Demystifying Alternative Refrigerants

Background, Policies, and Analysis

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A Report of BPA's Emerging Technologies Initiative

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An Emerging Technologies Report

The following report was funded by the Bonneville Power Administration (BPA). BPA is committed to identify, assess and develop emerging technologies with significant potential for contributing to efficient use of electric power resources in the Northwest.

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Forward

In order to meet or exceed Bonneville Power Administration's (BPA's) energy conservation targets, BPA needs to understand the changing refrigerant market and the resulting impacts on energy use. For this reason, BPA sponsored this white paper to provide an overview of the current and future refrigerant landscape, including the impact of legacy refrigerants that have high global warming potential (GWP), as well as alternative refrigerants that possess a lower GWP. **The goal of this paper is to "demystify the refrigerant landscape" to facilitate further exploration.** Specifically, this paper seeks to help readers pursue a more energy-efficient future by providing detailed information on low-GWP alternative refrigerants, explaining current and future policies that will impact this sector, and providing additional information and resources for those interested in the evolving refrigeration marketplace.

BPA recognizes upcoming changes in systems that use refrigerants, primarily driven by regulation to limit the use and manufacture of high-GWP refrigerants. Systems that use refrigerants include air conditioners, residential refrigerators, commercial and industrial refrigeration systems, and chillers. Utilizing possible low-GWP replacements will change the current landscape. These new refrigerants bring many challenges, including toxicity and flammability. In addition, existing refrigeration and air conditioning systems may also have issues, including compatibility with the new refrigerant, complexity, performance, energy efficiency, and capacity.

This paper provides an overview of the different types of refrigerants that have high GWP and their possible replacements. The paper also explores the international and national policies that are in place that may impact the activities of BPA and ratepayers within BPA's service territory. The main questions that this white paper addresses are:

- What are the major classifications of refrigerants?
- Why are some refrigerants classified as pollutants while others are not?
- What should be considered when working with a new refrigerant?
- What existing regulations govern refrigerants and how are these regulations implemented?
- What are industry leaders doing now to address concerns about refrigerants?
- How do refrigerant leaks contribute to the Pacific Northwest's pollutant emissions?

The intended audience for this white paper includes refrigeration and air conditioning researchers at national labs, energy conservation program managers and implementers, as well as owners of refrigeration and air conditioning systems.

Section 1: Introduction

Background

The earth's surface temperature is expected to increase by 3.5 to 11 degrees Fahrenheit by 2100, according to NASA[1]. Effects of this warming are already evident. Although carbon dioxide (CO_2) emissions are the primary cause of this greenhouse effect, compounds other than CO_2 can act as powerful greenhouse gases as well. These substances include methane, which is primarily released from landfills and livestock; nitrous oxide, which is emitted from cars and heavy industry; and refrigerants that leak from air conditioners and refrigeration systems in homes, businesses, and industry.

Though the volume of refrigerants released into the atmosphere is far less than the volume of CO_2, refrigerants are a significant concern because they can act up to *15,000 times* more powerfully as greenhouse gases than CO_2. To put that into perspective, if the refrigerator in your home is not properly recycled and the 10.6 ounces of the refrigerant HFC-134a are allowed to leak into the atmosphere, those 10.6 ounces have about the same global warming impact as emitting 945 pounds of CO_2 [2] – roughly equivalent to the amount emitted from a one-way drive from Seattle to San Francisco. And because air conditioning and refrigeration are proliferating so rapidly around the planet, refrigerants are now the fastest growing type of climate pollutant[3].

To address this growing problem, the global community has agreed to replace traditional refrigerants with those that have low global warming potential (GWP).This paper provides an overview of the different types of refrigerants that have high GWP and their possible replacements. It also explores the international and national policies that are in place that may impact the activities of BPA and ratepayers within BPA's service territory.

Types of Refrigerants

There are five categories of refrigerants: chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), hydrofluoroolefins (HFOs), and so-called "natural" refrigerants. (Beginning on this page, there will be a quick-reference guide at the bottom of every page of this report that briefly summarizes for readers the key characteristics of each type of refrigerant.)

[1] NASA: http://earthobservatory.nasa.gov/Features/GlobalWarming/page5.php
[2] Greenpeace: http://www.greenpeace.org/international/Global/international/planet-2/report/2009/5/HFCs-Fgases.pdf
[3] United Nations: http://www.un.org/apps/news/story.asp?NewsID=55310#.WFw0TrYrLeQ

Refrigerant Quick Reference Table

	Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable		Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable
CFC	High	High	1996	No	**HFO**	Low	None	n/a	Varies
HCFC	High	Medium	2030	No	**HFO / HFC Blends**	Medium	None	n/a	Low to none
HFC	High	None	2036 (85%)	No	**Natural Refrigerants**	Low	None	n/a	Varies

CFCs

CFCs, composed of carbon, chlorine, and fluorine, became a popular type of refrigerant beginning in the 1930s because they were viewed as an attractive non-toxic, non-flammable alternative to the dangerous incumbent refrigerants, such as methyl chloride and sulphur dioxide. However, CFCs were phased out in the 1990s because they posed enormous risk to the earth's ozone layer. Common CFCs included R11, R12, R113, R114, and R115. Though no longer in production or in widespread use, a few legacy systems and appliances still operate using CFCs. Table 1 provides the reduction timeline for CFCs in the U.S.

Table 1. Reduction Timeline for CFCs in the U.S.

CFC Phase Out	
Year	**Percent reduction in consumption and production from 1989 baseline**
1991	15%
1992	20%
1993	25%
1994	75%
1995	75%
1996	100%

Source: UN: http://ozone.unep.org/pdfs/Montreal-Protocol2000.pdf

HCFCs

HCFCs have a structure very similar to CFCs, but with the addition of hydrogen. Because they share many of the physical properties of CFCs but are less damaging to the ozone layer, HCFCs were the most common replacement for CFCs in the 1990s and 2000s. However, HCFCs do still pose some risk to the ozone layer, and like CFCs, HCFCs are potent greenhouse gases. For this reason, HCFCs are in the process of being phased out, with 99.5 percent reductions slated to happen by 2020. Common HCFCs include R123 and R22. Indeed, R22 has possibly been the most widely used refrigerant in recent times, as it was ubiquitous in residential appliances, refrigeration systems, and automobile air conditioning systems for many years. Though R22 is no longer used in new equipment, a significant amount of the refrigerant is still operating in legacy systems. Table 2 provides the reduction timeline for HCFCs in the U.S.

Table 2. Reduction Timeline for HCFCs in the U.S.

HCFC Phase Out	
Year	**Percent reduction in consumption and production from 1996 baseline**
2004	35%
2010	75%
2015	90%
2020	99.5%
2030	100%

Source: EPA: https://www.epa.gov/ods-phaseout/phaseout-class-ii-ozone-depleting-substances

HFCs

As HCFCs have been phased out, HFCs, which contain hydrogen, fluorine, and carbon, have been the primary replacement. Unlike CFCs and HCFCs, HFCs pose no threat to the ozone layer because HFCs lack the chlorine atom that is responsible for the reaction that destroys ozone molecules. However, like CFCs and HCFCs, HFCs are greenhouse gases. As a result, HFCs have also been targeted for phase down (though not a total phase out) by international treaty. Those reductions have begun in recent years and are

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	Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable
HFO	Low	None	n/a	Varies
HFO / HFC Blends	Medium	None	n/a	Low to none
Natural Refrigerants	Low	None	n/a	Varies

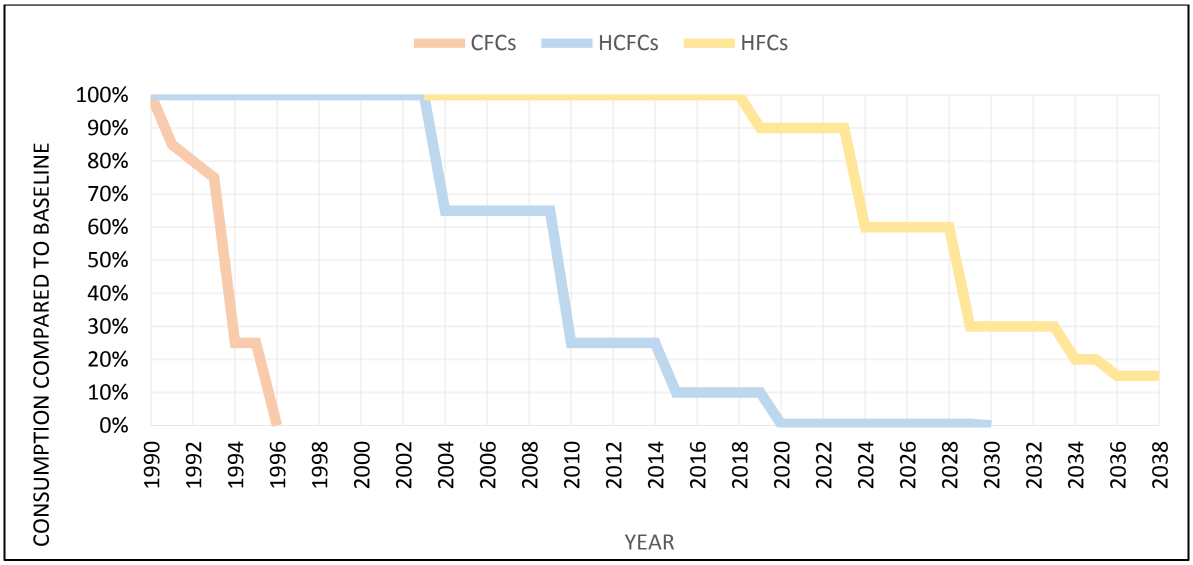
detailed in following sections. Common HFCs include R134a, R404a, R407C, and R410a. Table 3 provides the reduction timeline for HFCs in the U.S. Figure 1 shows the combined phase out and phase down timeline for legacy refrigerants for developed nations, including the U.S., under the Montreal Protocol.

Table 3. Reduction Timeline for HFCs in the U.S.

HFC Phase Down	
Year	**Percent reduction in consumption and production from 2011-2013 baseline**
2019	10%
2024	40%
2029	70%
2034	80%
2036	85%

Source: UN: http://www.unep.org/ozonaction/Portals/105/documents/7809-e-Factsheet_Kigali_Amendment_to_MP.pdf

Figure 1. Refrigerant Phase Out Timelines



Low-GWP HFOs

HFOs are an emerging type of synthetic refrigerant. Though not widely used at this time, HFOs are beginning to gain some market traction. Like HFCs, HFOs are composed of hydrogen, fluorine, and carbon. The only chemical difference between HFOs and HFCs is that HFOs have at least one double bond between carbon molecules. HFOs pose no risk to the ozone layer and, by themselves, are a minimally potent greenhouse gas. However, because HFOs can be flammable, these refrigerants are routinely combined with HFCs to create non-flammable blends[4]. While the resulting blends are less volatile, the addition of HFCs does increase the global warming potential. Common HFOs include R1234yf, R1336mzz(Z), and R1234ze(E). Common HFC/HFO blends include R444B, R448A, R449A, R450A, and R513A.

[4] CARB: https://www.arb.ca.gov/cc/shortlived/meetings/11282016/revisedproposedslcp.pdf

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Low-GWP Natural Refrigerants

As the phase-out of HFCs progresses, this class of refrigerants is seeing wider adoption. Unlike the above refrigerants, which did not exist until humans engineered them, this category is comprised of compounds that can be found in nature (albeit sometimes rarely). As such, this group is sometimes referred to as "natural" refrigerants. Natural refrigerants pose no significant threat to the ozone layer and have much less GWP than HFCs (or none at all). Common natural refrigerants include hydrocarbons (such as propane, butane, isobutene, and propylene), ammonia, and CO_2.

However, these refrigerants are not without their own complicating factors; many are flammable or toxic, so care must be taken when servicing, inspecting, or replacing refrigeration and air conditioning systems with these substances. To address the issues of toxicity and flammability, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has established ASHRAE Standard 34 as the categorization system for toxicity and flammability of refrigerants. These Standard 34 categories are outlined in Table 4 and Table 5. More detailed information on the risks of alternative refrigerants is provided later in this report.

Replacing an HFC with a natural refrigerant? Not so fast.

Natural refrigerants should not be considered a direct "drop-in" replacement for HFCs because natural alternatives often operate at different pressures, may corrode existing equipment, or lead to other types of system degradation. To further complicate the picture, some natural refrigerants also have an associated "energy penalty." This means that while the refrigerants themselves are less damaging when released into the atmosphere, they may cause equipment to consume more energy while in use (therefore generating a larger carbon footprint).

However, this energy penalty isn't a universal characteristic. In fact, some natural refrigerants actually make equipment operate *more* efficiently. Because research on using natural refrigerants in existing equipment is in its infancy, there is no authoritative resource that helps weigh all the relevant variables. Therefore, those working in the refrigeration field are urged to contact the manufacturer of legacy equipment and the maker of the relevant natural refrigerant for guidance in replacing HFCs.

Table 4. ASHRAE Standard 34 Categories of Toxicity and Flammability

	Low toxicity	High toxicity
Higher flammability	A3	B3
Lower flammability	A2	B2
	A2L*	B2L*
No flame propagation	A1	B1

*A2L and B2L are lower flammability refrigerants with a maximum burning velocity of ≤10 cm/s.

Table 5. Comparing Different Refrigerants using ASHRAE Standard 34

Refrigerant	Category
Ethane	A3
Propane	A3
Butane	A3
Isobutane	A3
Pentane	A3
Ammonia	B2L
CO_2	A1

Source: ASHRAE: http://tinyurl.com/h95zetb

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Section 2: Why Refrigerants are Important Climate Gases

To understand the impact of refrigerants on the earth's climate system, it is useful to first briefly review the mechanics of greenhouse gases and global warming.

Greenhouse Gases 101

When visible light energy from the sun strikes the earth, some of the energy is absorbed while much of the rest is re-emitted back outward toward space as less-energetic infrared photons (heat). During this outward trip, many of the infrared photons are intercepted by greenhouse gases in the atmosphere. Greenhouse gases are different from other common atmospheric molecules like oxygen and nitrogen in that they have a surplus of electrons or have electrons distributed unevenly across their structure. This misbalance of electrons makes greenhouse gases uniquely able to absorb the infrared photon that's been reflected up from the earth's surface.

Absorbing this heat energy causes greenhouse gas molecules to vibrate. To stabilize the vibration and return to a steady state, these molecules quickly re-emit the infrared radiation. Because the orientation of greenhouse gases in the atmosphere is effectively random due to constant movement and collisions with other molecules, the direction the re-emitted infrared radiation is also random. So instead of all the sun's reflected heat escaping back into space, as it would without any greenhouse gases, some of those infrared photons are redirected back down to the earth's surface or repeatedly bounce among the atmospheric greenhouse gases. As the concentration of greenhouse gases in the atmosphere increases, a greater number of outgoing infrared photons are trapped near the surface of our planet for a longer time and, thus, cause gradual heating.

While we think of the greenhouse gases as posing a climate threat, it is important to note that some level of greenhouse heating is important to sustain life. The earth's moon, which is the same distance from the sun, lacks any greenhouse gases – a major reason that surface temperatures average roughly -250°F at night. (The greenhouse effect isn't the only cause of our planet's more moderate temperatures, but is a major factor.) During much of human history, atmospheric levels of greenhouse gases and corresponding temperatures have been relatively stable. But since the industrial revolution, the volume of greenhouse gases released has been so large that this long-term balance is now shifting.

Why Refrigerants are Such Potent Greenhouse Gases

The first reason why legacy refrigerants are more powerful greenhouse gases than CO_2 is due to their chemical composition[5, 6, 7]. With numerous carbon, fluorine, hydrogen, and/or chlorine atoms, legacy refrigerants are much more complex than simple, three-atom CO_2 molecules. This molecular complexity is important because, as a general rule, complex molecules absorb incoming infrared radiation at a greater number of wavelengths, thus making them more effective thermal insulators. Chemistry dictates

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[5] Atmospheric Chemistry and Environmental Impact of Hydrofluorocarbons (HFCs) and Hydrofluoroethers (HFEs) *from volume 3N of the series The Handbook of Environmental Chemistry (pp 85-102)*
[6] Atmospheric Degradation of Halocarbon Substitutes*, chapter 12, of Scientific Assessment of Ozone Depletion: 1994.*
[7] *Lifecycle Global Warming Impact of CFCs and CFC-Substitutes for Refrigeration, Journal of Industrial Ecology.*

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that if CO_2 acts as a light atmospheric blanket that prevents heat from quickly escaping into space, refrigerants resemble a heavy down comforter.

The other reason refrigerants are such powerful greenhouse gases is because they can persist in the atmosphere for a very long time. Though some refrigerants persist for only a few days and, thus, play a minor role in heating the planet, others last for hundreds of years before being destroyed so can have far more climate impact.

HFC or HCFC atmospheric destruction is usually caused by hydroxyl radicals (or OH radicals). OH radicals, continuously created when the sun's radiation interacts with ozone in the atmosphere, are extremely reactive. The carbon-hydrogen (C-H) bonds are the part of these refrigerants that are susceptible to attacks from these volatile OH radicals. The rate of decomposition of HFCs and HCFCs in the atmosphere is directly related to the number and strength of C-H bonds. The weaker or more numerous the bonds, the faster OH radicals will react with the compound (lots of bonds means more opportunities for a reaction). Fewer and/or stronger bonds allow HFCs or HCFCs to persist in the atmosphere for much longer on average. After these compounds are broken down by an OH radical, they cease to act as greenhouse gases.

CFCs, on the other hand, lack C-H bonds, making them more chemically stable than HCFCs or HFCs and not susceptible to reaction with OH radicals. However, CFCs are vulnerable to ultraviolet (UV) radiation. When CFCs find their way to the stratosphere, the heavy bombardment of UV radiation at those heights eventually knocks a chlorine atom free from the CFC. These chlorine atoms are what wreaks havoc with the ozone layer, as each one typically annihilates thousands of ozone molecules through catalytic activity before it reacts with another molecule, such as methane, and is sequestered[8]. When the chlorine atom is cleaved from the CFC molecule by UV radiation, the rest of the CFC molecule breaks down into several sub compounds (which vary depending on the exact type of CFC). These residual molecules generally have little to no GWP. The typical lifespan of CFCs in the atmosphere can be from decades to hundreds of years – longer than most HFCs and HCFCs.

The reason HCFCs also deplete the ozone layer but at much lower rate than CFCs is because HCFCs will only lose their ozone-wrecking chlorine atoms to incoming UV radiation if they can travel up to the stratosphere before OH radicals react with them in the lower troposphere.

How to Compare Environmental Impacts of Refrigerants

There are two important metrics to look at when evaluating the impacts of a refrigerant on the atmosphere. The first is GWP, which tells us how powerfully a particular refrigerant acts as a greenhouse gas. The other metric is ozone depletion potential, or ODP, which quantifies the amount of damage a given refrigerant causes to the ozone layer.

GWP

To cleanly compare the global warming threat of refrigerants, GWP evaluates these compounds over a theoretical 25- or 100-year atmospheric lifetime. This is essentially a measure of how much one ton of a

[8] NASA: http://earthobservatory.nasa.gov/Features/Ozone/ozone_2.php

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gas will contribute to global warming over that 25- or 100-year span, relative to the emissions of one ton of CO_2. A 25- or 100-year GWP provides a common unit of measure, which allows us to add up emissions estimates of different gases and compare emissions reduction opportunities across sectors and gases.

ODP

Like 25- or 100-year GWP, ODP is a unitless measurement. ODP compares the lifetime ozone destructive potential of different substances, with CFC-11 serving as the baseline (CFC-11 has an ODP value of 1). All CFCs have an ODP somewhat close to 1, while HCFCs tend to be somewhat to significantly lower. ODP values scale linearly, meaning that a substance with an ODP of 0.5 causes, on average, half the ozone layer destruction as a substance with an ODP of 1.

Table 6 presents ODP and 100-year GWP of most common refrigerants. However, because there are hundreds of refrigerants, readers who wish to explore this area in more detail may want to refer to more comprehensive databases maintained by ASHRAE[9] (which also includes detailed safety information) or Montreal Protocol reference materials[10] and related UN documents[11]. Also, note that HFO/HFC blends are not included in this table. This is because these blends are proprietary and can vary by manufacturer. However, in general, these blends possess a 100-year GWP between 88 and 1,400 with an ODP of zero[12].

[9] http://www.hourahan.com/wp/wp-content/uploads/2010/08/2007-Refrig-Update.pdf
[10] http://conf.montreal-protocol.org/meeting/oewg/oewg-37/presession/Background_documents/TEAP TF XXVII-4 Report March 2016.pdf
[11] https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html#table-2-14
[12] CARB: https://www.arb.ca.gov/cc/shortlived/meetings/11282016/revisedproposedslcp.pdf

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Table 6. ODP, Atmospheric Lifetime, and 100-year GWP Comparison of Common Refrigerants

Refrigerant	ODP	Atmospheric lifetime (years)	GWP (100 year)	Notes
CFC-11	1	50	400	
CFC-12	1	102	8,500	
CFC-112	0.8	85	5,000	
CFC-114	1	300	9,300	
CFC-115	0.6	1700	7,300	
HCFC-22	0.55	13.3	1,700	
HCFC-123	0.02	1.4	93	
HCFC-124	0.022	5.9	480	
HCFC-141b	0.11	9.4	630	
HCFC-142b	0.065	19.5	2,000	
HCFC-225c/a	0.025	2.5	170	
HFC-23	0	270	14,800	
HFC-32	0	5.6	650	
HFC-125	0	32.6	2,800	
HFC-134a	0	14.6	1,430	
HFC-143a	0	48.3	3,800	
HFC-152a	0	1.5	140	
HFC-404a	0	40.4	3,260	Refrigerant blend
HFC-407c	0	15.7	1,530	Refrigerant blend
HFC-410a	0	17	1,730	Refrigerant blend
HFC-434a	0	30	3,245	Refrigerant blend
HFC-437a	0	17	1,805	Refrigerant blend
HFC-507a	0	40.5	3,300	Refrigerant blend
HFO-1234yf	0	0.029	1	
HFO-1234ze	0	0.045	1	
HFO-1336mzz	0	0.06	2	
R-170	0	12	6	Ethane
R-290	0	12	4	Propane
R-600	0	12	5	Butane
R-600a	0	12	5	Isobutane
R-601	0	12	11	Pentane
R-717	0	0.03	0	Ammonia
R-744	0	100	1	CO_2

Sources for table data:

CARB: https://www.arb.ca.gov/cc/rmp/rmprefrigerants.htm

Oak Ridge National Laboratory: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.693.4239&rep=rep1&type=pdf

United Nations Intergovernmental Panel on Climate Change: https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html

HPAC Engineering: http://www.hourahan.com/wp/wp-content/uploads/2010/08/2007-Refrig-Update.pdf

United Nations: http://conf.montreal-protocol.org/meeting/oewg/oewg-37/presession/Background_documents/TEAP%20TF%20XXVII-4%20Report%20March%202016.pdf

Wikipedia: https://en.wikipedia.org/wiki/List_of_refrigerants

University of Minnesota: https://www.esci.umn.edu/sites/www.esci.umn.edu/files/groups/biogeo/papers/2009_AREP_Archer_etal.pdf

KTH Royal Institute of Technology (Sweden): https://www.kth.se/en/itm/inst/energiteknik/forskning/ett/projekt/koldmedier-med-lag-gwp/low-gwp-news/nagot-om-hfo-koldmedier-1.602602

Note: The chemical prefixes are sometimes substituted with the letter "R." For instance, HCFC-22 is also commonly referred to as R-22 or R22. It is important to note that different testing methodologies or calculation definitions can yield slightly varying GWP values, so readers may have encountered figures that differ by a small amount from those stated below. The authors have attempted to provide the most credible, up-to-date figures possible in the table below. Even though there may be small variations in accepted values of GWP, the critical message conveyed in the table below is the large magnitude of difference in GWP and ODP among different refrigerants.

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Section 3: Agreements and Rules that Regulate Refrigerants

International Agreements

The Montreal Protocol

The most important international agreement that regulates refrigerants is the Montreal Protocol on Substances that Deplete the Ozone Layer. The Montreal Protocol was enacted in 1989 to combat the spread of CFCs, which were identified as the primary culprit behind the depletion of the Earth's ozone layer. The ozone layer protects life on the planet by absorbing most of the sun's incoming UV radiation, which causes cell damage and genetic mutation in all living organisms and can lead to skin cancer in humans.

In the 1970s, scientists began to understand that a single chlorine atom from a CFC molecule could destroy up to 100,000 ozone molecules – a rate much faster than the ozone layer could naturally regenerate[13]. This means that every pound of high-ODP CFCs in the atmosphere could destroy up to *40 tons* of ozone. In response to the alarming buildup of CFCs in the atmosphere and corresponding ozone depletion, the Montreal Protocol was enacted and eventually ratified by 197 nations – one of the most successful international environmental agreements in history. As a party to the Montreal Protocol, the U.S. phased out CFCs completely in 1996[14].

The Montreal Protocol and Kigali Amendment in a Nutshell

The Montreal Protocol, finalized in 1987 and enacted January 1, 1989, is a global agreement to protect the ozone layer by totally phasing out the production and consumption of ozone-depleting substances (ODS). The Montreal Protocol's Scientific Assessment Panel estimates that implementing the Montreal Protocol may allow the ozone layer to return to its pre-industrial levels by 2060-2075. The Protocol is legally binding and currently has 197 signatory nations.

Since it was enacted, parties to the Protocol have agreed to several amendments, which expand the types of substances covered and accelerate some of the phase-out timelines.

The most recent amendment was ratified in Kigali, Rwanda, in late 2016. The Kigali Amendment is the first amendment that seeks to restrict the production and use of refrigerants based solely on global warming potential, as all ozone-depleting refrigerants are already phased out or will be soon. The Kigali Amendment seeks to reduce global production of HFCs by 85 percent by 2036 in developed countries and by 2045-2047 for developing countries, which the UN says will avoid up to 0.5°C of global temperature rise by 2100. The UN notes that the Kigali Amendment, which has now been ratified by all 197 Montreal Protocol countries, could be the "single largest real contribution the world has made so far" in combating global climate change.

As the primary replacement for CFCs, HCFCs are still ozone destroyers, but not on the scale of CFCs. For this reason, the Montreal Protocol mandated phase out of HCFCs by 2040. However, because HCFCs are also powerful greenhouse gases and because of increasing global warming concerns,

[13] EPA: https://www.epa.gov/ozone-layer-protection/basic-ozone-layer-science
[14] EPA: https://www.epa.gov/ods-phaseout/phaseout-class-i-ozone-depleting-substances

Refrigerant Quick Reference Table

	Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable
CFC	High	High	1996	No
HCFC	High	Medium	2030	No
HFC	High	None	2036 (85%)	No
HFO	Low	None	n/a	Varies
HFO / HFC Blends	Medium	None	n/a	Low to none
Natural Refrigerants	Low	None	n/a	Varies

signatories agreed in 2007 to an accelerated phase out. That phase out is in progress now and will be largely complete by 2020, by which time the U.S. will have reduced HCFCs by 99.5 percent[15].
Early evidence seems to indicate that efforts to curb CFCs and HCFCs are having an impact. In June 2016, a team of researchers found that the "hole" in the ozone layer has shrunk by 4 million square kilometers from its maximum extent in 2000. Furthermore, the hole, which appears seasonally, is showing up for less time every year and is less deep than in past years[16].

The Kigali Amendment

To replace HCFCs, policymakers and the refrigeration industry turned to HFCs. Unlike CFCs and HCFCs, HFCs pose no significant threat to the ozone layer. In this regard, the Montreal Protocol has been successful at eliminating ozone-depleting refrigerants. However, HFCs are also potent greenhouse gases. To address the climate threat posed by HFCs, the Kigali Amendment to the Montreal Protocol was ratified in October 2016. The Kigali Amendment requires the 197 Montreal Protocol countries to begin phasing down HFCs over the coming decade, with the goal of an 85 percent reduction by 2036 in developed countries and 2045-2047 for developing countries (from a 2011-2013 baseline)[17].

It is worth noting that the Montreal Protocol and Kigali Amendment are separate agreements from the Paris Climate Accord that nations around the world signed in 2016. While the current U.S. Administration has walked away from the Paris Climate Agreement, so far no public statements have been made regarding Montreal or Kigali. As some experts have written[18], there are reasons the current U.S. administration may wish to keep the Kigali Amendment in place. Indeed, as of June 2017, the terms of that agreement remain the law of the land in the United States.

Europe's Treaty on Refrigerants

The European Union (EU) has also enacted a continental phasedown plan for HFCs, though the U.S. is not a party to that agreement. The EU cuts HFCs more aggressively over the next several years, but those cuts level out and eventually align closely to the Kigali Amendment by the 2030s[19].

National Policies and Enforcement

EPA and the SNAP Program

Like most environmental issues, implementation and enforcement of the Montreal Protocol falls within the jurisdiction of the U.S. Environmental Protection Agency (EPA). To comply with Montreal, the EPA added Sections 608 and 612 to the Clean Air Act. Section 608[20] facilitates refrigerant phase-down by providing timelines, technician certification guidelines, disposal requirements, and other practical guidance for meeting the Montreal Protocol and Kigali Amendment. Meanwhile Section 612 established the Significant

[15] EPA: https://www.epa.gov/ods-phaseout/phaseout-class-ii-ozone-depleting-substances
[16] National Geographic: http://news.nationalgeographic.com/2016/06/antarctic-ozone-hole-healing-fingerprints/
[17] United Nations Environmental Program:
http://www.unep.org/Documents.Multilingual/Default.asp?DocumentID=27086&ArticleID=36283&l=en
[18] https://www.esource.com/Blog/ESource/1-3-17-Kigali
[19] The Linde Group: http://www.boconline.ie/internet.lg.lg.irl/en/images/Guide%20to%20F-gas%20regulations674_130947.pdf
[20] https://www.epa.gov/section608

Refrigerant Quick Reference Table

	Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable
CFC	High	High	1996	No
HCFC	High	Medium	2030	No
HFC	High	None	2036 (85%)	No
HFO	Low	None	n/a	Varies
HFO / HFC Blends	Medium	None	n/a	Low to none
Natural Refrigerants	Low	None	n/a	Varies

New Alternatives Policy (SNAP) Program[21]. SNAP is the program through which the EPA implements the Montreal Protocol by evaluating and regulating ozone-depleting chemicals and their replacements. (Punishment for violating these provisions of the Clean Air Act can be given to any facility owner, operator, or service technician, and can reach $32,500 per violation per day[22].)

After overseeing the successful phase out of CFCs, SNAP has been working to phase out HCFCs since the early 2000s. On Jan. 1, 2020, all HCFCs will be banned for production or import. All use of these compounds – even in servicing legacy equipment – will be banned by 2030[23]. While there are still some products in the market that use HCFCs (most notably R-22), those products will become increasingly rare over the coming years. Because R-22 has been the most-widely used refrigerant for some time, SNAP has posted common R-22 questions[24] and a directory of replacements[25]. However, it's important to note that there is no universal alternative for R-22. If legacy systems are not replaced altogether, system operators will need to weigh the specifics of their refrigeration system with the specific qualities of potential replacement refrigerants or blends.

With the HCFC phase out nearly complete, SNAP is increasingly focused on HFCs. So far, SNAP has issued two rounds of phase outs for different types of HFC refrigerants across a range of applications. Because there is a large number of HFCs and many have different phase-out dates for different applications, it is not practical to list all the details here. However, below are links to the fact sheets and full rules the EPA has released that include details on all the HFCs that have so far been regulated.

Rule 20

Issued July 2015 – Fact Sheet[26], Full Rule[27]

Applications addressed (and phase-out dates):

- Supermarket refrigeration (July 20, 2016-January 1, 2017)
- Remote condensing units (July 20, 2016-January 1, 2018)
- Standalone retail food refrigeration equipment (July 20, 2016-January 1, 2020)
- Vending machines (July 20, 2016-January 1, 2019)

Common refrigerants covered (for a comprehensive list, refer to the Rule 20 fact sheet):

- HFC-134A
- R-404A/R-507A
- R-407A/C/F
- R-410A

[21] https://www.epa.gov/snap
[22] EPA: https://www.epa.gov/sites/production/files/2015-08/documents/section_608_of_the_clean_air_act.pdf
[23] ASHRAE: https://www.ashrae.org/File%20Library/docLib/Technology/FAQs2015/TC-02.05-FAQ-33.pdf
[24] https://www.epa.gov/snap/questions-and-answers-about-r-22a-safety
[25] https://www.epa.gov/snap/acceptable-substitutes-residential-and-light-commercial-air-conditioning-and-heat-pumps
[26] https://www.epa.gov/sites/production/files/2015-08/documents/snap_regulatory_factsheet_july20_2015.pdf
[27] https://www.gpo.gov/fdsys/pkg/FR-2015-07-20/pdf/2015-17066.pdf

Refrigerant Quick Reference Table

	Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable		Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable
CFC	High	High	1996	No	**HFO**	Low	None	n/a	Varies
HCFC	High	Medium	2030	No	**HFO / HFC Blends**	Medium	None	n/a	Low to none
HFC	High	None	2036 (85%)	No	**Natural Refrigerants**	Low	None	n/a	Varies

Rule 21

Issued December 2016 – [Fact Sheet][28], [Full Rule][29] Applications addressed (and phase-out dates):

- Centrifugal chillers (January 1, 2024)
- Positive displacement chillers (January 1, 2024)
- Cold storage warehouses (January 1, 2023)
- Retail food refrigeration (January 1, 2021)
- Food processing (January 1, 2021)
- Vending machines (January 1, 2021)
- Household refrigerators and freezers (January 1, 2021)

Common refrigerants covered (for a comprehensive list, refer to the Rule 21 fact sheet):

- HFC-134A
- R-407A/B/C/F
- R-434A
- R-437A

HFOs: Low or High GWP?

HFOs have barely been in existence for a decade, so both industry and regulators are still grappling with how to address these refrigerants. In some applications (namely centrifugal, reciprocating, and screw chillers), HFOs have been approved by SNAP as a direct replacement for legacy refrigerants. Since HFOs by themselves pose minimal climate and global warming risks, these designations are relatively uncontroversial.

However, in many applications, HFOs are blended with HFCs. The refrigerant industry rightfully points out that these blends are not harmful to the ozone layer and pose a major reduction in GWP compared with pure HFCs. However, with GWPs that can exceed 1,000, some experts believe that the climate impacts of these blends are too great to fall under the umbrella of "low GWP," though these impacts are less than pure HFCs,

So far, there has been no official designation in the U.S. for these blends regarding what constitutes "high GWP." However, in the EU, the legally accepted maximum value to be considered a "low-GWP" refrigerant is a 100-year value of 150 or less (or up to 750 in some applications). While not officially mandated in the U.S., many stakeholders have begun to adopt these values as well.

More information on the status and physical characteristics of HFOs and HFO blends can be found in the *Research and Development Roadmap: Next Generation Low-GWP Refrigerants*, discussed in Appendix 2 of this report.

Areas Not Yet Regulated by SNAP

The following HFC applications have not yet been assigned a specific phase-out date by SNAP[30]:

- Industrial process refrigeration
- Blast chillers or blast freezers
- Standalone ice makers
- Very low temperature equipment (-50°F or lower)
- Equipment designed to make or process cold food and beverages that are dispensed via a nozzle, such as ice cream machines, slushy iced beverage dispensers, and soft-drink dispensers

[28] https://www.epa.gov/sites/production/files/2016-12/documents/snap_action_scr2_factsheet.pdf
[29] https://www.gpo.gov/fdsys/pkg/FR-2016-12-01/pdf/2016-25167.pdf
[30] Emmerson Climate Technologies: http://www.emersonclimate.com/en-us/About_Us/industry_stewardship/E360/Documents/Webinar-Presentations/14-EPA-Final-Refrigerant-Ruling.pdf

Refrigerant Quick Reference Table

	Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable		Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable
CFC	High	High	1996	No	**HFO**	Low	None	n/a	Varies
HCFC	High	Medium	2030	No	**HFO / HFC Blends**	Medium	None	n/a	Low to none
HFC	High	None	2036 (85%)	No	**Natural Refrigerants**	Low	None	n/a	Varies

SNAP and Ammonia

Of particular interest to BPA is ammonia (R-717) because it is the most commonly used alternative refrigerant in the industrial sector. Currently, ammonia absorption and ammonia vapor compression are [listed by SNAP as acceptable]() for refrigerated warehouses, chillers, process air conditioning, and industrial process refrigeration. SNAP does not list ammonia as a suitable refrigerant for very-low temperature refrigeration. However, even though ammonia is approved for many common industrial uses, ASHRAE Standard 34 does list it as a category B2 refrigerant, meaning that it is toxic and has low (but not zero) flammability. Both the U.S. Occupational Safety and Health Administration (OSHA) and the EPA have resources on their websites that address safe handling, disposal, and spill treatment guidelines for ammonia and other toxic or flammable natural refrigerants.

Note that phase outs apply to refrigerants for use in new systems and replacing refrigerants in existing systems. However, systems already operating with legacy refrigerants and not leaking may legally continue to operate. "New" systems are defined by the EPA as being built before the deadline (the sale, shipping, or commissioning dates are not taken into account in considering whether a system is compliant)[31].

Private Sector Initiatives

In September 2014[32] and again in October 2015[33], the private sector made commitments in tandem with Obama Administration executive actions to reduce emissions of HFCs. These commitments are different for each major player in the refrigerant industry and vary both in scope and ambition. The types of commitments include developing a low-GWP performance test center (Danfoss), reducing refrigerant-related emissions from products by 50 percent by 2020 (Ingersoll Rand), accelerating adoption of HFC-free retail refrigeration systems (Target), and forming an expert committee with $1 million in funding to identify and prioritize research projects needed to fill knowledge gaps (Air-Conditioning, Heating, and Refrigeration Institute [AHRI]). For a more comprehensive list of industry action on low-GWP refrigerants, refer to Appendix 1.

Further voluntary private sector commitments were made in early 2016 by AHRI and the Association of Home Appliance Manufacturers (AHAM)[34]. However, these commitments were less aggressive than the later-adopted Kigali Amendment[35] and, thus, may no longer be sufficient to meet Federal phase-down timelines.

California Initiatives

California currently adheres to the SNAP/Montreal Protocol guidelines. However, the state also engages in additional oversight via the California Air Resources Board (ARB), which has run the Refrigerant

[31] Emmerson Climate Technologies: http://www.emersonclimate.com/en-us/About_Us/industry_stewardship/E360/Documents/Webinar-Presentations/14-EPA-Final-Refrigerant-Ruling.pdf
[32] http://www.igsd.org/documents/20140916HFCFactSheet.pdf
[33] https://www.whitehouse.gov/the-press-office/2015/10/15/fact-sheet-obama-administration-and-private-sector-leaders-announce
[34] CARB: https://www.arb.ca.gov/cc/shortlived/meetings/11282016/revisedproposedslcp.pdf
[35] AHAM: https://www.aham.org/AHAM/News/Latest_News/Home_Appliance_Industry_Sets_Goals_to_Eliminate_Use_of_HFC_Refrigerants.aspx

Refrigerant Quick Reference Table

	Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable		Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable
CFC	High	High	1996	No	**HFO**	Low	None	n/a	Varies
HCFC	High	Medium	2030	No	**HFO / HFC Blends**	Medium	None	n/a	Low to none
HFC	High	None	2036 (85%)	No	**Natural Refrigerants**	Low	None	n/a	Varies

Management Program[36] (RMP) since January 2011. In addition to providing information and resources on refrigerants, the RMP also requires the owner of any stationary system that contains over 50 pounds of refrigerant to register each system in the state's R3 Database[37]. Registration in the database is compulsory for commercial, industrial, and institutional refrigeration systems but is not required for HVAC systems used for general air conditioning (though those systems are still subject to the service practice requirements of ARB)[38]. The RMP requires that systems are inspected monthly to annually, depending on specifics of that system[39] and that inspections be carried out by a technician who is EPA- and state-certified. Inspection reports are filed into the R3 Database; if a technician discovers a system is leaking a high-GWP refrigerant, the owner has 14 days to fix the leak or replace the system. The RMP also tracks sales, recycling, and disposal of refrigerants.

For more information on ARB's refrigerant mitigation strategy, the agency's Short-Lived Climate Pollutant Program website[40] offers numerous useful resources.

In Southern California, the South Coast Air Quality Management District's Rules 1415 and 1415.1[41] lay out a slightly different timeline and reporting protocol than the RMP guidelines, but the jurisdiction of that agency doesn't overlap any geographical areas where BPA is active.

Pacific Northwest Initiatives

No states in the Pacific Northwest engage in agreements, rules, regulations, or policies that differ from Federal guidelines or the Montreal Protocol and Kigali Amendment with regard to phasing out or banning refrigerants on climate change grounds. However, some states and municipalities have specific guidelines for disposal, recycling, or reporting. Details of those programs vary, so readers are advised to check with relevant state and local agencies for guidance.

[36] https://www.arb.ca.gov/cc/rmp/rmp.htm
[37] https://ssl.arb.ca.gov/rmp-r3/
[38] ARB: https://www.youtube.com/watch?v=5P_0K3CCsic&feature=youtu.be
[39] https://www.arb.ca.gov/cc/rmp/rmpcomply.htm
[40] https://www.arb.ca.gov/cc/shortlived/shortlived.htm
[41] http://www.aqmd.gov/home/regulations/compliance/rule-1415-stationary-air-conditioning-systems

Section 4: Climate Impacts of Refrigerants in the Pacific Northwest

Comparing the Impacts of Refrigerant Emissions to Electricity Generation

To date, there's been no known effort to quantify the exact emissions of refrigerant leaks across BPA's service territory. However, it is possible to make a reasonable estimate by applying research conducted by ARB in California to this region.

In 2015, ARB published an in-depth inventory of HFCs within California[42]. Though there are some demographic, economic, and climactic differences between California and the Northwest, the ARB numbers still serve as the most reasonable numbers on which to base impacts of refrigerants within BPA's service territory. ARB found that non-automotive HFC refrigerants had an annual leak rate in California of 11.42 million metric tons of CO_2 equivalent in 2013, based on 100-year GWP. Adjusting for population (a factor of 2.95 difference between that of California[43] and BPA's service territory[44]), this amounts to an estimated 3.87 million metric tons of CO_2-equivilent HFCs (8.53 billion pounds) at 100-year GWP that were emitted within BPA's territory in 2013 (Table 7).

Table 7. Estimated Annual Amount of HFCs Released in BPA's Service Territory

Sector	Estimated thousands of metric tons CO_2 equivalent (100-year GWP) [45]
Commercial	2,573
Industrial	746
Residential	553
Total	3,871

To put the problem of leaking refrigerants into perspective, the Pacific Northwest Utilities Conference Committee (PNUCC) estimates that the Northwest region emitted 56-57 million metric tons of CO_2 from power generation in 2013[46]. This indicates that refrigerants account for roughly 7 percent as much of the global warming impacts as the entire electric power sector in the region. By comparison, all the wind power in the region totaled 7.3 percent of all electricity in 2015[47]. So leaking refrigerants "cancel out" essentially all the wind power generated each year in the Northwest from a global warming perspective.

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[42] ARB: https://www.arb.ca.gov/cc/inventory/slcp/doc/hfc_inventory_tsd_20160411.pdf
[43] US Census: http://www.census.gov/quickfacts/table/PST045215/06
[44] BPA: https://www.bpa.gov/news/pubs/generalpublications/gi-bpa-facts.pdf
[45] *These numbers were gathered from ARB analysis (https://www.arb.ca.gov/cc/inventory/slcp/data/slcp_fgas_100yr1.pdf) in California then applied to the population of BPA's service territory. As such, these figures are estimates, as they do not attempt to adjust for variabilities in climate, demographics, or other variables. Nevertheless, these numbers should provide a reasonably accurate picture of the Northwest.*
[46] PNUCC: http://www.pnucc.org/sites/default/files/Carbon%20Emissions%20-%20a%20Northwest%20Perspective%20July%202014_0.pdf
[47] BPA: https://www.bpa.gov/news/pubs/generalpublications/gi-bpa-facts.pdf

Refrigerant Leaks in the Pacific Northwest

It turns out that the largest individual annual polluters (by far) are large, refrigerated, cold storage facilities (Table 8). The biggest offenders in aggregate are unitary and residential central air conditioners. Since BPA likely has a lower penetration of these units than California, these numbers might be slightly exaggerated, especially in areas farther north and west within BPA's territory. Another aggregate offender to consider is mid-sized centralized refrigeration systems, which are moderately high in both sheer number and volume of annual leakage per unit.

Regarding targets for end-of-life or recycling efforts, the biggest overall sources of pollution are small items that are large in number, such as central air conditioning units and refrigerators (Table 9). Meanwhile, the largest individual sources of pollution are large refrigerated warehouses and large refrigerated process cooling facilities, which both typically emit on the order of 1,000 pounds of refrigerants each at end of life.

Refrigerant Quick Reference Table

	Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable		Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable
CFC	High	High	1996	No	**HFO**	Low	None	n/a	Varies
HCFC	High	Medium	2030	No	**HFO / HFC Blends**	Medium	None	n/a	Low to none
HFC	High	None	2036 (85%)	No	**Natural Refrigerants**	Low	None	n/a	Varies

*Table 8. Typical Refrigerant Leak Rates by End Use during Equipment Operational Life**

Equipment Type or Emissions sub-sector [48]	Estimated units in BPA territory	Avg. charge of refrigerant (lbs)	Avg. annual leak rate	Avg. annual leak rate per unit (lbs)	Estimated annual loss for all units across BPA (lbs)
Refrigeration – large centralized system ≥ 2,000 lbs	285	3,635	16.6%	603	171,818
Refrigeration – medium centralized system 200-2,000 lbs	8,041	704	17.6%	124	996,272
AC – large centrifugal chiller ≥ 2,000 lbs	1,751	3978	2.3%	91	160,192
AC – medium centrifugal chiller 200-2,000 lbs	553	1007	1.4%	14	7,790
AC chiller – packaged, 200-2,000 lbs.	3,454	526	6.9%	36	125,368
Refrigeration – large cold storage ≥ 2,000 lbs	51	7929	15.9%	1261	64,104
Refrigeration – medium cold storage, 200-2,000 lbs	142	494	18.9%	93	13,293
Refrigeration process cooling ≥ 2,000 lbs	36	5242	10.0%	524	18,658
Refrigerated condensing units, 50-200 lbs	26,339	122	15.0%	18	482,003
Unitary A/C,50-200 lbs	24,881	100	11.3%	11	281,159
Refrigerated condensing units, 50 lbs or less	106,610	31.4	15.0%	4.7	502,134
Refrigerated standalone display cases	232,610	7.1	0.0%	0.00	0
Refrigerated vending machines	177,763	0.66	0.0%	0.00	0
Unitary A/C, 50 lbs or less (central)	858,847	15.1	10.0%	1.5	1,296,860
Commercial AC (window unit)	220,203	1.54	2.0%	0.03	6,782
Residential appliance (refrigerator-freezer)	6,006,339	0.34	1.0%	0.003	20,422
Residential A/C (central)	2,451,186	7.5	10.0%	0.75	1,838,390
Residential A/C (window unit)	1,262,712	1.54	2.0%	0.03	38,892

* on a per-unit basis and total for all units across BPA's territory

[48] Table is adapted to the BPA service territory using ARB data: https://www.arb.ca.gov/cc/inventory/slcp/doc/hfc_inventory_tsd_20160411.pdf.

Refrigerant Quick Reference Table

	Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable
CFC	High	High	1996	No
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HFC	High	None	2036 (85%)	No

	Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable
HFO	Low	None	n/a	Varies
HFO / HFC Blends	Medium	None	n/a	Low to none
Natural Refrigerants	Low	None	n/a	Varies

*Table 9. Typical Annual Refrigerant Leak Rates by End Use at Equipment End-of-Life**

Equipment Type or Emissions sub-sector [49]	Estimated units in BPA territory	Average end-of-life loss	Average charge at end of life (lbs)	Estimated end-of-life loss per unit (lbs)	Estimated annual end-of-life loss across BPA (lbs)
Refrigeration – large centralized system ≥ 2,000 lbs	285	20%	2871	574	8,759
Refrigeration – medium centralized system 200-2,000 lbs.	8,041	20%	577	115	49,485
AC – large centrifugal chiller ≥ 2,000 lbs	1,751	20%	3887	777	54,023
AC – medium centrifugal chiller, 200-2,000 lbs	553	20%	993	199	4,376
AC chiller – packaged, 200-2,000 lbs	3,454	20%	490	98	13,620
Refrigeration – large cold storage ≥ 2,000 lbs	51	20%	5788	1158	2,355
Refrigeration – medium cold storage, 200- < 2,000 lbs	142	20%	316	63.2	428
Refrigeration process cooling ≥ 2,000 lbs	36	20%	4718	944	1,279
Refrigerated condensing units 50 to 200 lbs	26,339	20%	122	24.4	25,641
Unitary A/C 50-200 lbs	24,881	20%	89	17.8	23,532
Refrigerated condensing units ≤ 50 lbs	106,610	34%	27	9.18	39,209
Refrigerated standalone display cases	232,610	100%	7.1	7.1	66,186
Refrigerated vending machines	177,763	100%	0.66	0.66	6,264
Unitary A/C, ≤ 50 lbs (central)	858,847	56%	12.1	6.78	328,464
Commercial AC (window unit)	220,203	100%	1.17	1.17	17,173
Residential appliance (refrigerator-freezer)	6,006,339	77%	0.29	0.22	76,679
Residential A/C (central)	2,451,186	80%	5.3	4.24	554,793
Residential A/C (window unit)	1,262,712	100%	1.17	1.17	98,359

* on a per-unit basis and total for all units across BPA's territory

[49] Table is adapted to the BPA service territory using ARB data: https://www.arb.ca.gov/cc/inventory/slcp/doc/hfc_inventory_tsd_20160411.pdf.

Refrigerant Quick Reference Table

	Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable
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	Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable
HFO	Low	None	n/a	Varies
HFO / HFC Blends	Medium	None	n/a	Low to none
Natural Refrigerants	Low	None	n/a	Varies

Section 5: Choosing the Right Refrigerants

With the phase-out dates for HFCs now established for many applications, the big decision system operators need to make is how to go about replacing high-GWP refrigerants with lower GWP alternatives.

To assist operators with evaluating options, SNAP maintains a database of acceptable alternatives, sorted by application. After looking at all the possible options, it is possible – with the help of a certified technician or other expert – to narrow the list to the best alternative given the particulars of a refrigeration system (or to determine if whole-system replacement is the best course of action). It is also important to note that using alternative refrigerants in a legacy system poses cost challenges because equipment will typically have to be modified, tested, and certified to operate with different refrigerants. Though this is usually a straightforward process for a qualified professional, it can still be a time-consuming task.

When considering alternative refrigerants, toxicity and flammability may play into the decision-making process. To address this, ASHRAE maintains a directory of flammability and toxicity of common refrigerants as part of Standard 34[50], including data on air concentration limits and occupational exposure limits. Some refrigerants may be inappropriate for use in certain operating environments, even though they have a low GWP.

If needed, data sets even deeper than ASHRAE Standard 34 are available. For more details on the health impacts of all common refrigerants, Toxicity Data to Determine Refrigerant Concentration Limits[51], commissioned by the Air-Conditioning and Refrigeration Technology Institute (ARTI), is possibly the most in-depth resource available. And for more information on flammability, including flashpoints and air saturation flammability thresholds, the SNAP program offers some detailed data, but it is in the Federal Register, which can be difficult to search and is not always complete. The National Institute of Standards and Technology (NIST) is currently developing new metrics for refrigerant flammability, but those have not yet been finalized. Most refrigerant makers also provide comprehensive information on the toxicity, flammability, and operational parameters of their products.

Finally, to actually put all this information to use in the field, ASHRAE has developed Standard 15: Safety Standard for Refrigeration Systems[52]. This standard outlines how to handle refrigerants safely, service equipment, and address problems such as leaks. It is a useful resource for system operators, field technicians, or BPA staff to help make sure industry best practices are followed when selecting and working with refrigerants.

[50] http://www.techstreet.com/ashrae/standards/ashrae-15-2013-packaged-w-34-2013?utm_source=promotion&utm_medium=landingpage&utm_campaign=86021&utm_term=86021&utm_content=86021&ashrae_auth_token=&gateway_code=ashrae&product_id=1868609

[51] http://www.ahrinet.org/App_Content/ahri/files/RESEARCH/Technical Results/MCLR-Program/Toxicity Data to Determine Refrigerant Concentration Limits-Calm-2000-DOE-CE-23810-110.pdf

[52] http://www.techstreet.com/ashrae/standards/ashrae-15-2013-packaged-w-34-2013?utm_source=promotion&utm_medium=landingpage&utm_campaign=86021&utm_term=86021&utm_content=86021&ashrae_auth_token=&gateway_code=ashrae&product_id=1868609

Refrigerant Quick Reference Table

	Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable		Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable
CFC	High	High	1996	No	**HFO**	Low	None	n/a	Varies
HCFC	High	Medium	2030	No	**HFO / HFC Blends**	Medium	None	n/a	Low to none
HFC	High	None	2036 (85%)	No	**Natural Refrigerants**	Low	None	n/a	Varies

Section 6: Conclusions

Because of ongoing environmental issues and technology development, the refrigeration industry continues to evolve. Starting with fears of ozone depletion in the 1980s, the global community sought to address the challenges posed by refrigerants with the Montreal Protocol, which originally phased out CFCs. Since then, this protocol has been expanded to cover HCFCs that have both major ozone depletion potential and high global warming potential. The latest amendment to this protocol, ratified in 2016 in Kigali, Rwanda, brought virtually every country on earth together to agree to phase down HFCs over the coming decades. In place of these HFCs, the most viable candidates are so-called natural refrigerants, HFOs, and/or HFO/HFC blends.

However, the phase-down of HFCs is not without challenges. Natural refrigerants bring challenges, such as toxicity and flammability. Furthermore, the refrigeration systems themselves may also have issues when transitioning away from HFCs, including compatibility with the new refrigerants, performance, and energy efficiency. Meanwhile, HFOs and HFO/HFC blends are just entering the market, and much remains unresolved about these compounds, including whether some should even qualify as “low” GWP at all. So far, many of these issues surrounding next-generation refrigerants remain unresolved.

In the U.S., implementation, guidance, and enforcement of the Montreal Protocol falls within the jurisdiction of the U.S. EPA. The EPA provides timelines, technician certification guidelines, disposal requirements, and other practical guidance for meeting the Montreal Protocol and Kigali Amendment. The EPA also investigates and approves suitable replacements through the SNAP program.

Working within the framework of the SNAP program, BPA would like to provide resources to help operators make refrigerant-related decisions while helping to improve the energy efficiency of their systems. To this end, BPA is continuing to:

- Quantify the energy performance of traditional and natural refrigerant heat pump and refrigeration systems with field studies through the Refrigerants Collaborative project with the Electric Power Research Institute, Southern California Edison, Southern Company, and San Diego Gas & Electric, and
- Create energy conservation measures that replace existing equipment with new energy-efficient equipment that can work with low-GWP refrigerants.

Looking ahead, a number of issues will unfold in this space. Policy drivers within the U.S. could alter the way the SNAP program is administered or how the U.S. views various international treaties dealing with climate issues, including the Montreal Protocol. Technical questions remain unresolved as well, most notably in defining whether HFO/HFC blended refrigerants qualify as low-GWP under the Kigali Amendment. Further market-driven innovations promise to push this industry in new directions as established companies and startups achieve new technological advances. As these new challenges and opportunities arise, BPA would like to continue to maintain a position to help operators and utilities select energy-efficient options that meet the regulatory requirements while helping the entire market move forward in adopting energy-efficient, sustainable solutions.

Refrigerant Quick Reference Table

	Global Warming Potential	Ozone Depletion Potential	Phase Out Date	Toxic / Flammable
CFC	High	High	1996	No
HCFC	High	Medium	2030	No
HFC	High	None	2036 (85%)	No
HFO	Low	None	n/a	Varies
HFO / HFC Blends	Medium	None	n/a	Low to none
Natural Refrigerants	Low	None	n/a	Varies

References

References have been provided in the text and as footnotes throughout this report.

Appendix 1: Industry Positions on Low-GWP Refrigerants

Major industry entities have recently released policy statements on the Kigali Amendment or in response to other market developments. While this is not comprehensive listing, a few are included below to provide a better feel for the state of the industry and the mood among manufacturers and trade organizations as this sector evolves.

ASHRAE position document on refrigerants and their responsible use[53]

"ASHRAE's position is that the selection of refrigerants and their operating systems be based on a holistic analysis of multiple criteria. ASHRAE promotes responsible use of refrigerants and supports the efforts to advance technologies that minimize impact on the environment while enhancing performance, cost effectiveness, and safety."

Daikin's position on the Kigali Agreement for HFC phase down[54]

"Daikin welcomes the Kigali Agreement for an HFC phase down in CO_2 equivalent under the Montreal Protocol. To mitigate future global climate change, it is important to take a "Sooner, the Better" approach. Early implementation is a key to the further reduction of future impact. As soon as the most balanced and feasible solution for an application is found, Daikin will commercialize and disseminate the technology to contribute to the efforts to mitigate global climate change. Also, while taking "Sooner, the Better" approach, as a refrigerant manufacturer, Daikin will continue to seek the "optimal refrigerant" for every type of application for further mitigation of global climate change."

Other Efforts

As mentioned elsewhere, in September 2014[55] and again in October 2015[56], the private sector made commitments in tandem with Obama Administration executive actions to reduce emissions of HFCs. Those committing to reduce impacts of HFCs include:

- AHRI
- Carrier
- Chamois (formerly DuPont)
- Coca-Cola
- Daikin Industries
- Danfoss
- Dow Chemical
- Emerson Climate Technologies
- Honeywell
- Ingersoll Rand
- Johnson Controls
- Kroger
- PepsiCo
- Target
- Thermo Fisher Scientific
- True Manufacturing

[53] https://www.ashrae.org/File Library/docLib/About Us/PositionDocuments/Refrigerants-and-their-Responsible-Use-Position-Document-2014-pdf.pdf
[54] https://www.daikin.com/csr/EN_Kigali_Agreement_Daikin_Stance_FINAL.pdf
[55] http://www.igsd.org/documents/20140916HFCFactSheet.pdf
[56] https://www.whitehouse.gov/the-press-office/2015/10/15/fact-sheet-obama-administration-and-private-sector-leaders-announce

Appendix 2: Resources for Further Reading

- The National Renewable Energy Laboratory has developed a Research and Development Roadmap for Next-Generation Low Global Warming Potential Refrigerants[57]. The Roadmap seeks to identify and highlight high-priority R&D activities the U.S. Department of Energy could support to help accelerate the transition to next-generation, low-GWP refrigerants in HVAC equipment and covers residential refrigeration, self-contained commercial refrigeration, supermarket refrigeration, residential and commercial direct-expansion air conditioning, and chillers.

- In late 2016, the ARB released a new proposed Short-Lived Climate Pollutants Strategy[58]. The strategy lays out detailed background information on the history of HFCs, the current status, and the latest science, and outlines a path that California can take to mitigate such pollutants.

- The UN Environmental Program has many valuable resources on refrigerants, climate change, and the Montreal Protocol and Kigali Amendment. One of the most useful is the report HFCs: A Critical Link in Protecting Climate and the Ozone Layer[59]. It is a synthesis report that contains much of the same type of material as this document but in somewhat more detail.

- The U.S. EPA maintains robust Section 608[60] and SNAP Program[61] websites. These websites have a wealth of up-to-the-minute resources, including SNAP's comprehensive directories for acceptable HFC substitutes based on both environmental and human health considerations, technician certification information, resources for businesses and homeowners, and other valuable sources of information. These web portals are well-maintained and easy to navigate.

- The Institute for Governance and Sustainable Development (IGSD) is a Washington D.C.-based nonprofit that has produced several high-quality resources aimed at policymakers, analysts, and other stakeholders, including Primer on Hydrofluorocarbons (HFCs), Primer on Short-Lived Climate Pollutants (SLCPs)[62], and Alternatives to High-GWP Hydrofluorocarbons[63]. IGSD also maintains an online library with relevant, high-quality academic and government publications.

[57] https://energy.gov/eere/buildings/downloads/research-development-roadmap-next-generation-low-global-warming-potential
[58] https://www.arb.ca.gov/cc/shortlived/shortlived.htm
[59] http://www.ccacoalition.org/en/resources/hfcs-critical-link-protecting-climate-and-ozone-layer-synthesis-report
[60] https://www.epa.gov/section608
[61] https://www.epa.gov/snap
[62] http://www.igsd.org/primers/hfc/
[63] http://www.igsd.org/documents/HFCSharpeningReport.pdf