditioners and heat pumps (beginning in 2025) and split systems up to 12 kW capacity (beginning in 2027). Moreover, limits will be placed on domestic heat pumps and some air conditioners using HFCs with GWP of 150 or more between 2027 and 2029.

4.3 PFAS REGULATIONS

Although HFO refrigerants are generally considered environmentally friendly and short-lived in the environment (Figure 1.1), they can undergo photooxidation to various degradation products including TFA, which is highly persistent and mobile in water and soil and, therefore, has the potential for long-range transport (Russell et al. 2012, Kazil et al. 2014b, Solomon et al. 2016). Whereas the Organisation for Economic Co-operation and Development (OECD) considers TFA to be an ultra-short PFAS—the diverse and persistent group of chemicals called “forever chemicals”—the EPA definition of PFAS excludes HFOs and TFAs (USEPA 2021). Because of ongoing policy and science discussions regarding the potential effects of TFA in the environment due to degradation of HFOs, this critical review will provide a timely assessment of the current state of knowledge on the bioaccumulation, toxicity, prevalence, and distribution of TFAs as well as relevance to potential regulations.

Regulatory bodies such as the EPA and ECHA have signaled their desire to begin analyzing any PFAS or related compounds through a life cycle assessment framework (ECHA 2023). This entails analyzing how potentially harmful and persistent compounds are used and could influence both environmental and human health throughout their production, use in consumer products, and end-of-life disposal. Scientific arguments have been made to manage all PFAS compounds together as a chemical class because of their common characteristics of being highly persistent, bioaccumulative, and potentially hazardous (Kwiatkowski et al. 2020). The same authors further advocate for a life cycle approach to manage PFAS chemicals to comprehensively address the potential effects of perfluorocarboxylic acid (PFCA) precursors and TFA as a degradation product; they note that whether the source of threats to environmental and human health comes from a precursor or a degradation product of PFAS does not matter when considering the effects of these compounds as a whole (Kwiatkowski et al. 2021).

4.3.1 EU PFAS Legislation

The European agencies ECHA and OECD define PFAS as any chemical containing -CF2 or -CF3 groups, which would include most of the current HFC and some of the new HFO refrigerants and their degradation products (See Table 4.1 below) (OECD 2022, ECHA 2023). In February 2023, five European countries (Denmark, Germany, Netherlands, Norway, and Sweden) submitted REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals)-based restriction of PFAS to the European Chemical Agency (ECHA, 2023). More specifically, this proposal will ban all PFAS chemicals including, by PFAS definition, refrigerants such as R-143a, R-125, R-134a, R-1234yf, and R-1234ze(E). A comment period from March to September 2023 yielded more than 5,000. ECHA is reviewing/evaluating

these comments and any additional scientific information currently available. Any resulting regulations are scheduled to be put in place in 2025 and may create some uncertainty for the long-term use of several HFCs and HFOs.

Table 4.1. Focal refrigerants and degradation products of this report and whether these compounds are considered PFAS under TSCA (88 Fed. Reg. 70516), in the most recent PFAS definition updated by EPA or by ECHA (EU REACH).

Refrigerant Class	ASHRAE Identifier	Chemical Name	TSCA 2023	OECD 2021
HFCs	R-32	Difluoromethane	NO	YES
	R-125	Pentafluoroethane	YES	YES
	R-134a	1,1,1,2 tetrafluoroethane	YES	YES
	R-152a	1,1 difluoroethane	NO	YES
	R-227ea	1,1,1,2,3,3,3-heptafluoropropane	YES	YES
	R-245fa	1,1,1,3,3-pentafluoropropane	NO	YES
Halogenated Olefins	R-1234yf	2,3,3,3-tetrafluoro-1-propene	NO	YES
	R-1234ze(E)	trans-1,3,3,3-tetrafluoro-1-propene	NO	YES
	R-1336mzz(E)	trans-1,1,1,4,4,4-hexafluoro-2-butene	NO	YES
	R-1336mzz(Z)	cis-1,1,1,4,4,4-hexafluoro-2-butene	NO	YES
	R-1233zd(E)	trans-1-chloro-3,3,3-trifluoro-1-propene	NO	YES
	R-1224yd(Z)	(Z)-1-chloro-2,3,3,3-tetrafluoropropene	NO	YES
Natural	R-290	Propane	NO	NO
	R-717	Ammonia	NO	NO
	R-744	Carbon dioxide	NO	NO
Degradation Products	-	Trifluoroacetic acid	NO	YES
	-	Hydrofluoric acid	NO	NO
	-	Formyl fluoride	NO	NO
	-	Trifluoroacetyl-fluoride	NO	YES
	-	Trifluoro acetaldehyde	NO	YES
	-	Formic acid	NO	NO

TSCA = Toxic Substances Control Act; OECD = Organisation for Economic Co-operation and Development.
Sources: (OECD 2021, 2022, Federal Register 2023b).

4.3.2 EPA PFAS Regulations

On October 11, 2023, the EPA proposed the following structural definition of PFAS under the Toxic Substances Control Act (TSCA), 88 Fed. Reg. 70516 (Federal Register 2023b)—Per- and polyfluorinated substances that structurally contain at least one of the following structures: R-(CF2)-CF(R')R", where both the CF2 and CF moieties are saturated carbons; R-CF2OCF2-R', where R and R' can either be F, O, or saturated carbons; and CF3C(CF3)R'R", where R' and R" can either be F or saturated carbons.

The EPA's definition of PFAS under TSCA excludes refrigerants such as R-1234yf and R-134a as well as their degradation products, notably TFA. The EU, Canada, and several US states regard these F-gas refrigerants and TFA as PFAS. Over the past few years, the EPA has released multiple lists of PFAS via the CompTox Chemicals Dashboard (USEPA 2024b) and associated publications in the literature that alternatively include or exclude compounds relevant to this report [e.g., TFA; see Williams et al. (Williams et al. 2022) for a review of these evolving definitions, which are not regulatory in nature]. The

definition in TSCA 888 Fed. Reg. 70516 defines regulated PFAS compounds in the US. To minimize the introduction of PFAS to the environment, EPA recommends that industry and government work together to reduce their use not only in consumer products but also as precursors to produce commonly used items. In this review, we consider the environmental impacts of the most common refrigerants, their precursors, and their degradation products, consistent with EPA's guidance to consider the entire life cycle of PFAS compounds.

5. MOST COMMON REFRIGERANTS

5.1 FLUORINATED REFRIGERANTS

5.1.1 HFC Refrigerants

Hydrofluorocarbon refrigerants are composed of hydrogen, carbon, and fluorine atoms; are highly stable; and have excellent thermodynamic properties, which have led to their widespread use in various cooling applications. However, their high GWP and ODP have led to calls for more sustainable alternatives. The first generations of refrigerants, CFCs and HCFCs, have been regulated and phased out by the Montreal Protocol owing to their environmental concerns (e.g., high ODPs) and largely replaced by HFC refrigerants. However, CFC and HCFC refrigerants remain under production for specific industrial applications and as feedstocks or chemical precursors for the development of newer generations of refrigerants (e.g., HFOs and HCFOs) (Booten et al. 2020, USEPA 2023c). In this critical review we consider six HFCs: R-227ea, R-32, R-134a, R-152a, R-125, and R-245fa (Table 3.1; Table A1).

5.1.1.1 R-32 (difluoromethane)

R-32 has been proposed as a substitute for R-410A (a zeotropic mixture of R-32 and R-125) in residential and light commercial air conditioning units and heat pumps (USEPA 2023c). Its performance is very similar to that of R-410A across its entire operating range, but its GWP (675) is lower than that of R-410A (2,088) and is below the current F-gas regulation limit in RAC equipment (750), R-32 was not previously used due to its flammability (ASHRAE class 2L). Still, it is currently being reconsidered because of its relative lower GWP and good system performance. As such it is being considered as a single refrigerant and in blends with other HFOs (e.g., R-1234yf, R-1234ze) to address both safety and environmental considerations.

5.1.1.2 R-134a (1,1,1,2 tetrafluoroethane)

R-134a has been used as a high-temperature refrigerant since the early 1990s in RAC and MAC as a replacement for dichlorofluoromethane (R-12), which has a high ODP. Though R-134a has a negligible ODP, it has a GWP of 1,360 (Table 3.1) and an approximate atmospheric lifetime of 14 years. Because its concentration in the atmosphere and contribution to radiative forcing have been growing since its introduction, it was included in the Intergovernmental Panel on Climate Change list of greenhouse gases. R-134a began being phased out in the mid-2010s from use in the European Union because of a 2006 directive recommending the replacement in air conditioning systems of gases with a GWP above 100. In the US, newly manufactured light-duty vehicles stopped using R-134a in 2021, and the Society of Automotive Engineers has proposed it be replaced by R-1234yf in MAC systems. Individual states have also introduced regulations to probit the sale of canned R-134a to individuals to avoid nonprofessional recharge of MACs. R-134a is an EPA SNAP-approved refrigerant.

5.1.1.3 R-125 (pentafluoroethane)

Similar to R-134a, R-125 was introduced as a replacement for CFCs because of its low ODP, but because it has a relatively high 100-GWP (3,740) and an atmospheric lifetime of 31 years, it is included in the list of controlled substances of the Montreal Protocol (UNEP 1987). R-125 has been used in blends, particularly in a nearly azeotropic mixture with R-32 to form R-410a, which is currently being phased down (UNEP 2022b).

5.1.1.4 R-152a (1,1 difluoroethane)

With a relatively low GWP index of 164 (Table 3.1) and favorable thermophysical properties, 1,1-difluoroethane has been proposed as an environmentally friendly alternative to R134a (UNEP 2022a, USEPA 2023d).

5.1.2 Halogenated Olefin Refrigerants

Halogenated olefins are unsaturated organic compounds composed of hydrogen, fluorine, and carbon. Table A1 shows the following refrigerants reviewed in this report—four HFOs: R-1234yf, R-1234ze(E), R-1336mzz(E), and R-1336mzz(Z); and two HCFOs: R-1233zd(E) and R-1224yd(Z). HFOs such as R-1234yf were first patented in the 1950s, but because of the effectiveness and commercial success of CFC and HCFC refrigerants, HFOs were not mass produced until the 21st century (McLinden and Huber 2020). With the emphasis on low-GWP refrigerants motivated by the Kigali Agreement, HFO refrigerants have been able to provide alternative and effective options for many refrigeration systems. Whereas HFC and halogenated olefin (HFO/HCFO) refrigerants have a similar chemical basis, the presence of saturated carbon bonds in halogenated olefin refrigerants results in a significantly reduced lifespan, consequently leading to lower GWPs (McLinden and Huber 2020).

5.1.3 HFC/HFO Refrigerant Blends

Blended refrigerants are a mixture of single refrigerants at different proportions. Each single-component refrigerant has its own physical properties (e.g., pressure, temperature, and heat exchange). To use the properties of single refrigerants in applications, the individual components must be mixed in the right proportions. Blends can be used as substitutes or alternatives to single refrigerants with higher ODPs and GWPs. They are currently used in various industrial and commercial refrigeration systems (e.g., heat exchangers, flow evaporators, and condensers) (Booten et al. 2020). Many refrigerant blends were created to directly replace CFC and HCFC refrigerants that were ozone-depleting and high–greenhouse-warming gases and, therefore, have comparable properties. The refrigerant blends included in this review consist of two or more natural, HFC, or HFO single-component refrigerants (Table 3.1). Blends can be classified as either zeotropes or azeotropes, depending on whether the components evaporate and condense at a constant temperature acting like a single refrigerant (i.e., azeotrope) or have a gliding evaporation and condensing temperature (i.e., zeotrope) (ASHRAE 2013, 2019). The type of refrigerants and their proportion or percentage in the blend influence not only their thermal and performance properties but also their environmental impact and safety (ASHRAE 2013, Kundu et al. 2014, ASHRAE 2019). For instance, the R-448A is a zeotropic blend with a refrigerant mass composition of R-32 (26%), R-125 (26%), R-134a (21%), R-1234ze (7%), and 1R-234yf (20%). This zeotropic blend has an ASHRAE A1 designation, which indicates a low flammability risk; however, the blend has a high 100-GWP of 1,497 owing to its high percentage composition of HFC refrigerants (NRI 2024). The mechanical properties and major applications of blends as substitutes or alternatives to single refrigerants are summarized below. Table 3.1 shows the composition of the selected azeotropic and zeotropic blends reviewed here and their ODP and GWP contributions.

5.1.3.1 R-448A (HFC/HFO blend)

R-448A is a refrigerant alternative to R-22 and R-404A for medium- and low-temperature refrigeration. It provides performance capacity higher than that of R-22 but like that of R-404A under equivalent operating conditions. R-448A can be used in both new and retrofit commercial ice machines, refrigerated transport, stand-alone retail food refrigeration equipment, supermarket systems, and remote condensing units. R-448A is an EPA SNAP-approved refrigerant and is classified by ASHRAE 34 as a nonflammable and nontoxic (A1) refrigerant with a 100-GWP of 1,415 (WMO 2019, IPCC 2022, Rettich et al. 2022, NRI 2024, USEPA 2024a).

5.1.3.2 R-449A (HFC/HFO blend)

R-449A is a refrigerant replacement for R-22, R-404A, R-407A and R-507A; it's suitable for new and retrofit commercial ice machines, refrigerated commercial ice machines, refrigerated transport, stand-alone low-temperature retail food refrigeration, supermarket systems, and remote condensing units. As a retrofit, R-449A offers improved performance and similar performance capacity in operating systems. R-449A is an EPA SNAP-approved refrigerant and is classified by ASHRAE 34 as a nonflammable and nontoxic (A1) refrigerant with a 100-GWP of 1,504 (Table 3.1) (USEPA 2016, WMO 2019, Rettich et al. 2022, Chemours LLC 2024, USEPA 2024a).

5.1.3.3 R-449B (HFC/HFO blend)

R-449B refrigerant can be installed in new and retrofit R-22, R-404A and R-507A commercial refrigeration supermarket systems, remote condensing units, low-temperature stand-alone equipment, refrigerated food processing and dispensing equipment, commercial ice machines, and refrigerated transport. It offers an improved energy efficiency over R-404a in refrigeration equipment. R-449B is an EPA SNAP-approved refrigerant and is classified by ASHRAE 34 as a nonflammable and low-toxicity, non-ozone-depleting class A1 refrigerant with a 100-GWP of 1,519 (Table 3.1) (Arkema Inc. 2016, WMO 2019, USEPA 2020b, 2024a).

5.1.3.4 R-450A (HFC/HFO blend)

R-450A is a refrigerant replacement for R-134a, for use in medium- and low-temperature refrigeration applications, appliances, and retrofitting R-12 or blends in operating systems. It has a performance capacity and energy efficiency similar to that of R-12; under higher pressures, R-450A exhibits performance similar to those of R-401A and R-409A. R-450A is an EPA SNAP-approved refrigerant and is classified by ASHRAE 34 as a nonflammable and nontoxic (A1) refrigerant with a 100-GWP of 618 (Table 3.1) (NRI 2020a, Rettich et al. 2022, USEPA 2024a).

5.1.3.5 R-452A (HFC/HFO refrigerants)

R-452A is a refrigerant designed to replace R-404A in new or existing installations in medium- and low-temperature transport refrigeration and remote condensing units. It has capacity and energy efficiency like those of R-404A and R-507 refrigerants. R-452A is an EPA SNAP-approved refrigerant and is classified by ASHARE 34 as nonflammable and nontoxic (A1) refrigerant with a 100-GWP of 2,336 (Table 3.1) (Federal Register 2017, NRI 2020b, UNEP 2022b, Climalife 2024c).

5.1.3.6 R-454B (HFC/HFO blend)

R-454B is a refrigerant with a higher critical temperature and broader operating range than those of other refrigerants, such as R-410A. Its cooling capacity and coefficient of performance for cooling are higher

than those of R-410A. R-454B is classified by ASHRAE 34 as a nontoxic and lower flammable (A2L) refrigerant with a 100-GWP of 516 (Table 3.1) (Chemours LLC 2021, Rettich et al. 2022, UNEP 2022b).

5.1.3.7 R-454C (HFC/HFO blend)

R-454C is a refrigerant with a thermodynamic performance that allows it to be used as a replacement for R-22 and R-404A in medium- and low-temperature refrigeration systems. It has a good energy performance compared with that of R-404A and represents an alternative to R-407C for air conditioning, dehumidification, and heat pump applications. R-454C is classified by ASHRAE 34 as a nontoxic and lower flammable (A2L) refrigerant with a 100-GWP of 162 (Table 3.1) (Hou et al. 2022, UNEP 2022b, Climalife 2024a).

5.1.3.8 R-455A (HFC/HFO/CO2 blend)

R-455A is a refrigerant with an extended operating envelope, high efficiency, high critical temperature, and low critical pressure. It is a refrigerant alternative to R-404A and propane for low-, medium-, and high-temperature applications in new systems such as plug-ins, condensing units, food service, water-loop, and monoblock applications. R-455A is classified by ASHRAE 34 as a nontoxic and mildly flammable refrigerant (A2L) with a 100-GWP of 162 (Table 3.1) (Honeywell Inc 2021, UNEP 2022b).

5.1.3.9 R-456A (HFC/HFO blend)

R-456A is a high-performing refrigerant developed to reduce the greenhouse emissions footprint of existing vehicle air conditioning systems. It is a substitute for R-134a in MAC with an increased cooling capacity boost of 10% for the vehicle while keeping the same energy efficiency of R-134a. R-456 can be used in R-134a systems without changes or modifications in the vehicle system. R-456A is classified by ASHRAE 34 as a nontoxic and nonflammable refrigerant (A1) with a 100-GWP of 707 (Table 3.1) (UNEP 2022b, Honeywell Inc 2024, Mexichem UK Ltd 2024).

5.1.3.10 R-471A (HFC/HFO blend)

R-471A is a refrigerant with improved energy efficiency. It is used in medium-temperature refrigeration systems such as commercial refrigeration applications in supermarkets, cold stores, industrial processes, and convenience stores. R-471A is classified by ASHRAE 34 as a nontoxic and nonflammable refrigerant (A1) with a 100-GWP of 159 (Table 3.1) (UNEP 2022b, Climalife 2024b, EES 2024).

5.1.3.11 R-476A (HFC/HFO blend)

R-476A is a refrigerant currently under development and evaluation (Federal Register 2023a). It is a replacement for R-22, designed mainly for use in stationary air conditioning applications. R-476A is classified by ASHRAE 34 as a nontoxic and nonflammable refrigerant (A1) with a 100-GWP of 151 (Table 3.1) (UNEP 2022b, Federal Register 2023a).

5.1.3.12 R-499C (HFTC/HFO blend)

R-499C is a refrigerant that has lower discharge temperatures with close capacity and energy efficiency to match those of R-22. It is a refrigerant replacement to R-22 in residential and commercial air conditioners and in direct expansion chillers. R-499C is suitable for new installations and retrofits of existing systems using R-22. R-499C is classified by ASHRAE 34 as a nontoxic and nonflammable (A1) refrigerant with a 100-GWP of 1,519 (Table 3.1) (Chemours LLC 2019, UNEP 2023).

5.1.3.13 R-513A (HFC/HFO blend)

R-513A has a higher coefficient of performance in cooling mode compared with that of R-134a (Méndez-Méndez et al. 2023). It is a refrigerant substitute for R-134a in both new and retrofit retail food refrigeration, refrigerated food processing and dispensing equipment, and chillers. R-513A is an EPA SNAP-approved refrigerant and is classified by ASHRAE 34 as a nontoxic and nonflammable (A1) refrigerant with a 100-GWP of 647 (Table 3.1) (Rettich et al. 2022, UNEP 2022b, Méndez-Méndez et al. 2023, USEPA 2024a).

5.1.3.14 R-515B (HFC/HFO blend)

R-515B is a substitute for use in new centrifugal and positive displacement chillers and industrial process air conditioning. R-515B is an EPA SNAP-approved refrigerant and is classified by ASHRAE 34 as a nontoxic and nonflammable (A1) refrigerant with a 100-GWP of 430 (Table 3.1) (Rettich et al. 2022, UNEP 2022b).

5.1.3.15 R-516A (HFC/HFO blend)

R-516A is a refrigerant with a higher coefficient of performance for low evaporating temperatures compared with those of R-134a (Méndez-Méndez et al. 2023). It is used in medium- and low-temperature refrigeration applications such as centrifugal chillers, stand-alone refrigeration, cascade refrigeration, and screw chillers. R-516A is a suitable substitute for R-134a and has also good compatibility with existing system components for R-134a or R-1234yf. R-516A is classified by ASHRAE 34 as a nontoxic and mildly-flammable (A2L) refrigerant with a 100-GWP of 147 (Table 3.1) (UNEP 2022b, Méndez-Méndez et al. 2023, Arkema Inc. 2024).

5.2 NATURAL REFRIGERANTS

Natural refrigerants include ammonia, carbon dioxide, hydrocarbons (e.g., propene), water, and air. R-744 (CO_2) is industrial or scientific grade produced from waste streams of industrial processes, whereas hydrocarbon R-290 (propane) is primarily created as a byproduct of natural gas and oil extraction (ASHRAE 2014, US DoE 2023). Compared with the fluorinated refrigerants discussed in this review, natural refrigerants have much lower GWPs (1–3) and no OD potentials (ASHRAE 2014). They have been used in various refrigerant applications such as HVAC chillers, cooling systems for technological applications, and cryogenics for many decades. Owing to issues such as safety concerns, high pressures, flammability, or sometimes lower operating efficiencies, natural refrigerants have not been used in large-scale air conditioning applications, and fully sealed systems of relative low charge must be implemented in the use of natural refrigerants such as hydrocarbons for any air condition application (USEPA 2014).

5.2.1 Ammonia

Ammonia (R-717) has historically been used in refrigeration owing to its high thermal capacity, self-notification from leaks due to its distinct smell, minor flammability, and affordability. A total of 80% of ammonia is used for agriculture, with its use as a refrigerant capturing only 2% of the total ammonia market (Boerner 2019). Ammonia has shown great promise as a natural refrigerant and low-GWP substance. With an RCL of 320 ppm v/v, ammonia is considered by the EPA to be an extremely hazardous substance (anhydrous ammonia), hence its application across a wide variety of operating units remains limited.

5.2.2 Carbon Dioxide

Carbon dioxide (R-744) is one of the oldest used refrigerant chemicals, starting in the mid-19th century as engineers experimented with new refrigerant designs and chemical compositions. As synthetic refrigerants such as CFCs began to enter the market in the 1930s, CO_2 use as a refrigerant fell out of favor (McLinden and Huber 2020). Currently, 91% of commercial CO_2 use is regulated to urea production and enhanced oil recovery operations, with its usage in refrigerant products accounting for a minimal share of the market (IEA 2019). The use of CO_2 has grown exponentially in the past decade owing to its low GWP, limited flammability, nontoxic nature, and high RCL of 40,000 ppm v/v. With the recent invention of trans-critical CO_2 high-pressure systems, these refrigerant chemicals can now be found in automobile air conditioning, heat pumps, and multistage refrigerant systems.

5.2.3 Propane

Propane (R-290) was primarily used in the early stages of refrigeration; however, as CFCs became commercially popular in the 1930s, interest in use of propane disappeared (McLinden and Huber 2020). As concerns about climate change and new international regulations have come into force, there is renewed interest in propane due to its low GWP, nontoxicity, and similar coefficients of performance compared with those of other HFCs. Although these characteristics make R-290 an excellent candidate to replace many refrigerant chemicals, its high flammability and RCL of 5,300 ppm v/v limit the possible operating systems in which it can be used.

Table 5.1. Environmental and safety considerations of the selected refrigerant chemicals and blends.

Identifier	Refrigerant Group	Chemical Formula; Refrigerant Composition	Environmental Conditions						Safety Considerations					
			Atmospheric Lifetime (years)	Radiative Efficiency ($W/m^2/ppb$)	20-GWP Year (kgCO2e/ kg GHG)	100-GWP Year (kgCO2e/ kg GHG)	ODP	Estimated TFA Yield (mol %)	LFL (kg/m3)	LFL (%)	UFL (%)	RCL (ppm v/v)	OEL (ppm v/v)	ASHRAE Safety Group Classification
R-32	HFC	CH2F2	5.4	0.111	2,690	771	0	0	0.307	12.7	33.5	36,000	1,000	A2L
R-125		CHF2CF3	30	0.234	6,740	3,740	0	<10	NF	NF	NF	75,000	1,000	A1
R-134a		CH2FCF3	14	0.167	4,140	1,530	0	<20	NF	NF	NF	50,000	1,000	A1
R-152a		CH3CHF2	1.6	0.102	591	164	0	0	0.13	4.2	20.2	12,000	1,000	A2
R-227ea		CF3CHFCF3	36	0.273	5,850	3,600	0	100	NF	NF	NF	84,000	1,000	A1
R-245fa		CHF2CH2CF3	7.9	0.245	3,170	962	0	<17	NF	NF	NF	34,000	300	A1
R-1234yf	Halogenated Olefins	CF3CF=CH2	0.033	0.026	1.81	0.501	0	100	0.289	6.2	12.3	16,000	500	A2L
R-1234ze(E)		(E)-CF3CH=CHF	0.052	0.045	4.94	1.37	0	<30	0.303	5.7	11.3	16,000	800	A2L
R-1336mzz(E)		(E)-CF3CH=CHCF3	0.334	0.132	64.3	17.9	0	<60	NF	NF	NF	7,200	400	A1
R-1336mzz(Z)		(Z)-CF3CH=CHCF3	0.074	0.069	7.48	2.08	0	< 20	NF	NF	NF	13,000	500	A1
R-1233zd(E)		(E)-CF3CH=CHCl	0.116	0.065	14	3.88	<0.0004	<30	NF	NF	NF	16,000	800	A1
R-1224yd(Z)		(Z)-CF3CH=CHCl	0.058	0.0335	2	1	0.00012	97	NF	NF	NF	60,000	1,000	A1
R-290	Propane	C3H8	0.036	0.00E+00	0.00175	0.00178	0	0	0.038	2.2	9.5	5,300	1,000	A3
R-717	Ammonia	NH3	0.019	0.0014	<1	<<1	-	0	0.116	14.8	33.5	320	25	B2L
R-744	Carbon Dioxide	CO2	-	1.33E-05	1	1	0	0	NF	NF	NF	40,000	5,000	A1
R-448A	Zeotrope	R-32/125/1234yf/134a/1234ze(E)	-	-	3,235	1,415	-	Possible	NF	NF	NF	110,000	890	A1
R-449A	Zeotrope	R-32/125/1234yf/134a	-	-	3,358	1,504	-	Possible	NF	NF	NF	100,000	830	A1
R-449B	Zeotrope	R-32/125/1234yf/134a	-	-	3,419	1,519	-	Possible	NF	NF	NF	100,000	850	A1
R-450A	Zeotrope	R-134a/1234ze(E)	-	-	1,708	618	-	NS	NF	NF	NF	72,000	880	A1
R-452A	Zeotrope	R-32/125/1234yf	-	-	4,295	2,336	-	Possible	NF	NF	NF	10,000	780	A1
R-454B	Zeotrope	R-32/1234yf	-	-	1,806	516	-	Possible	NS	11.25	22	19,000	850	A2L
R-454C	Zeotrope	R-32/1234yf	-	-	565	162	-	Possible	NS	>7	<15	19,000	620	A2L
R-455A	Zeotrope	R-744/32/1234yf	-	-	565	162	-	Possible	NS	11.8	12.9	30,000	650	A2L
R-456A	Zeotrope	R-32/134a/1234ze(E)	-	-	1,987	707	-	NS	NF	NF	NF	77,000	900	A1
R-471A	Zeotrope	R-1234ze(E)/227ea/1336mzz(E)	-	-	271	159	-	Possible	NF	NF	NF	NS	NS	A1
R-476A	Zeotrope	R-134a/1234ze(E)/1336mzz(E)	-	-	421	151	-	NS	NF	NF	NF	NS	NS	A1
R-499C	Zeotrope	R-32/125/134a/1234yf	-	-	3,441	1,519	-	Possible	NF	NF	NF	NS	NS	A1
R-513A	Azeotrope	R-1234yf/134a	-	-	1,788	647	-	Possible	NF	NF	NF	NS	NS	A1
R-515B	Azeotrope	R-1234ze(E)/227ea	-	-	704	430	-	Possible	NF	NF	NF	72,000	650	A1
R-516A	Azeotrope	R-1234yf/134a/152a	-	-	424	147	-	Possible	NS	NS	NS	27,000	590	A2L

Note: Blends with refrigerant composition containing R-227ea or R-1234yf are indicated as “possible” for TFA yield.
GWP = global warming potential; ODP = ozone depletion potential; OEL = occupational exposure limit; RCL = refrigerant concentration limit; LFL = lower flammability limit; UFL = upper flammability limit; NA = not available; NS = not specified; NF = nonflammable; RCL = refrigerant concentration limit; CNS = central nervous system; NOEL = non-observed-effect level; LOEL = lowest observed effect level; LC50 = lethal concentration at 50%; BCF = bioconcentration factor; NIOSH = National Institute for Occupational Safety and Health; IDLH = immediately dangerous to life and health limit (ASHRAE 2013).

6. MANUFACTURING CONSIDERATIONS

6.1 IDENTIFICATION OF FEEDSTOCKS

Feedstocks are raw materials or chemical precursors employed to produce high-value products (e.g., refrigerants and blends). Table 6.1 shows examples of chemical feedstocks used to manufacture fluorinated refrigerants, such as methylene chloride (CH_2Cl_2), chloroform ($CHCl_3$), carbon tetrachloride (CTC, CCl_4), trichloroethylene (C_2HCl_3), perchloroethylene (C_2Cl_4), and methyl chloroform ($C_2H_3Cl_3$). Additionally, refrigerant such as CFCs, HFCs, and HCFCs have been used as chemical feedstocks in the production of certain refrigerants (e.g., HFOs) (Booten et al. 2020).

One of the main concerns of feedstocks is the unintended leakage during refrigerant production because some of these feedstocks and products have high GWP and/or ODP values. Examples include methyl chloroform (GWP = 160 AR5, ODP = 0.1–0.16), CFC-11 (100-GWP = 6,230 AR6), CFC-12 (100-GWP = 12,500 AR6), CFC-113 (100-GWP = 6,520 AR6), and CTC (100-GWP = 2,110 AR6, ODP = 0.82–1.1) (WMO 2014, Yu 2017, IPCC 2021, USEPA 2022, 2023a). The Montreal Protocol and subsequent international amendments have banned the use of many of these high GWP and ODP chemicals for end use in refrigerant operating units, yet some are currently in use to produce next-generation HFO and HCFO chemicals (Booten et al. 2020). For example, HFCs and HCFCs are permitted as chemical feedstocks under international agreements because these chemicals are prohibited to be released into the atmosphere (Booten et al. 2020). International regulations require corporations and nation-states to report both the use and destruction of these chemicals to ensure the goals of the Montreal Protocol are met (UNEP 1999).

However, current monitoring of the atmosphere suggests that concentrations of feedstock such as CTC are greater than expected according to international limits (Liang et al. 2016). Because some chemical precursors or feedstocks are still in use in the production of other fluorochemicals (e.g., HFOs), the aims of this section are to examine how the refrigerant industry has met the legal requirements under the Montreal Protocol and Kigali Amendment and to analyze environmental impacts of the production of next-generation HC and HFO refrigerant chemicals.

Natural refrigerants such as R-744 and R-290 are created primarily as byproducts of natural gas and oil extraction (IEA 2019, US DoE 2023). In this regard, 91% of commercial R-744 use is regulated to urea production and enhanced oil recovery operations, with its use in refrigerant products accounting for a minimal share of the market (IEA 2019). Unlike R-744 and R-290, R-717 is directly produced through the energy-intensive Haber-Bosch process, which accounts for ~1% of global CO_2 emissions (Boerner 2019). For all three refrigerants, the industrial manufacturing process is energy intensive, and for R-290 it relies heavily on the production and use of fossil fuels (Boerner 2019, IEA 2019, US DoE 2023). However, whereas the overall production of these chemicals is energy intensive, only a small fraction of hydrocarbons produced are used in refrigerant products, capturing around ~6% of the market, and are instead used primarily in other industrial processes (Boerner 2019, IEA 2019, US DoE 2023).

Fluorinated refrigerants, such as HFCs, HCFCs, and HFOs, are mass produced using chemical feedstock (Sherry et al. 2017, USEPA 2023e). In the United States, R-1234yf is produced using Kharasch reactors, which have an effective yield of 90%, with the remaining effluent containing CTC, anhydrous HCl, and heavy tar as waste (Sherry et al. 2017). Carbon tetrachloride can also be used as a feedstock in the production of R-1234yf and R-1234ze (USEPA 2020a, Garry et al. 2022). Because CTC is a major contributor to ozone depletion and climate change, its production and consumption are controlled under the Montreal Protocol and the United States Clean Air Act amendments (WMO 2014, Yu 2017, USEPA 2022, 2023a). Furthermore, CTC is classified as both a toxic substance at high concentrations and a human carcinogen (MAK Collection 2012, ATSDR 2021). In addition to the Kharasch reactor production,

Chinese manufacturers primarily use catalytic reactors to produce HFO with total yield ranging from 30% to 85% (Wang et al. 2017). Most CTC and anhydrous HCl produced from HFO production are recycled when possible and can be resold for use in the production of other chemicals, such as ethylene dichloride and methyl chloride (Sherry et al. 2017).

Table 6.1. Feedstocks used in the production of fluorochemical refrigerants.

Feedstock	Chemical Formula	Total Lifetime (years, unless otherwise indicated)	Radiative Efficiency (W/m2/ppb)[g]	20-GWP Year (kgCO2e/kg GHG)	100-GWP Year (kgCO2e/kg GHG)	ODP	Fluorochemical Production
Methylene chloride	CH_2Cl_2	0.9	0.004	16	43	0.015	HCF-32
Chloroform	$CHCl_3$	149 days	0.07	66	18	NR	HCFC-22, HFC-125
Carbon tetrachloride	CCl_4	26	0.174	3,790	2,110	0.89	CFC-11, CFC-12, HFC-245fa
Trichloroethene	C_2HCl_3	4.9 days	5.74E-03	<1	<1	<0.004	HFC-134a
Perchloroethene	C_2Cl_4	90 days	0.053	21.7	5.9	NR	HFC-134a, HFC-125, CFC-113, CFC-113a
1,2-dichloroethane	$C_2H_4Cl_2$	65 days	0.01	5.1	1.4	NR	1,1,1-Trichloroethane
Methyl chloroform	$C_2H_3Cl_3$	5	0.07	555	153	0.14-0.17	HCFC-141b, HCFC-142b, HFC-143a
HCFC-22	$CHClF_2$	11.9	0.21	5,310	1,780	0.024-0.034	Polytetrafluoroethylene (PTFE) or Teflon®
HCFC-142b	$C_2H_3ClF_2$	18	0.19	5,140	2,070	0.023-0.057	Vinylidene difluoride

Sources: (USEPA 1976, OECD 1994, Federal Register 2023c) (Trichloroethylene TCE Federal Register 2023; EPA Ethylene Dichloride 1976; OECD No 1001 1994; Claxton et al., 2019; US EPA 2022 Ozone-depleting substances; UNEP 2023 New ozone-depleting substances; Hodnebrog AGU et al. 2020; NCBI 2023-1,2-Dichloroethane; ECB-Tetrachloroethyelene 2005; Trichloroethylene Federal Register 2017; EPA 1989; Khalil and Rasmussen 1999; IPCC Working Group I 2007).
NR: not reported.

6.2 ESTIMATES OF EMISSIONS FROM SOURCES AND PRODUCTION

Direct venting of refrigerant feedstock chemicals into the atmosphere is prohibited, and ozone-depleting refrigerants cannot be sold directly to consumers for emissive units (SCHF 2017). Many of these precursors are recycled; however, small amounts can be released through fugitive emissions or through effluent water from refrigerant production facilities (Federal Register 2011, SPARC 2016, Behringer et al. 2021). Although heavily regulated, HFO production still use substances such as HCFCs that have the potential to deplete the ozone layer and contribute to global warming. Fugitive emissions can occur, and evidence suggests that significant emissions are unaccounted for—specifically those of CTC (SPARC 2016). Table 6.2 shows the fugitive emissions of major feedstocks used in refrigerant production. In annual reports submitted to the United Nations Environment Programme (UNEP) under Article 7 of the Montreal Protocol, estimated emissions of CTC ranged from 0 to 8 Gg per year. Further analysis by the Stratosphere-Troposphere Processes and their Role in Climate project and Sherry et al. suggest CTC emissions range from as high as 35 Gg per year to 15–25 Gg per year, respectively (SPARC 2016, Sherry et al. 2018). Possible sources include legacy emissions from landfills and chlorine production, unreported non-feedstock CTC emissions, and fugitive emissions during the production of chemicals such as perchloroethylene, HFCs, methyl chloride, and divinyl acid chloride (Sherry et al. 2018). Owing to strict regulations created by the Montreal Protocol, Sherry et al. estimated current fugitive CTC emissions from HFC plants at ~0.2 Gg per year (Sherry et al. 2018).

Table 6.2. Feedstock emissions of commonly used refrigerant precursors, collected from the EPA Toxic Release Inventory (TRI) (USEPA 2023e). Fugitive emissions were self-reported from refrigerant manufacturing facilities. Emissions were calculated by taking the sum of reported emissions from nonpoint air emissions and point air emissions as reported on TRI chemical form R.

Feedstock	Fugitive Emissions in Tons
HCFC-22	267.07
HCFC-124	41.1
HCFC-123	23.66
HCFC-23	9.13
CFC-113	6.95
Carbon tetrachloride	3.03
HCFC-124a	1.76
HCFC-253fb	1.1

The EPA's Toxic Release Inventory is the culmination of self-reported data by chemical manufacturing facilities across the country. Data in the assessment cover the period of January 1 to December 31 of the prior year. For these data sheets, chemical amounts are reported for processing, recycling, release into the environment, and transfer to other facilities. When reviewing data for chemical refrigerant manufacturing, fugitive emissions were counted only for the facility producing the refrigerant chemicals. At some production sites, thousands of pounds of materials were transferred off site for disposal, which may entail fugitive releases of the chemical into the atmosphere. Owing to these reporting difficulties, the tonnage of chemical precursors or feedstocks released into the environment from Table 6.2 can be considered a conservative estimate. However, current fugitive emissions of these chemicals can be considered minimal from US refrigerant manufacturers, which emphasizes the success of the Montreal Protocol and its related regulations (US EPA 2023 TRI program). Exceptions to this are chemicals such as chlorodifluoromethane (R-22), CTC, and fluoroform (R-23) commonly used in chloro-chemical and fluoropolymer manufacturing. The relative importance of chloro-chemical and fluoropolymer manufacturing in contributing to the rising levels of R-22 and R-23 in the environment is unknown (ECHA 2008, Fu et al. 2021). Further monitoring and regulations should be put in place to better understand how some of these

chemical precursors are being used in the fluorochemical and pesticide industries and what steps industry is taking to minimize their release into the environment.

7. DEGRADATION PRODUCTS OF REFRIGERANTS

Among the greatest uncertainties associated with the environmental effects of refrigerants are the persistence, bioaccumulation, and toxicity of their degradation products. The reaction of HFOs and HFCs with hydroxyl (OH) radicals in the atmosphere yields degradation products of varying persistence and toxicity. HFOs are environmentally friendly in part because their carbon double bond is highly reactive with OH radicals, leading to their short atmospheric lifetimes and low GWP. However, because these compounds degrade quickly, they have the potential to create significant yields of varying degradation products. One of the most well-known degradation products, particularly from HFCs and HFOs, is TFA. Its classification as an ultra-short PFAS is under considerable debate, which has policy implications because both the European Commission and the EPA have signaled commitments to systematically decrease the use of PFAS compounds (Glüge et al. 2020). Regardless of how it is classified, TFA is generally regarded as persistent; and therefore, continued monitoring due to uncertainties in dispersion/deposition and potential effects in marine organisms is advised.

In this section, we review the current understanding of TFA formation, yields, and environmental impacts, as well as other potential degradation products of refrigerants.

7.1 TFA

7.1.1 Sources

It is recognized that TFA can be produced by the photooxidation of HFOs and HFCs in the atmosphere. Other potential sources of TFA are the manufacture of fluorinated chemicals, geogenic sources, biodegradation of pharmaceuticals, and combustion of fluorinated chemicals in household waste. Still, significant uncertainty and controversy surround these other sources, which deserve further investigation. Because HFO use is projected to increase in the coming years, the concentrations of TFA and other degradation products can potentially increase, highlighting the critical need to quantify potential sources. However, this report will focus only on anthropogenic sources of TFA, primarily the atmospheric transformation of TFA.

7.1.1.1 Photooxidation of HFOs

Because of their double bonds, HFO and HFC refrigerants can react with atmospheric OH radicals to form TFA. R-1234yf has been the focus of many studies owing to its high theoretical yield (100% TFA), but other HFOs can also produce TFA (Figure 7.1). In the case of R-1234yf, the reaction starts by the OH addition at either Carbon 1/ C_1 (right branch) or C_2 (left branch). The highly reactive alkyl radicals immediately react with O_2 to produce peroxyradicals. RO_2 molecules react with NO, and the subsequent thermal degradation forms the $CF_3C(O)F$. Hydrolysis of such compounds ultimately forms TFA.

Another refrigerant shown to generate significant amounts of TFA is R-134a (Figure 7.1). Unlike with R-1234yf, the oxidation of R-134a proceeds by hydrogen abstraction. The addition of O_2 at the C_1 position generates the peroxyradical, which ultimately forms the $CF_3C(O)F$ upon a reaction with NO. Hydrolysis of the $CF_3C(O)F$ leads to the formation of TFA. The TFA formation rate from HFC-134a is much slower compared with that of R-1234yf when accounting for the slower initiation process (i.e., hydrogen abstraction) and steric hindrance, which ultimately affects the TFA yield.

Also shown in Figure 7.1 is the oxidation of R-1233zd(E). Unlike with R-1234yf and HFC-134a, the oxidation of HCFO-1233zd(E) generates trifluoroacetaldehyde instead of TFA. CH_3CHO is known to photolyze in the atmosphere, forming products such as CF_3, CHF_3, and CO (Calvert 2011). The formation of fluoroform or CHF_3 from the refrigerants has serious atmospheric implications owing to the high GWP (14,800) and a lifetime of 270 years calculated for CHF_3. However, a recent chamber study with Fourier-transform infrared spectroscopy as a detector showed the absence of CHF_3 during the photolysis of CF_3CHO (Sulbaek Andersen and Nielsen 2022).

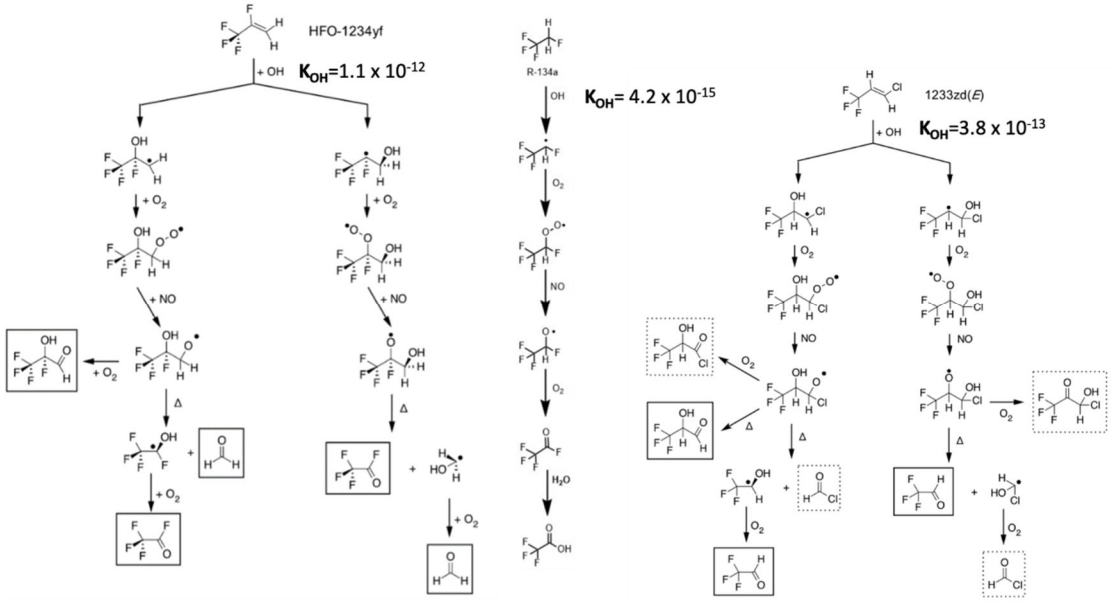

Figure 7.1. Daytime oxidation mechanism of R-1234yf, R-134a, and R-1233zd(E). OH radical reaction rates are given in units of cm^3 $molecule^{-1}$ s^{-1}. Chemical mechanisms of R-1234yf and R-1233zd(E) were adapted from: J. B. Burkholder, R. A. Cox and A. R. Ravishankara, *Chemical Reviews*, 2015, 115, 3704–3759 (Burkholder et al. 2015).

7.1.1.2 Manufacture and remediation of fluorinated chemicals

In the chemical industry, TFA is used as an organic solvent and acid catalyst for organic synthesis and as an intermediate reagent for the preparation of pharmaceutical and agrochemical compounds (López and Salazar 2013, Freeling and Björnsdotter 2023). Some pesticides and prescription drugs containing the C-CF3 moiety have been reported to also contribute to TFA formation in surface waters (Scheurer et al. 2017, Tisler et al. 2019, Freeling and Björnsdotter 2023).

More recently, remediation technologies are being developed for removing fluorinated organic chemicals, including PFAS, from the environment. However, some of these removal processes can cause fluorinated chemicals to decompose and release TFA as a byproduct of the remediation process (Qu et al. 2016, Sun et al. 2020). For example, photolysis of PFCA decomposed into TFA and fluorine ions (Qu et al. 2016). Similarly, the degradation of PFCA with C5 and C4 via sulfate radical oxidation resulted in 10% and 30% yields of TFA, respectively (Lutze et al. 2018). Much lower yield ranges (0.3%–1.2%) were reported from the thermolysis of fluoropolymer compounds at 500°C and above (Cui et al. 2019). Furthermore, biodegradation in a simulated landfill soil system revealed that 4:2 fluorotelomer alcohol and 2-(trifluoromethyl)acrylic acid could be degraded in aerobic microbial conditions to form TFA (7.8 mol%) and TFA (6.3 mol%), respectively (Sun et al. 2020). Considering the diversity of TFA formation routes and contributions to the environment, more research is needed to identify and quantify other unknown TFA sources.

7.1.2 TFA Yield

An important knowledge gap regarding TFA formation is the uncertainty of the theoretical molar yields from the oxidation of refrigerants, both in daytime and nighttime. A recent assessment report (UNEP EEAP 2022) provides the estimated molar yield for several refrigerants (Figure 7.2). Molar yields were calculated based on their theoretical reaction with OH radical and the subsequent interaction with RO_2 and NO. However, the uncertainty can reach as much as 90%, which reduces the degree of confidence on the production of TFA from the degradation of refrigerants (see Figure 7.2). The various proposed reaction mechanisms of the formation of the degradation products adds to the wide range of the yields presented. This merits the need for an empirical and uniform measurement that can calculate TFA yields from daytime and nighttime oxidation of refrigerants. Accurate yield information will provide a more reliable global concentration of TFA, which will enhance the proper apportionment of possible anthropogenic and biogenic sources.

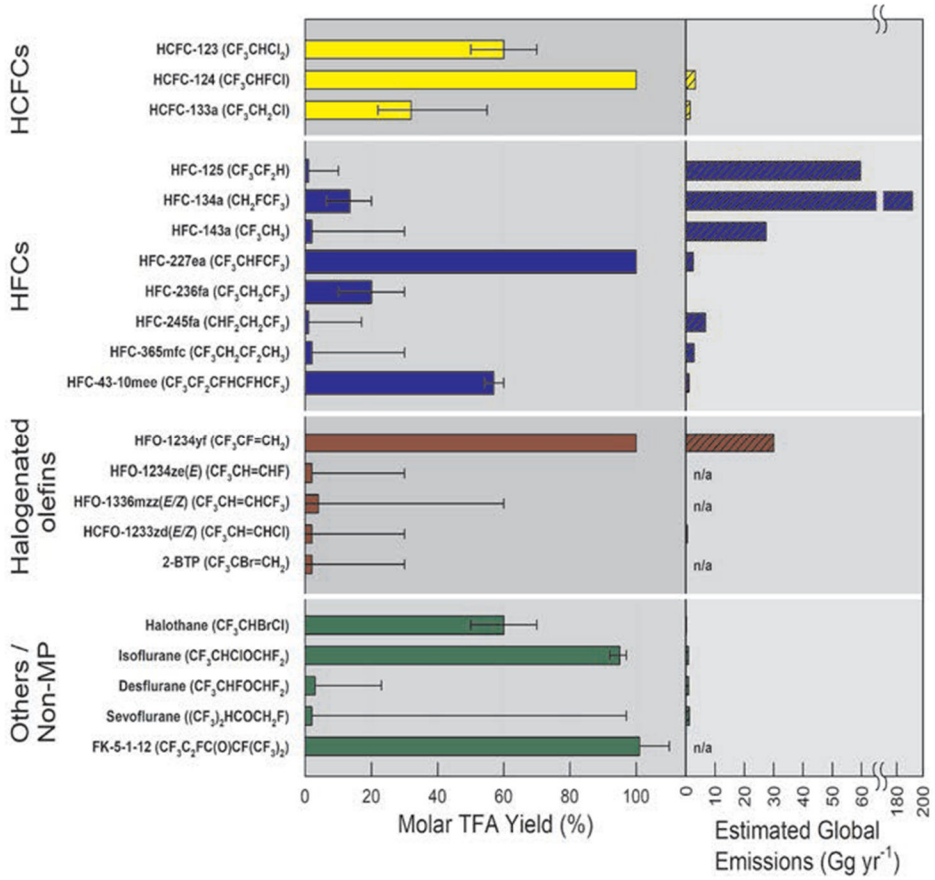

Figure 7.2. Calculated molar TFA yields from the atmospheric degradation of refrigerants. Adapted from: Environmental effects of stratospheric ozone depletion, UV radiation, and interactions with climate change (UNEP EEAP 2022).

7.1.3 Atmospheric Measurement and Modeling of TFA

7.1.3.1 Measurement of TFA in the atmosphere

Few studies have reported the direct measurement of TFA in the atmosphere. Recent data regarding local and regional atmospheric concentration and associated deposition fluxes of TFA, which are the basis of global 3D models, are limited owing to low ambient concentrations of TFA and the intrinsic

instrumentation needed. Surveys of the research literature revealed only three TFA measurements, all implemented in China. The method of collection of TFA in both gas and particle phases was based on the technique developed by Martin et al. (2003). Briefly, annular denuders were used to absorb gas-phase TFA. The internal walls of the denuders were coated by a water/methanol solution containing Na_2CO_3 and glycerol. Before sampling, pretreatment of the denuders was implemented by rinsing them with double-distilled water, acetone, and hexane. Particle-bound TFAs were collected using quartz filters that are baked at 450°C for 6 hours before sampling. The sampling period typically lasts for 48 hours, but shorter collection times (i.e., 4 hours) were also employed to evaluate diurnal variation. After the collection, TFA was extracted through successive additions of double-distilled water and subsequently was introduced to either gas chromatography – mass spectrometry or liquid chromatography with tandem mass spectrometry. TFA is typically derived using 2,4-DFAn and DCC to generate acid anilide. In a measurement at the top of a six story university building in Beijing, the average concentrations of TFA in gas and particle phases were 1,330 pg/m^3 and 245 pg/m^3, respectively. This suggests that TFA favors partitioning in the gas phase instead of in the particle phase, which is driven by TFA's volatility. Short-term measurement of TFA (~4 hours) revealed a consistent noon-time peak, highlighting the dominant photochemical/secondary source of TFA in the atmosphere. The same research group implemented a box-model simulation to account for the source of TFA, and the results indicated that only 6%–33% of total deposition flux can be attributed to HFC-134a. This underscores the contribution of other sources (Wu et al. 2014). A follow-up study, which investigated the dynamic and thermodynamic adsorption of TFA to aerosols in the same university building, reported similar concentrations of TFA in both gas (1,396 pg/m^{-3}) and particle (62 pg/m^{-3}) phases (Guo et al. 2017).

The atmospheric distribution of TFA was also experimentally evaluated in an industrial area in Jinan, China, where fluorochemicals such as TFA are developed and manufactured. A similar annular/filter pack system was used to collect ambient TFA. After a 7 day collection, TFA concentrations in gas and particle phases were 4,106 pg m^{-3} and 145 pg m^{-3}, respectively; these values were at least twice as high as those of collections in the university building. Daytime TFA concentrations well exceeded the nighttime measurements, emphasizing the dominant photochemical source of TFA in the industrial area (Xie et al. 2020)

The tedious collection and extraction of atmospheric TFA concentration pose a limitation for the in-depth apportionment of the source of TFA. A fast, reliable, chemical-free measurement is necessary to account for the variation of TFA in the atmosphere. One suggestion is to exploit the capabilities of a proton transfer reaction time-of-flight mass spectrometer (PTR-ToF-MS), an extremely sensitive and real-time analyzer of organic compounds in gas and particle phases. The Department of Energy's Oak Ridge National Laboratory owns two PTR-ToF-MS 6000X2 units, which have a detection limit and sensitivity of less than 1 pptv and 2,000 cps/ppbv, respectively. Each unit has a mass resolution of 6,000 and therefore can easily separate ions with the same nominal mass. A PTR-ToF-MS requires no toxic compounds such as methanol during its operation. The only requirement of PTR-ToF-MS is that the target analyte should have a proton affinity higher than that of water (699 kcal/mol); TFA's proton affinity is 711.7 kJ/mol. Moreover, PTR-ToF-MS is a portable instrument, thus it can be deployed in regions where TFA's presence is expected.

7.1.3.2 Modeling of TFA production, loss, and dispersion

Several models are used to assess TFA production, loss, and dispersion. One such model, **STOCHEM-CRI**, is a global 3D chemistry transport model that divides the whole troposphere into 50,000 constant mass air parcels (Khan et al. 2015, Holland et al. 2021). With such parametrization, the transport and chemistry can be easily uncoupled to understand overall variability of the precursors and products in the atmosphere. The meteorological data used to inform this model (e.g., pressure, temperature, humidity, precipitation, and surface parameters) come from the UK Meteorological Office. The global emission

inventories for the TFA precursor are based on anthropogenic sources listed in the Emissions Database for Global Atmospheric Research and on emission sources of other species from the Precursor of Ozone and their Effects in the Troposphere inventory. The production and loss pathways of TFA from R-1234yf are shown in Figure 7.3 (Kazil et al. 2014a, David et al. 2021, Holland et al. 2021).

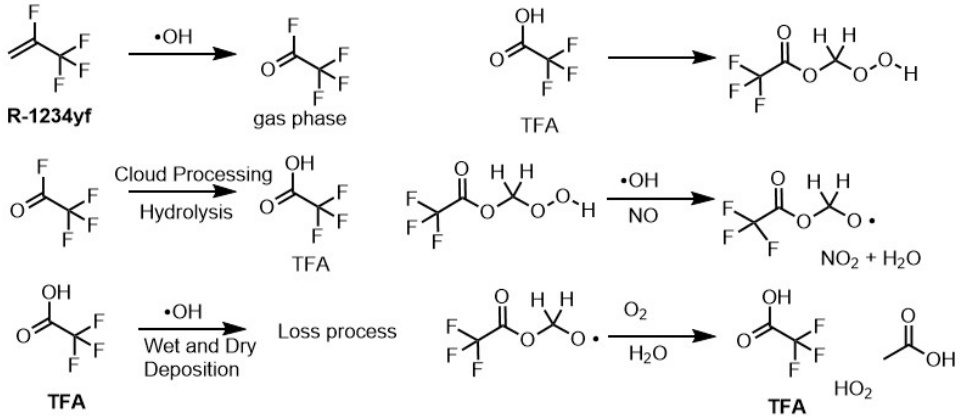

Figure 7.3. TFA production and loss mechanisms were added to the CRI mechanism of the STOCHEM-CRI model. Initial OH attack rates are 7.3×10^{-13} exp(−1540/T) and 1.26×10^{-12} exp(−35/T) cm^3 s^{-1} for R-134a and R-1234yf (DeMore 1993, Papadimitriou et al. 2008). The yield rates of TFA from the two refrigerants are 0.21 and 1.0, on the assumption that the hydrolysis of $CF_3C(O)F$ generates 100% TFA. The typical TFA loss pathways are subsequent OH attack and deposition (dry and wet) processes. Among these processes, the TFA lifetime is primarily influenced by wet deposition, which reduces the lifetime to 9 days, compared with 4 months from a reaction with OH radicals. In the prior study (Holland et al. 2021), succeeding reactions to stabilized forms of intermediates (Stabilized Criegee intermediates; SCI) such as CH_2OO further reduce the TFA lifetime by 5 days, particularly in forested regions with high SCI production from biogenic alkene oxidations (Holland et al. 2021).

The Goddard Earth Observing System with Chemistry (GEOS-Chem) and Weather Research and Forecast with Chemistry (WRF-Chem) were also used to account for the regional dispersion of TFA (David et al. 2021). GEOS-Chem is a global 3D model of atmospheric chemistry that employs the GEOS data from the NASA Global Modeling and Assimilation Office (Henze et al. 2007). The simulation using GEOS-Chem in India, China, and the Middle East (Figure 7.4) was performed with 2∘ × 2.5∘ resolution and 47 vertical levels with Model of Emissions of Gases and Aerosols from Nature (MEGAN) and Global Fire Emissions Database (GFED) as the basis of biogenic volatile organic carbon and biomass-burning emissions.

GEOS-Chem, particularly the wet deposition process, was validated by comparing observed sulfate rainwater concentrations from 2000 to 2015. The model consistently underestimated sulfate by 13% in India and China because of the wider area integration of the GEOS-Chem compared with the narrow point analysis of ground-based measurements. With at least two factor differences, the GEOS-Chem was deemed appropriate to assess TFA wet deposition analysis.

GEOS-Chem and WRF-Chem calculations showed atmospheric TFA concentration ranging between 1.82 and 3.94 ppt in India, China, and the Middle East (Figure 7.4). The TFA values presented here are based on future emissions of R-1234yf scenarios for the period of 2020 to 2040. The main assumption is that, according to the authors, TFA production is directly related to the increase of R-1234yf. Concentrations of OH radicals, the initiator of the oxidation, are also expected not to change (David et al. 2021).

Figure 7.6 shows the surface distribution of TFA generated from R-134a and R-1234yf. The plot assumes the total replacement of use of R-134a to R-1234yf. The shift to R-1234yf substantially enhanced the TFA emission, with a maximum 250-fold enhancement across Europe based on the STOCHEM-CRI

model (Holland et al. 2021). Globally, the complete transition led to a 33-fold increase, which is equivalent to 2,150 tonnes of TFA.

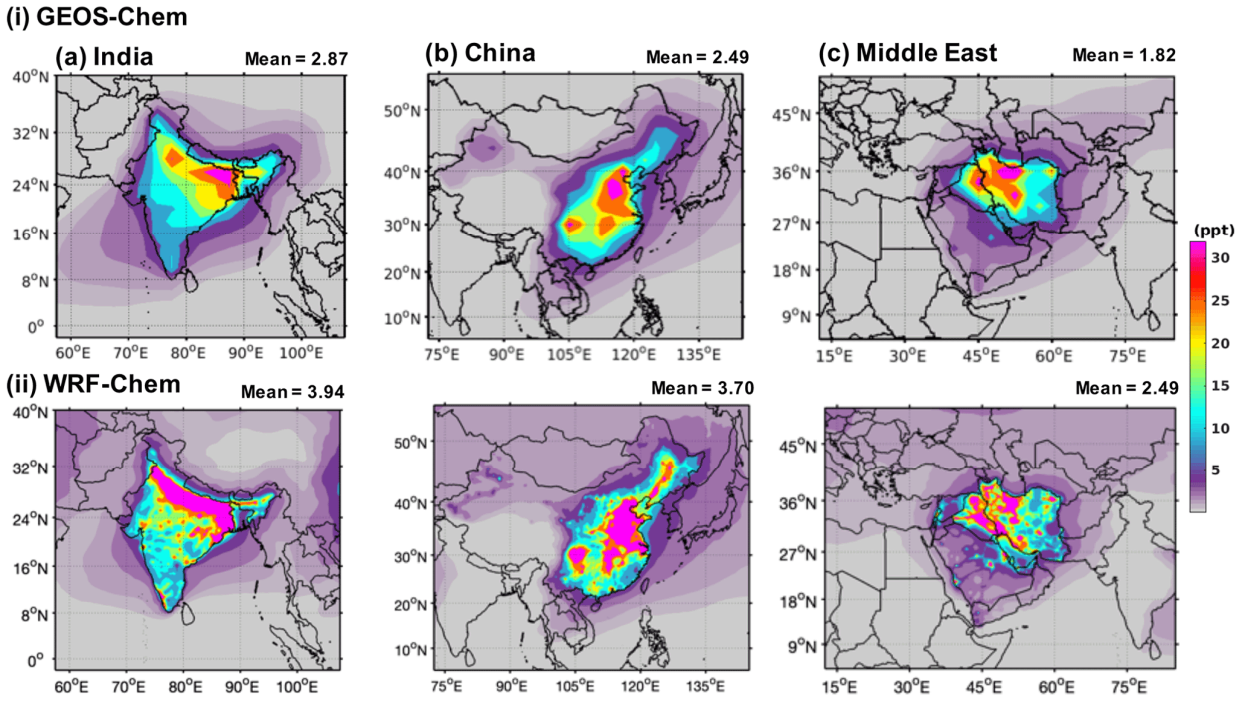

Figure 7.4. Yearly projected mixing ratios (2020–2040) of the TFA from R-1234yf from India, China, and Middle East emissions, calculated using GEOS-Chem (top) and WRF-Chem (bottom). Adapted from: L. M. David, M. Barth, L. Höglund-Isaksson, P. Purohit, G. J. M. Velders, S. Glaser and A. R. Ravishankara, Atmos. *Chem. Phys.*, 2021, 21, 14833–14849 (David et al. 2021).

Refrigerants such as HFCs, owing to their longer atmospheric lifespan, are expected to mix more thoroughly in the atmosphere compared with their HFO counterparts (UNEP 2022). As such, the degradation products of HFC refrigerants are expected to be deposited globally, and subsequent degradation products are likely being deposited in both the Arctic and Antarctic owing to their longer atmospheric lifespans.

Furthermore, degradation products from HFO refrigerants are expected to be more localized because of their atmospheric lifespans, ranging in days, compared with the multiyear lifespans of HFC refrigerants (David et al. 2021, UNEP 2022a). Estimates of overall refrigerant emissions and subsequent degradation products, and the accuracy of such data, vary across regions and the countries focused on for relative models. Depending on the geographic location of emissions, HFO refrigerants' degradation products could still be transported thousands of kilometers before being deposited through precipitation or dry deposition (Russell et al. 2012). For instance, a 3D chemical transport model indicated that TFA from the oxidation of R-1234yf could be deposited outside the source or domain region, even with the short lifetime of R-1234yf (~5–10 days) (David et al. 2021). Figure 7.5 shows that a maximum of ~50% of the TFA is deposited within the domain, much less on the land area indicated in the study. Identification of the exact location outside the domain and quantification of the degree of deposition were difficult owing to diminishing concentrations outside the source domain. Nevertheless, a sizable portion of the TFA could travel thousands of kilometers even if R-1234yf were short lived. Even with the addition of an ozone sink pathway of TFA through the formation of a Criegee intermediate (Holland et al. 2021), transport of TFA is still expected with some dispersion in the ocean (Figure 7.6).

Similar to other PFCAs, TFA is characterized by extreme resistance to environmental degradation, thus accumulation has been observed in several locations, such as sludge from wastewater (Fredriksson et al. 2022), seasonal wetlands (Cahill et al. 2001), and oceans (Solomon et al. 2016). Studies also showed the presence of TFA in drinking water (Neuwald et al. 2022), beer, and tea (Scheurer and Nödler 2021).

The simulated concentration of TFA in China, shown in Figure 7.4 (David et al. 2021), corresponded well with direct experimental measurement of TFA in two different sites (Wu et al. 2014; Guo et al. 2017; Xie et al. 2020). This highlights the exceptional capacity of the models to simulate and project atmospheric TFA concentrations.

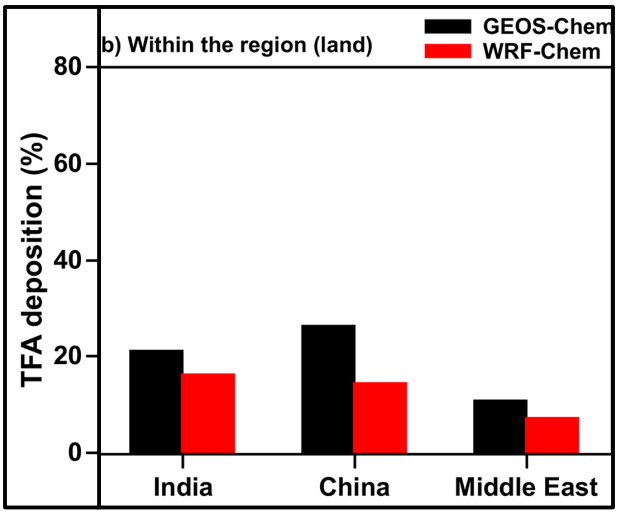

Figure 7.5. Yearly TFA deposition calculated within the domains and source regions of India, China, and the Middle East. Adapted and modified from: L. M. David, M. Barth, L. Höglund-Isaksson, P. Purohit, G. J. M. Velders, S. Glaser, and A. R. Ravishankara, *Atmos. Chem. Phys.*, 2021, 21, 14833–14849 (David et al., 2021).

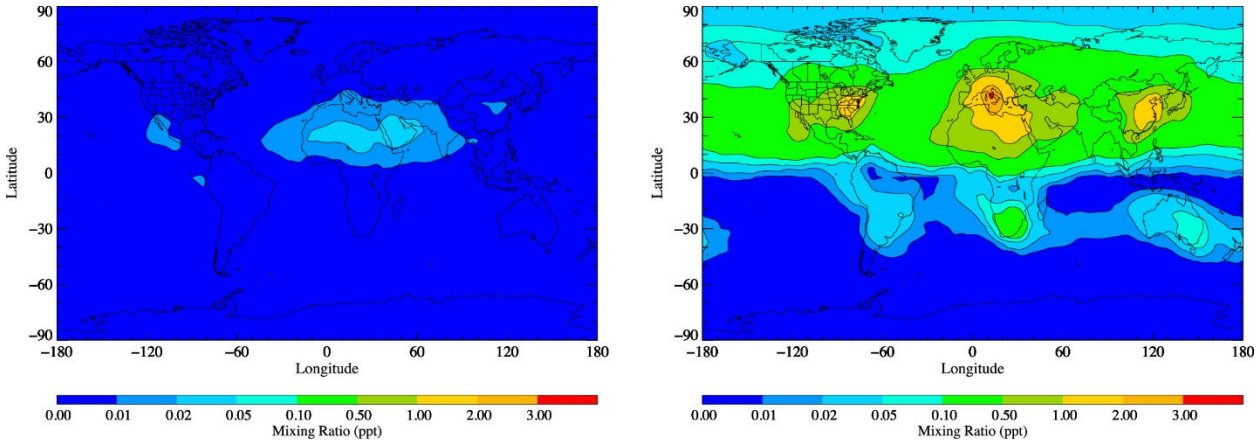

Figure 7.6. Modeled TFA global concentration in parts per trillion (ppt) from the OH oxidation of (left) HFC-134a and (right) R-1234yf. Plots adapted from: R. Holland, M. A. H. Khan, I. Driscoll, R. Chhantyal-Pun, R. G. Derwent, C. A. Taatjes, A. J. Orr-Ewing, C. J. Percival and D. E. Shallcross, *ACS Earth and Space Chemistry*, 2021, 5, 849–857 (Holland et al. 2021).

7.1.4 TFA in the Environment

TFA enters aquatic ecosystems through deposition and transport by rain to the surface water (Kazil et al. 2014b, Holland et al. 2021) as a salt that dissociates in water to its anionic state (trifluoroacetate)

(Garavagno et al. 2024). Because TFA is a strong acid, there have been concerns about its effects on acid rain formation. Currently, the atmospheric formation of TFA from refrigerant degradation is not considered to be a significant contributor (<0.5%) to acid rain (Solomon et al. 2016, Lindley et al. 2019, UNEP 2022a). However, as the replacement of R-134a for R-1234yf continues, a higher cumulative contribution of refrigerant degradation to TFA formation is expected, with projected global yields of 30.5–49.0 Tg by 2100, potentially leading to unintended future consequences in the atmosphere (UNEP 2022a, WMO 2022). For example, TFA rainwater concentrations ranging from 0.89 to 7.8 µg/L have been estimated for the western US from predicted R-134a and R-1234yf emissions (Kazil et al. 2014b). Reported TFA concentrations in aqueous phases and aquatic ecosystems include fog and rain in California (31–3,779 ng/L); rain and snow in Switzerland (3–1,550 ng/L); rainwater in two cities in Japan (29–76 ng/L) and in the Pearl River Delta in China (46–974 ng/L); and rainwater in Chile (6–87 ng/L), Malawi (4–15 ng/L), and Canada (<0.5–350 ng/L) (Wujcik et al. 1998, Boutonnet et al. 1999, Berg et al. 2000, Scott et al. 2005, Taniyasu et al. 2008, Wang et al. 2014).

TFA and its salts are highly soluble in water (log K_{ow}=−2.1), and they can persist in the environment because TFA has no known degradation pathways in water (Boutonnet et al. 1999, Solomon et al. 2016). In aquatic ecosystems, the highest TFA concentrations have been reported in saline lakes such as Utah's Great Salt Lake (50−270 g/L), ocean waters (≈ 200 ng/L), and the Dead Sea (6,400 ng/L) (Boutonnet et al. 1999, Solomon et al. 2016). It is important to mention that ecosystems such as the Great Salt Lake in Utah and playas have high background concentrations of TFA salts within their waters, but TFA in freshwater might be considered of anthropogenic origin (Solomon et al. 2016, Behringer et al. 2021, WMO 2022). Municipal wastewater treatment plants (WWTPs) also represent primary and secondary point sources of TFA for the aquatic ecosystem. Detectable levels of TFA in WWTP facilities are associated with TFA-contaminated effluents from industrial sites (e.g., fluorochemical production) because TFA cannot be removed by traditional water treatment processes (Zhou et al. 2022), photodegradation mechanisms (Qu et al. 2016), or microbial communities (Benesch et al. 2002). The presence of TFA-forming substances in municipal WWTPs' influents might also contribute to the detectable levels of TFA in these facilities (Scheurer et al. 2017, Tisler et al. 2019). Municipal and industrial landfills can also become a source of TFA through leachate derived from solid wastes. Levels of TFA up to 6.9 µg/L in landfill leachate were reported as part of an assessment of ultra-short-chain perfluoroalkyl acids (PFAAs) in Swedish landfills (Björnsdotter et al. 2019). Dry deposition and contaminated soils can also contribute to the levels of TFA in the environment. For example, TFA was present in Chinese farmland soils (0.25–21.5 ng/g dw) and accounted for the majority of total PFASs (19.6–95.3%) detected in the soils (Lan et al. 2020). These concentrations were associated with dust samples also collected on site and containing TFA at detectable levels (21.4–348 ng/g dw) (Lan et al. 2020).

TFA was detected at concentrations between 28 and 190 ng/g in pine needles from North America (Scott et al. 2005). The authors of this study suggested that urban-related locations in the mountain valleys where samples were collected may be the source of TFA (Scott et al. 2005). In a later study assessing occurrence and phase distribution of 23 long- and short-PFASs around landfills in China, TFA was detected in air samples with concentrations ranging from 1.4 to 3.0 ng/m^3, which was reported to contribute to 80% of all PFCAs detected (Tian et al. 2018). In the same study, TFA was also present in the leaves of local plant species in concentrations between 0.56 and 3.0 µg/g dw, contributing to over 86% of all PFCAs quantified (Tian et al. 2018). Here, the authors concluded that landfills not only act as sources of PFASs, including short-chain PFASs such as TFA, but they can also contribute to the airborne contamination and dry deposition of these compounds (Tian et al. 2018). TFA was also quantified in poplar leaves (767 ng/g dw), maize leaves (767 ng/g dw), maize straw (11.8–149 ng/g), and kernels (15.8–102 ng/g dw) cultivated in soils from different geographic sites (e.g., farmland, forest soils, and urban centers) in China (Lan et al. 2020). The authors indicated that in some of the soils, TFA represented

19.6%–95.3% of the total PFASs with at least two carbon atoms, and TFA levels tended to decrease from the coast to the inland area (Lan et al. 2020).

7.1.5 Environmental Effects of TFA

7.1.5.1 Ecotoxicity

The ecotoxicity of TFA has been studied in aquatic and terrestrial systems using a range of organisms. For example, *Daphnia magna* acute effects and potential for bioaccumulation from exposure to sodium TFA and its deprotonated trifluoroacetate anion have been investigated in laboratory and field studies. In the case of aquatic organisms, the median toxic dose or effective concentration (EC50) of zebrafish (*Danio rerio*) and *Daphnia magna* was estimated to be greater than 1,200 mg/L for both species (Boutonnet et al. 1999). Overall, TFA LC50/EC50 concentrations are high, indicating that the TFA concentrations would have to reach 10–10,000 mg/L in water (Berends et al. 1999, Boutonnet et al. 1999, Hanson and Solomon 2004, Garavagno et al. 2024) for effects to occur. The most sensitive aquatic organism studied is an algal species with an EC50 of 4.8 mg/L (Berends et al. 1999, Boutonnet et al. 1999). As described in the previous section, studies that have measured concentrations of TFA in water find high parts per thousand to low parts per billion concentrations in natural waters, indicating that TFA at present in aquatic systems likely does not pose an ecological risk, based on organisms studied so far. For terrestrial species, the lowest concentration at which effects were seen was 10 mg/L, which reduced growth of common bean and corn plants (Smit et al. 2009), and 6.74 µL/kg in soil, which impacted soybean-microbial interactions (Oehrle et al. 2004). Overall, concentrations at which adverse effects are observed are likely orders of magnitude greater than those of average environmental concentrations of TFA. However, some measurements of TFA in natural systems find higher concentrations (Boutonnet et al. 1999, Solomon et al. 2016), closer to values shown to have adverse effects and concentrations that are predicted to increase. Further, data gaps are present, such as measuring the effect of TFA on marine organisms other than algae, especially filter feeders.

The potential toxicity of TFA has also been reported for aquatic primary producers such as algae and macrophytes. The most sensitive algal species, *Selenastrum capricornutum*, had an EC50 between 1.5 and 4.8 mg/L (Boutonnet et al. 1999). Higher EC50s in the range of 1,200–2,400 mg/L were estimated for other freshwater algae (Boutonnet et al. 1999, Garavagno et al. 2024). For one species of macrophyte (duckweed), a LOEC of 600 mg/L was reported, whereas an EC50 for a second species was predicted to be within 222.1–10,000 mg/L (Hanson and Solomon 2004).

Adverse effects from exposure to TFA have also been reported in some plant species. For example, a LOEL of 10 mg/L for growth reduction was observed for both common bean and corn plants exposed to an experimental water-culture system with NaTFA (Smit et al. 2009). TFA inhibited the photosynthetic electron transport and limited gas exchange in plants (Smit et al. 2009). Another study, assessing the effects of TFA on soil microbial communities and four wetland plant species, reported that microbial soil respiration was not affected by TFA concentrations up to 10 mg/L (Benesch et al. 2002). In the same study, the authors reported no effects on plant health or photosynthetic mechanisms or germination success of plant seeds exposed up to 1 mg/L of TFA, but TFA accumulation in seeds (0.017 mg/L) and foliar tissue (0.248–0.295 mg/L) was observed in the wetland plant species exposed up to 1 mg/L of TFA for 3 months (Benesch et al. 2002). In a later study, the potential effects of TFA on the symbiosis between a bacterium and soybean were investigated in an experimental setting. The results indicated that soybean seedling development was delayed at TFA levels of 6.74 µL/kg in soil and 0.031 µL/L in nutrient solution (Oehrle et al. 2004).

7.1.5.2 Bioaccumulation

Because TFA and its alkali salts are completely water soluble, TFA is not expected to bioaccumulate in organisms except for terrestrial plants and is unlikely to biomagnify through food webs owing to its structure (UNEP 2022a, Xu et al. 2022). TFA has been found to bioaccumulate in plants from contaminated soil (Boutonnet et al. 1999, Benesch et al. 2002, Scott et al. 2005, Tian et al. 2018, Zhang et al. 2019), and one study of potential trophic transfer from plant leaves to herbivorous insects found that the concentration of TFA was actually *lower* in the insects compared with the plant leaves (Lan et al. 2020).

Even though TFA accumulation reported in these studies is low compared with concentrations that have been found to cause negative effects in lab exposures, more studies are needed to better understand the uptake mechanisms of TFA by plants, especially for those that showed some indication of adverse effects. Further, wetland plants may be at higher risk for TFA accumulation as they grow in water or where soils are flooded or saturated, although the EC50 for TFA exposure to duckweed, an aquatic plant, was 1,100 mg/L (Berends et al. 1999). Compared with longer-chain PFAS, short-chain PFAS are less bioaccumulative but have high persistence and aquatic mobility (Hale et al. 2020), which in turn can increase the uptake rate in aquatic plants owing to long-term exposure. This also raises concerns about accumulation of TFA by aquatic organisms, especially marine organisms, because higher concentrations of TFA have been measured in oceans. Filter feeding organisms, such as bivalves or even large marine mammals, may accumulate high concentrations of TFA owing to the filtration of large volumes of water, even if the aqueous concentration of TFA is relatively low. Bioaccumulation and biomagnification of TFA in marine organisms have not been investigated to our knowledge, and measurement of TFA concentrations across marine food chains is crucial to assess the environmental impact of TFA in marine ecosystems.

Last, TFA concentrations are expected to increase in the future because of the increasing use of fluorinated refrigerants such as R-1234yf and other sources. Studies have already found increasing concentrations of TFA in plants; for example, TFA concentrations in leaves increased by a factor of 5 between 1990 and 2020, up to ~1 mg/kg dry weight (Freeling et al. 2022). TFA concentrations are predicted to continue to increase in the environment owing to degradation of fluorinated refrigerants and other TFA sources, such as pesticides and pharmaceuticals containing CF3 groups (Scheurer et al. 2017, Brunn et al. 2023), so more research on the long-term effects, persistence, and bioaccumulation of TFA is needed to stay ahead of potential ecological effects.

7.1.5.3 TFA and human exposure

Outside of occupational accidents during the production of pesticides, pharmaceuticals, or organics intermediates, TFA is unlikely to induce direct health effects from environmental exposures because it likely will be diluted by the time of exposure (Dekant and Dekant 2023). In a study, TFA levels in serum remained elevated in half of the volunteers after 6 days, whereas maximal TFA levels were observed at 24 h (Sutton et al. 1991). TFA has also been detected as part of ultrashort-chain PFCAs in serum of Chinese adults, with median concentrations of 8.64 ng/mL and 8.46 ng/mL for men and women, respectively. In this study, serum TFA concentrations were positively correlated with age, which could suggest accumulation in humans (Duan et al. 2020). Although TFA was a significant contributor (>90%) to the total PFASs detected, a specific source for PFAS or TFA was not indicated for the Chinese population study (Duan et al. 2020). Most recently, studies have focused on detecting and quantifying TFA in the general population (Kim et al. 2022, Zheng et al. 2023). In a study screening for persistent and mobile organic compounds, TFA was detected in 30% of urine samples from Flemish adolescents; the study authors did not specify a source for persistent and mobile organic compounds or TFA (Kim et al. 2022). In a more recent study to examine current PFAS exposure patterns in people and their residences,

PFAAs and their precursors were measured in dust and drinking water from US homes and in blood and urine samples from those homes' residents (Zheng et al. 2023). The authors of that study reported that TFA was among the predominant PFAAs in most of the samples, and significant positive correlations were found between concentrations of TFA and concentrations of PFAS with 4 and 7 carbons in dust or water vs. those in serum (Zheng et al. 2023). The authors suggested that drinking water contaminated from municipal sources could be the source of PFAS, whereas the source of TFA might be dust, based on the significant correlations reported in the study (Zheng et al. 2023). Finally, the few studies assessing toxicity endpoints beyond acute effects (e.g., reproduction, development, mutagenicity, or genotoxicity) have not found evidence of adverse effects of TFA on these endpoints across a wide range of exposure concentrations (Dekant and Dekant 2023). However, the number of studies is small; more environmental and health studies are needed to further assess the long-term potential effects of TFA on the general population.

7.1.5.4 Contribution of TFA to atmospheric particle formation: Implications for global radiative forcing

Atmospheric aerosols are one of the components of the atmosphere affecting the earth's radiative budget by scattering solar radiation and acting as cloud condensation nuclei (Fan et al. 2016, Samset et al. 2018). The intricate formation and composition of atmospheric particles evidently influence the feedback loop between aerosol and climate (Yli-Juuti et al. 2021). Thus, the growth of particles from both anthropogenic and biogenic sources is a crucial process for understanding and forecasting the global climate.

As an acidic species, TFA is expected to participate in new particle formation events. Aerosol formation is a critical atmospheric process that generates seed for the formation of clouds, which affect atmospheric radiative forcing and climate. Moreover, in megacities (e.g., Beijing and Seoul), new particle formation events enhanced the particulate matter pollution (Qiu et al. 2023). The electron withdrawing effect of fluorine atoms enhances the acidity of the TFA and other PFCAs, which can stabilize the nucleating clusters in the atmosphere (Lu et al. 2020).

Theoretical simulations of the formation of sulfuric acid-dimethylamine-H_2O clusters based on measurements in Fudan University, China, showed an increase of aerosol formation by 2.3 times when TFA participated in cluster formation (Lu et al. 2020). A follow-up work extended the simulation study to four cities (Beijing, Shanghai, Los Angeles, and New Delhi) with varying levels of atmospheric pollutants and environmental parameters (i.e., temperature and relative humidity).

Figure 7.7 shows a comparison of the particle formation rates of the four cities, with and without the participation of TFA in cluster formation. The increase in aerosol formation rates due to TFA was highly evident in heavily polluted areas of Beijing, whereas New Delhi reported the lowest enhancement factor. This was attributed to the dependence of cluster with TFA: negative on temperature and positive on nucleation precursors such as dimethyl amine (Liu et al. 2021). These characteristics are highly typical during the winter months in Beijing, which explains the 12 times increase in cluster formation.

Furthermore, a recent study showed the important role of TFA in particle formation events with methanesulfonic acid as a precursor cluster (Hu et al. 2023). In that study, the rate of aerosol formation increased by 7.28 times at low-temperature conditions with elevated levels of methylamine and TFA.

These studies highlight the necessity to consider TFA's roles in essential atmospheric processes to fully assess its ecological fates.

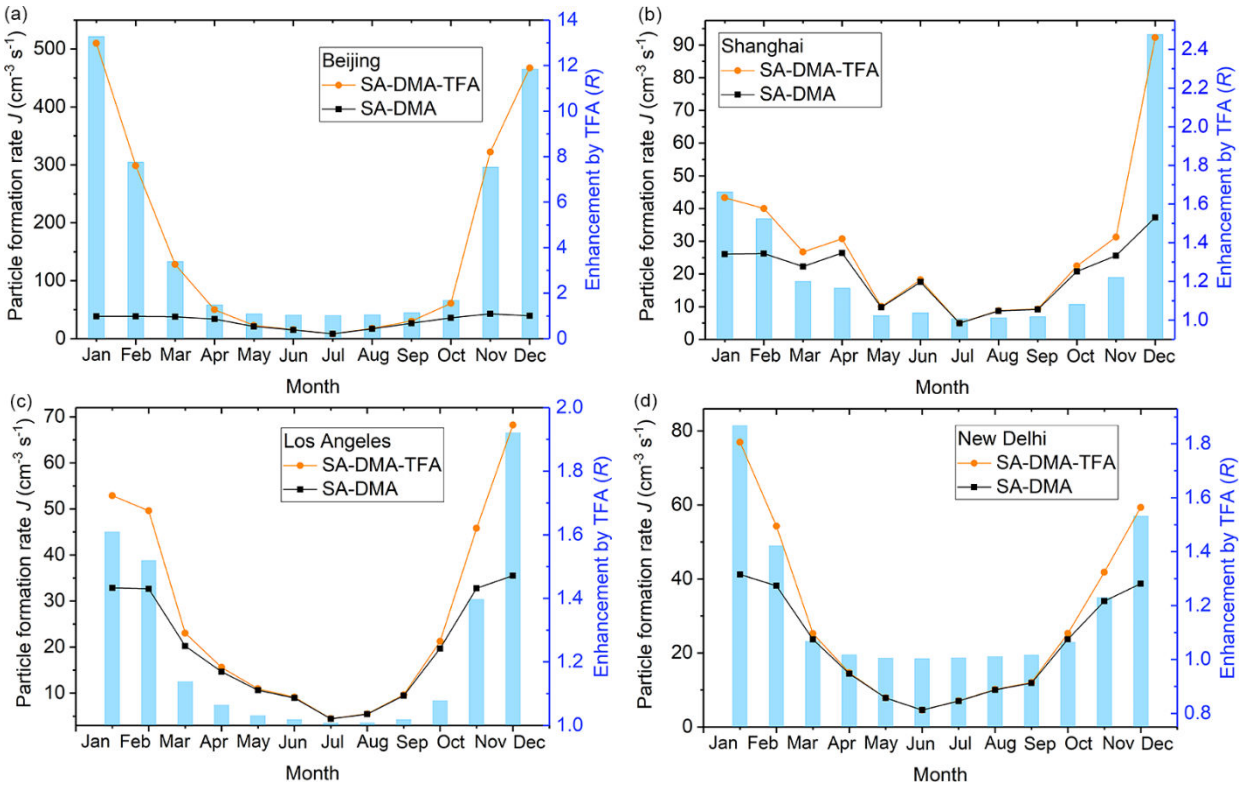

Figure 7.7. Monthly enhancement effect of TFA on cluster formation in Beijing, Shanghai, Los Angeles, and New Delhi. Adapted from: (Liu et al. 2021).

7.2 OTHER DEGRADATION PRODUCTS

Natural refrigerant products such as CO_2 have no known degradation products or negative effects outside of their contributions to GHG emissions. Ammonia can react in the atmosphere and contribute to increasing levels of itself, NO_x, and nitric acid (NOAA 2000). Propane can also react into the atmosphere and form various carbonyl degradation products. When reacted with OH radicals in the atmosphere, propane's degradation into terminal products can create toxic compounds such as acetone, acetaldehyde, and propionaldehyde (Rosado-Reyes and Francisco 2007). Whereas the fugitive releases of these natural refrigerants contribute to anthropogenic pollution, their current use as refrigerants comprises a small share of their relative commercial markets (NOAA 2000, Rosado-Reyes and Francisco 2007).

Other degradation products of HFCs and HFOs include hydrofluoric acid, formyl fluoride, trifluoro-acetyl-fluoride, trifluoro acetaldehyde, and formic acid (Behringer et al. 2021). Many of these degradation products have the potential to produce acid rain; although their short atmospheric lifespans may prevent global effects, regional effects are possible. Additionally, a recent study reported that the oxidation (i.e., ozonolysis) of HFO-1234ze(E), HFO-1336mzz(Z), and HFO-1243z directly generated fluoroform, HFC-23, a high-GWP compound measured using the Medusa preconcentration gas chromatography-mass spectrometry in a chamber study (McGillen et al. 2023). Further research will be required to confirm these degradation pathways and identify additional atmospheric transformations currently not known for other HFC and HFO refrigerants. Because HFO use is projected to increase in the coming years, the concentrations of TFA and other degradation products could potentially increase, highlighting the critical need to understand the environmental impacts of these compounds.

7.2.1 Potential Unaccounted Oxidation Products of Refrigerants in the Atmosphere

7.2.1.1 Dimerization of degradation products of refrigerants

Most of the recent studies dealing with the transformation of refrigerants in the atmosphere limit the oxidation to TFA, hydrofluoric acid, and CO (Burkholder et al. 2015, Holland et al. 2021), with most occurring through daytime OH oxidation. However, the production of highly reactive RO_2 radicals, upon the addition of O_2 to alkyl radicals, could also react with other RO_2 radicals to form compounds with longer carbon chains. In particular, dimers are formed from the accretion of two oxidation products or even from the self-RO_2 reaction. With the onset of new mass spectrometers, observation of dimeric oxidation products in the atmosphere provided insights into their role in new particle formation and growth (Zhang et al. 2015, Mohr et al. 2017). Yields of dimer formation (i.e., 0.2%–2.5% by mole) vary depending on the level of anthropogenic emissions (e.g., NO) but can explain 5%–60% of the aerosol mass of terpene oxidation (Zhao et al. 2018).

With the potential formation of larger PFAS, empirical studies dealing with the other oxidation routes of refrigerants besides TFA will be a necessity to fully account for the health and environmental impacts of newly developed refrigerants. For example, fluorinated refrigerants (particularly HFOs) could generate dimers mechanistically during their oxidation process. The oxidation of R-1234yf could generate a C_3 RO_2, which could then proceed to a self-RO_2 reaction (see Figure 7.8) to form a C_6 with eight fluorine dimer compounds. The formation of larger compounds decreases the volatility of the species, which could have serious implications on particle growth and accumulation. Moreover, typical refrigerants are sold as blended products containing at least two refrigerants. Mixing the intermediate products of R-1234yf with R-134a could produce C_5 and C_6 compounds with 8–11 fluorine atoms in their structures. Moreover, RO_2 from refrigerants could interact with predominant volatile organic compounds (VOCs) in the region where the refrigerant was emitted. For instance, α-pinene is one of the major VOCs in forest environments. Such biogenic VOCs can also produce RO_2 intermediates, which could also react with the RO_2 from the refrigerants. High-molecular-weight dimers are formed through the interaction of RO_2 through self- or cross-reactions. Dimerization of such processes could lead to the production of a long-chain PFCA with 13 carbons. The same could occur in urban environments with benzene, toluene, and ethylbenzene as the major VOCs emitted from automobiles. With toluene RO_2, a C_{12} PFAS might occur instead of C_3 short-chain compounds. These pathways are theoretical; more studies are needed to fully understand the potential effects of refrigerants and their degradation products.

7.2.1.2 Nighttime transformation of refrigerants

As indicated earlier, the formation of TFA from refrigerants is the product of daytime OH oxidation processes. However, nighttime emissions could still lead to oxygenated fluorinated products through nitrate (NO_3) oxidation. The expected NO_3 yields are less than those OH chemistry but might still contribute to the ecological fate of refrigerants in the atmosphere. The NO_3 oxidation of α-pinene leads to high mass loading with 41 highly oxygenated organonitrates containing four to nine oxygen atoms. One study showed monoterpene oxidation at night can serve as a temporary or permanent sink of NO_x (Nah et al. 2016). Understanding the full diurnal oxidation process of refrigerants like terpenes might generate important implications regarding their ecological effects and their role in local atmospheric processes.

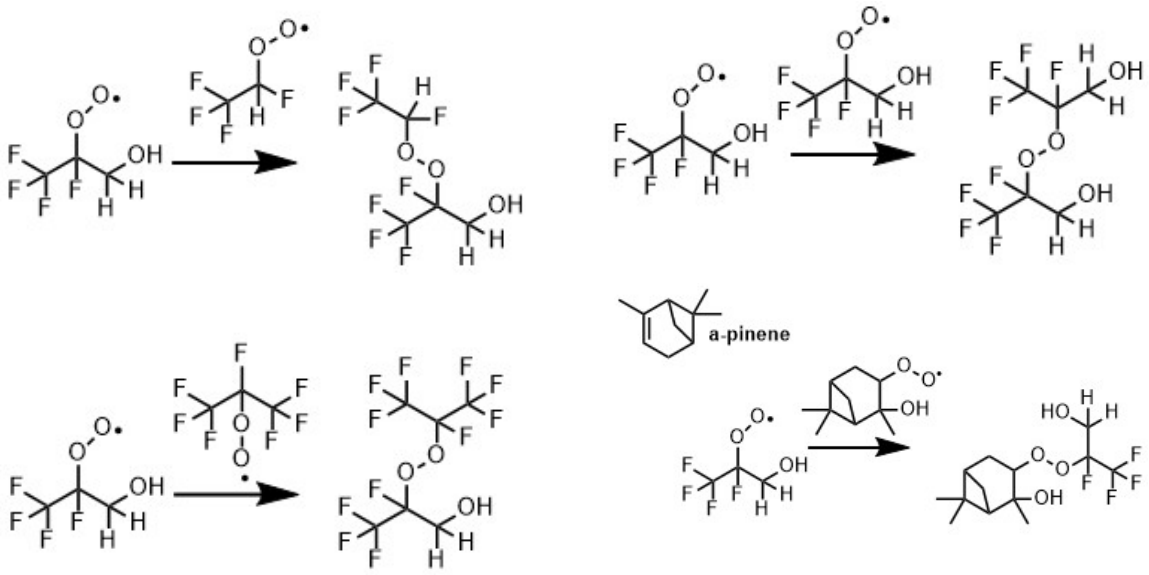

Figure 7.8. Formation of larger fluorinated compounds from the dimerization/accretion of RO_2 radicals of R-1234yf with self-RO_2 and other radicals from refrigerants (e.g., HFC-134a), isoprene, and toluene.

8. UNCERTAINTIES, DATA GAPS, RESEARCH NEEDS

The impending extreme heat in the next decades will intensify the critical value of refrigeration and air conditioning. However, the increased utilization of refrigerants, particularly the next generation compounds, could have unintended environmental impacts. For instance, the atmospheric degradation of HFOs can generate PFAS (i.e., TFA), which is persistent, and has been found in blood, drinking water, beverages, dust, plants, and agricultural soils, requiring further investigation.

The formation of TFA, quantified as yield in some publications, has been the subject of many studies. Recent estimates published in the UNEP Environmental Effects Assessment Panel report (UNEP 2022a) are mostly theoretical. These latest results show large uncertainties, indicating the need for further experimental evaluations to reduce the uncertainty regarding TFA yields. The varying proposed reaction mechanism of the formation of the degradation of TFA products adds to the wide range of the yields presented. This merits the need for an empirical and uniformed measurement that can calculate TFA yields from the daytime and nighttime oxidation of refrigerants. Accurate yield information will provide a more reliable global concentration of TFA, which will enhance the proper apportionment of possible anthropogenic and biogenic sources. Work on the end-degradation products is necessary to elucidate their short- and long-term effects in the environment. Furthermore, work is required on transformation pathways or secondary conversion from one class of refrigerant to another class of refrigerant [e.g., R-1336mzz(Z) to R-22] which could lead to unintended environmental impacts such as increasing the GWP values or the generation of PFAS-related compounds. Additional research will be necessary to validate these degradation pathways and uncover atmospheric transformations that are thus far undiscovered for HFC and HFO refrigerants.

The measurement of TFA in the atmosphere is challenging. Some work has been done, but this review highlights the need for new methodologies. Therefore, a novel method is proposed that uses advanced instrumentation. This approach may facilitate the collection of more data, which could in turn be used to assess the significance of TFA formation. These data could play a crucial role in validating and calibrating models and in completing a comprehensive risk assessment. The tedious process of collecting

and extracting atmospheric TFA poses a limitation for the in-depth source apportionment of TFA. A fast, reliable, and chemical-free measurement of TFA is necessary to account for variations of TFA in the atmosphere. The PTR-ToF-MS appears to be a promising technique for TFA measurement; its portability, sensitivity, and real-time analysis capabilities make it well-suited for analyzing organic compounds in both gas and particle phases.

The dispersion of TFA in the atmosphere depends on the following: (1) geographic location of the release, (2) meteorological conditions, and (3) chemical reactivity of the molecule. These factors could also affect the breakdown process (i.e., yield). This is a very complex phenomena so other as-yet unknown aspects could affect TFA distribution and reach to the aquatic systems. This review found several models that tried to make predictions in different regions of the planet. Still, the lack of measurements makes validation of these models challenging.

The effects on organisms, such as the aquatic life mentioned previously, depend on exposure, concentrations, and the potential effect these breakdown compounds may have not only on the biota but also on the ecosystem (i.e., particle formation). Sufficiently understanding toxicity effects usually requires complex experimental studies and solid, statistically proven results.

The peer-reviewed publications, technical reports, and regulatory and international agreements analyzed in this document reflect the state of the art regarding a few selected fluorinated refrigerants, their breakdown products, and their reported effect on the environment. The data indicate a gap in experimental studies to measure actual TFA formation during refrigerant breakdown in the environment. Additional comprehensive studies with direct empirical evidence that directly tackle the atmospheric transformation and dispersions of TFA are advisable. The WMO (2022) and the UNEP Environmental Effects Assessment Panel (2022) reports show an increased confidence that TFA produced from the breakdown of new low-GWP refrigerants will not harm the environment over the next few decades. Nevertheless, the uncertainties associated with the sources (i.e., yield) and sinks (i.e., distribution) of TFA and its persistence warrant continued uniform monitoring in the environment.

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APPENDIX A. CHEMICAL STRUCTURES

Table A1. Chemical structures of the refrigerants selected for this review.

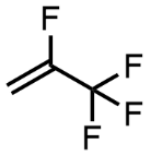
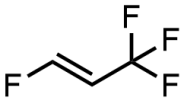
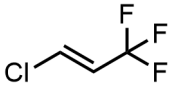
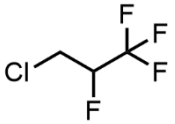
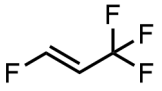
Refrigerant	Chemical Structure
R-No: R-1234yf **Chemical Name (IUPAC):** 2,3,3,3-tetrafluoro-1-propene **Designation:** HFO-1234yf **Chemical Formula:** $CH_2=CFCF_3$ **CAS Number:** 754-12-1 **EC/List Number:** 468-710-7	
R-No: R-1234ze(E) **Chemical Name (IUPAC):** trans-1,3,3,3-tetrafluoroprop-1-ene **Designation:** HFO-1234ze(E) **Chemical Formula:** Trans-$C_3F_4H_2$ **CAS Number:** 29118-24-9 **EC/List Number:** 471-480-0 / 810-135-4	
R-No: R-1233zd(E) **Chemical Name (IUPAC):** trans-1-chloro-3,3,3-trifluoroprop-1-ene **Designation:** HCFO-1233zd(E) **Chemical Formula:** $C_3ClF_3H_2$ **CAS Number:** 102687-65-0 **EC/List Number:** 700-486-0	
R-No: R-1224yd(Z) **Chemical Name (IUPAC):** (Z)-1-chloro-2,3,3,3-tetrafluoropropane **Designation:** HCFO-1224yd(Z) **Chemical Formula:** (Z)-CF_3-CF=CHCl (Z) **CAS Number:** 111512-60-8 **EC/List Number:** 824-458-3	
R-No: R-1336mzz(E) **Chemical Name (IUPAC):** (Z)-1,1,1,4,4,4-hexafluor-2-butene **Designation:** HFO-1336mzz(E) **Chemical Formula:** $CF_3CHCHCF_3$ **CAS Number:** 66711-86-2 **EC/List Number:** 811-213-0	

Table A1. Chemical structures of the refrigerants selected for this review (continued).

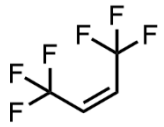
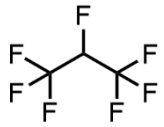
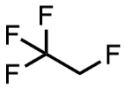
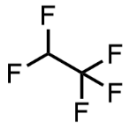
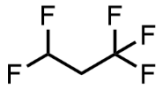
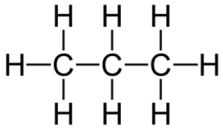
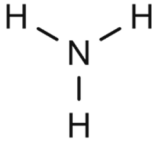
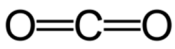
Refrigerant	Chemical Structure
R-No: R-1336mzz(Z) **Chemical Name (IUPAC):** cis-1,1,1,4,4,4-hexafluorobut-2-ene **Designation:** HFO-1336mzz(Z) **CAS Number:** 692-49-9 **Chemical Formula:** cis-$CF_3CH=CHCF_3$ **EC/List Number:** 700-651-7	
R-No: R-227ea **Chemical Name (IUPAC):** 1,1,1,2,3,3,3-heptafluoropropane **Designation:** HFC-227ea **Chemical Formula:** C_3HF_7 **CAS Number:** 431-89-0 **EC/List Number:** 207-079-2	
R-No: R-32 **Chemical Name (IUPAC):** difluoromethane **Designation:** HFC-32 **Chemical Formula:** CH_2F_2 **CAS Number:** 75-10-5 **EC/List Number:** 200-839-4	
R-No: R-134a **Chemical Name (IUPAC):** 1,1,1,2-tetrafluoroethane **Designation:** HFC-134a **Chemical Formula:** CH_2FCF_3 **CAS Number:** 811-97-2 **EC/List Number:** 212-377-0	
R-No: R-152a **Chemical Name (IUPAC):** 1,1-difluoroethane **Designation:** HFC-152a **Chemical Formula:** $C_2H_4F_2$ **CAS Number:** 75-37-6 **EC/List Number:** 200-866-1	

Table A1. Chemical structures of the refrigerants selected for this review (continued).

Refrigerant	Chemical Structure
R-No: R-125 **Chemical Name (IUPAC):** pentafluoroethane **Designation:** HFC-125 **Chemical Formula:** CF_3CHF_2 **CAS Number:** 354-33-6 **EC/List Number:** 206-557-8	
R-No.: R-245fa **Chemical Name (IUPAC):** 1,1,1,3,3-pentafluoropropane **Designation:** HFC-245fa **Chemical Formula:** $C_3H_3F_5$ **CAS Number:** 460-73-1 **EC/List Number:** 419-170-6	

IUPAC = International Union of Pure and Applied Chemistry; CAS = Chemical Abstracts Service; EC = European Commission; HFC = hydrofluorocarbon; HFO = hydrofluoroolefin; HCFO = hydrochlorofluoroolefin.

Table A2. Chemical structures of natural refrigerants.

Refrigerant	Chemical Structure
Refrigerant Name: R-290 **Chemical Name (IUPAC):** propane **Chemical Formula:** C_3H_8	
Refrigerant Name: R-717 **Chemical Name (IUPAC):** anhydrous ammonia **Chemical Formula:** NH_3	
Refrigerant Name: R-744 **Chemical Name (IUPAC):** carbon dioxide **Chemical Formula:** CO_2	

IUPAC = International Union of Pure and Applied Chemistry.

Table A3. Chemical composition of refrigerant blends.

Refrigerant Name: R-448A **Blend Type:** Zeotrope **Commercial Name:** Soltice® N40 **Chemical Composition:** R-32/125/1234yf/134a/1234ze(E) (26.0/26.0/20.0/21.0/7.0)
Refrigerant Name: R-449A **Blend Type:** Zeotrope **Commercial Name:** Opteon ™ XP40 **Chemical Composition:** R-32 /125 /1234yf /134a (24.3/24.7/25.3/25.7)
Refrigerant Name: R-449B **Blend Type:** Zeotrope **Commercial Name:** Forane® 449B **Chemical Composition:** R-32/125/1234yf/134a (25.2/24.3/23.2/27.3)
Refrigerant Name: R-450A **Blend Type:** Zeotrope **Commercial Name:** Solstice® N13 **Chemical Composition:** R-134a/1234ze(E) (42.0/58.0)
Refrigerant Name: R-452A **Blend Type:** Zeotrope **Commercial Name:** Solstice© 452A **Chemical Composition:** R-32/125/1234yf (11.0/59.0/30.0)
Refrigerant Name: R-454B **Blend Type:** Zeotrope **Commercial Name:** Opteon™ XL41 **Chemical Composition:** R-32/1234yf (68.9/31.1)
Refrigerant name: R-454C **Blend Type:** Zeotrope **Commercial Name:** Opteon® XL20 **Chemical Composition:** R-32/1234yf (21.5/78.5)
Refrigerant Name: R-455A **Blend Type:** Zeotrope **Commercial Name:** Soltice® L40X **Chemical Composition:** R-744/32/1234yf (3.0/21.5/75.5)
Refrigerant Name: R-456A **Blend Type:** Zeotrope **Commercial Name:** Solstice© 456A **Chemical Composition:** R-32/134a/1234ze(E) (6.0/45.0/49.0)
Refrigerant Name: R-471A **Blend Type:** Zeotrope **Commercial Name:** Solstice© N71 **Chemical Composition:** R-1234ze(E)/227ea/1336mzz(E) (78.7/4.3/17.0)
Refrigerant Name: R-476A **Blend Type:** Zeotrope **Commercial Name:** NS **Chemical Composition:** R-134a/1234ze(E)/1336mzz(E) (10.0/78.0/12.0)
Refrigerant Name: R-499C **Blend Type:** Zeotrope **Commercial Name:** NS **Chemical Composition:** R-32/125/1234yf/134a (20.0/20.0/31.0/29.0)

Table A3. Chemical composition of refrigerant blends (continued).

Refrigerant Name: R-513A **Blend Type:** Azeotrope **Commercial Name:** Solstice© 513A **Chemical Composition:** R-1234yf/134a (56.0/44.0)
Refrigerant Name: R-515B **Blend Type:** Azeotrope **Commercial Name:** Solstice© N15 **Chemical Composition:** R-1234ze (E)/227ea (91.1/8.9)
Refrigerant Name: R-516A **Blend Type:** Azeotrope **Commercial Name:** Forane© 516A **Chemical Composition:** R-1234yf/134a/152a (77.5/8.5/14.0)

NS = not specified.