Market Characterization

Fire Suppression, Commercial Comfort Cooling, Cold Storage, Refrigerated Food Processing and Dispensing Equipment, and Household Refrigeration Industries in the United States

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Prepared for
U.S. Environmental Protection Agency
Stratospheric Protection Division
Office of Atmospheric Programs
1200 Pennsylvania Avenue, NW
Washington, DC 20460

Prepared by
ICF International
1725 Eye Street, NW
Washington, DC 20006

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Acronyms and Abbreviations

Acronym / Abbreviation	Definition
3PL	Third party logistics
ACE	Armored Combat Earthmover
AHRI	Air-Conditioning, Heating, & Refrigeration Institute
ANSI	American National Standards Institute
APUs	Auxiliary power units
Ar	Argon
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASV	Autonomous surface vehicles
BTU	British Thermal Units
CAA	Clean Air Act
CFC	Chlorofluorocarbon
CO_2	Carbon dioxide
CVN	Aircraft carrier (nuclear propulsion)
DoD	U.S. Department of Defense
EER	Energy efficiency ratio
EPA	U.S. Environmental Protection Agency
FAASV	Field artillery ammunition supply vehicle
FEMP	Federal Energy Management Program
FKs	Fluoroketones
GE	General Electric
GWP	Global warming potential
HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofluorocarbons
HFOs	Hydrofluoro-olefins
HFPEs	Hydrofluoropolyethers
HMMWV	Up-armored high mobility multipurpose wheeled vehicle
IG	Inert gas
IIAR	International Institute of Ammonia Refrigeration
IPLV	Integrated part load value

Acronym / Abbreviation	Definition
ISO	International Organization for Standardization
kg	Kilogram
kW	Kilowatt
LAES	Locally applied extinguishing systems
LAVs	Light armored vehicles
LCS	Littoral combat ship
LEED	Leadership in Energy & Environmental Design
LHA	Landing helicopter assault
LHD	Landing helicopter deck
LPD	Landing platform/dock
LVSR	Logistics vehicle system replacement
MRAP	Mine resistant ambush protected
MT	Metric tons
MTVR	Medium tactical vehicle replacement
N_2	Nitrogen
NFPA	National Fire Protection Association
NIK	Not-in-kind
ODP	Ozone depletion potential
ODS	Ozone depleting substances
OSHA	Occupational Safety and Health Administration
RAD	Responsible Appliance Disposal
SCAFE	Self-contained automatic fire extinguishing systems
SEE	Small emplacement excavator
SNAP	Significant New Alternatives Policy
UL	Underwriters Laboratories
UNFI	United Natural Foods, Inc.
USDA	United States Department of Agriculture

Executive Summary

This report characterizes the current state of the U.S. market for the industries that are anticipated to be impacted by the Environmental Protection Agency's (EPA's) proposed rule on changing the listing status for certain substitutes under the Significant New Alternatives Policy (SNAP) program. This report includes information on the fire suppression, commercial comfort cooling, cold storage, refrigerated food processing and dispensing equipment, and household refrigeration industries. Historically, each of these industries has relied on ozone depleting substances (ODS), which are substances that destroy the stratospheric ozone layer that shields the Earth from overexposure to the sun's ultraviolet radiation. Each chapter of this document characterizes one of these industries in terms of the market size and companies, historical and current use of ODS and alternatives, the availability of climate-friendly alternatives, and barriers identified in transitioning to new alternatives.

1 U.S. Fire Suppression Industry

1.1 Introduction

The fire suppression industry has historically used halons, a class of halogenated chemicals containing bromine, as clean extinguishing agents (i.e., those that do not leave residue following system discharge) in many different applications. Halons have a unique combination of characteristics including being electrically non-conductive, dissipating rapidly without residue (i.e., clean), efficiently extinguishing most types of fires, and low toxicity. These agents are extremely effective on ordinary combustibles, flammable liquids and gases, and electrical fires (i.e., Class A, Class B, and Class C fires, respectively). These characteristics allow systems employing these agents to effectively protect valuable and sensitive assets in locations such as computer and control rooms, electronic data processing facilities, museums, military equipment, shipboard machinery space, and oil and gas industry facilities.

Halons have very high ozone depletion potentials (ODPs)[1] because they contain bromine, which has a higher reactivity with ozone than chlorine. Specifically, the ODPs of halon 1211 and halon 1301 are listed in the Montreal Protocol with ODP values of 3.0 and 10.0, respectively. Under the U.S. Clean Air Act (CAA), the United States banned the production and import of newly produced halons beginning January 1, 1994, in compliance with the Montreal Protocol. The U.S. government also imposed an excise tax on halons and passed regulations to reduce emissions of halon through technician training and proper disposal. The U.S. fire suppression industry supported the phaseout of halon production by working to find effective substitutes and to reduce unnecessary emissions of halon. Because the Montreal Protocol ended global halon production in 2010, recycled halon is relied on for continuing uses of halons.

In response to the early phaseout of halon production, industry took actions to find alternatives including lower ODP hydrochlorofluorocarbons (HCFCs), non-ozone-depleting hydrofluorocarbons (HFCs), as well as a variety of lower Global Warming Potential (GWP) or no-GWP alternatives (e.g., inert gases, carbon dioxide (CO_2), powdered aerosols, foams, water) in the early 1990s. Although HFCs do not contribute to ozone depletion, these substances are powerful greenhouse gases thousands of times more potent per pound than CO_2 and their emissions contribute to climate change. Industry also took actions to minimize emissions and halon recycling emerged as an important initiative to both reduce unnecessary emissions and to ensure supplies of halons during the transition. Other efforts included changes to national and international fire codes and standards to discourage the use of halons for testing and training while supporting the adoption of the alternatives listed as acceptable replacements for halons by EPA's SNAP program.

The remainder of this chapter characterizes the U.S. fire suppression sector in terms of key market players, historical and current extinguishing agent use, and the availability of alternative, more climate-friendly fire suppression agents.

[1] ODP is a measure relative to CFC-11, which has an ODP of 1.0.

1.2 Market Characterization

This section provides an overview of fire suppression end-uses and applications, as well as the current equipment market and key manufacturers.

1.2.1 Overview of Fire Suppression Products

The fire suppression industry uses fire extinguishing agents for a variety of applications. This market characterization covers two main product categories: **total flooding systems** and **streaming applications**.[2,3]

- **Total flooding systems** are designed to automatically discharge a fire extinguishing agent by detection and related controls or manually by a system operator, and achieve a specified minimum agent concentration throughout a confined space (i.e., volume percent of the agent in air). Within this category are two specialized applications: explosion suppression and inerting against explosions and fires.

- **Streaming applications** use portable fire extinguishers that can be manually manipulated to discharge an agent in a specific direction and release a specific quantity to extinguishing agent at the time of a fire.

Fire suppression applications have a wide variety of characteristics that depend on the details of the hazard being protected against and the assets being protected. Specifically, the following criteria must be considered before a product is chosen to protect a particular area (UNEP 2014):

- Whether the space may be occupied at the time a fire occurs;

- Whether fire extinguishing is to be achieved by local application of an agent directly onto burning materials or by creation of a fire extinguishing atmosphere in a defined volume (total flooding); and

- Asset value and sensitivity of objects and spaces being protected.

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[2] Self-contained automatic fire extinguishing systems (SCAFE) and locally applied extinguishing systems (LAES) are not covered in this market characterization. SCAFE and LAES did not historically use ODS and therefore EPA's SNAP program has not traditionally analyzed these fire suppression applications.

[3] Other specialized fire suppression products such as explosion suppression and fire/explosion inerting are not covered in this market characterization because of their specialized application and limited market presence. These systems decrease the likelihood of combustion by maintaining a chemically-inert and non-reactive atmosphere. They are used in military, oil processing, and other similar applications.

Table 1 lists the national and international standards related to fire extinguishing products (i.e., total flooding systems, streaming applications) from organizations such as the National Fire Protection Association (NFPA), International Organization for Standardization (ISO), American National Standards Institute (ANSI), and Underwriters Laboratories (UL). These standards include requirements, specifications, and recommendations for the design, installation, testing, maintenance, and safety factors for different types of fire suppression agents in total flooding systems and streaming applications.

Table 1. Standards on National and International Fire Suppression Products

Product Category	Standard	Title	Description
Total Flooding Systems	NFPA 2001	Standard on Clean Agent Extinguishing Systems	• Sets minimum agent design concentrations for halogenated agents and inert gases and minimum safety factors for different fire hazards
	NFPA 12	Standard on Carbon Dioxide Extinguishing Systems	• Requirements for carbon dioxide fire extinguishing systems to help ensure that such equipment will function as intended throughout its life
	NFPA 12A	Standard on Halon 1301 Fire Extinguishing Systems	• Requirements for total flooding halon 1301 systems to help those who design, install, test, inspect, approve, list, operate, maintain, decommission, and remove halogenated agent systems ensure that such equipment will function as intended throughout its life
	NFPA 750	Standard on Water Mist Fire Protection Systems	• Standardization of design, installation, maintenance, and testing requirements for water mist fire suppression systems
	ISO 14520	Gaseous Fire-Extinguishing Systems	• Requirements and recommendations for design, installation, testing, maintenance and safety of gaseous firefighting systems in buildings, plant or other structures • Characteristics of various agents and corresponding types of fire
	ISO 6182-9	Fire protection – Automatic sprinkler systems	• Requirements and test methods for water mist nozzles
Streaming Applications	NFPA 10	Standard for Portable Fire Extinguishers	• Requirements to ensure that portable fire extinguishers will work as intended to provide a first line of defense against fires of limited size
	NFPA 12B	Standard on Halon 1211 Fire Extinguishing Systems	• Minimum requirements for design, installation, testing, inspection, and maintenance of halon 1211 extinguishing systems
	ANSI/UL 711	Standard for Rating and Fire Testing of Fire Extinguishers	• Requirements for rating, and performance during fire tests, of fire extinguishers intended for use in attacking Class A, B, C, D, and K fires[a] • Requirements for performance during fire tests of fire extinguishing agents for application on Class D fires

Product Category	Standard	Title	Description
	UL 2129	Halocarbon Clean Agent Fire Extinguishers	• Requirements for construction and performance of portable halocarbon clean agent fire extinguishers
Total Flooding and Streaming Applications	ANSI/UL 1058	Standard for Halogenated Agent Extinguishing System Units	• Requirements for construction and operation of halogenated agent fire extinguishing system units intended to be installed, inspected, tested, and maintained in accordance with NFPA 12A and NFPA 12B
Aviation Total Flooding and Streaming Applications	NFPA 408	Standard for Aircraft Hand Portable Fire Extinguishers	• Requirements for type and size of portable fire extinguishers for all types of aircraft • Requirements for training flight-crew members on extinguisher use in the event of a fire onboard an aircraft
	FAA Minimum Performance Standard (MPS) (DOT/FAA/AR-01/37)	Handheld Fire Extinguishers as a Replacement for Halon 1211 on Civilian Transport Category Aircraft	• Specifies two extinguisher tests that replacement agents must pass in addition to requiring national certifications to ensure that replacement agents will meet or exceed performance of halon 1211 both in fighting fires and maintaining a safe breathing environment in aircraft cabins
	FAA MPS (DOT/FAA/TC-TN12/11)	Aircraft Cargo Compartment Halon Replacement Fire Suppression Systems	• Establishes the MPS that a Halon 1301 replacement aircraft cargo compartment fire suppression system must meet as part of the aircraft certification procedures
	FAA MPS	Fire Extinguishing Agents/Systems of Civil Aircraft Engine and Auxiliary Power Unit Compartments	• Establishes the MPS that engine and APU compartment fire extinguishing systems must meet
	FAA MPS (DOT/FAA/AR-96/122)	Lavatory Trash Receptacle Automatic Fire Extinguishers	• Establishes the MPS that an agent must meet and provides an equivalent level of safety to that of halon • Establishes the fire load, trash disposal receptacle test article, test procedures, and pass/fail criteria for built-in extinguishers for lavatory disposal receptacles

[a] Class D fires are combustible metal fires and Class K fires are kitchen fires involving cooking oils, grease, or animal fat.

1.2.2 Total Flooding Systems

Total flooding systems, which historically employed halon 1301 as a fire suppression agent, are used in both normally occupied and unoccupied areas. In addition to halon 1301, the current market for total flooding systems also includes HCFCs, HFCs, inert gases, and a variety of not-in-kind (NIK) extinguishing agents (e.g., powdered aerosols, foams, water). These agents are discussed in more detail in Section 1.3.1, below. In the United States, approximately 90 percent of total flooding systems installed protect anticipated hazards from ordinary combustibles (i.e., Class A fires), while the remaining 10 percent protect applications involving flammable liquids and gases (i.e., Class B fires) (Wickham 2002).[4]

It is also estimated that approximately 75 percent of total flooding systems protect electronics (e.g., computers, telecommunications, process control areas) while the remaining 25 percent serve to protect other applications, primarily in civil aviation (e.g., engine nacelles/auxiliary power units (APUs), cargo compartments, lavatory trash receptacles), military weapons systems (e.g., combat vehicles, machinery spaces on ships, aircraft engines and tanks), oil/gas and manufacturing industries (e.g., gas/oil pumping, compressor stations), and maritime (e.g., machinery space, cargo pump rooms) (Wickham 2002). Table 2 includes the primary applications for total flooding systems in the United States (Robin 2011; JENSEN HUGHES, Inc. 2015).

Table 2. Total Flooding System Applications

Commercial (including maritime)	Industrial	Aviation	Military
• Telecommunication facilities • Computer rooms • Data processing centers • Maritime • Museums • Libraries • Hospitals • Medical facilities	• Clean rooms • Petrochemical facilities • Production lines • Grain elevators	• Engine nacelles • APUs • Cargo compartments • Aircraft lavatory trash receptacles	• Crew spaces of armored vehicles • Aviation engine nacelles and dry bays • Shipboard machinery spaces

Known total flooding system manufacturers within the United States are listed below. The companies listed were identified during literature review while developing this report, and do not necessarily represent an inclusive list of all companies manufacturing within the United States.

- Amerex Corporation
- Badger Fire Protection
- BFPE International
- Fike Corporation
- FireBoy-Xintex
- FireCombat
- Firetrace International
- Meggitt
- Minimax
- PyroChem
- Reliable Fire & Security
- Sevo Systems
- TYCO (Ansul)
- UTC (Kidde)

1.2.3 Streaming Applications

Streaming applications, which have historically used halon 1211 as an extinguishing agent, include portable fire extinguishers designed to protect against specific hazards. In addition to halon 1211, the current market for streaming applications also includes HCFCs, HFCs, and a variety of other agents (e.g., dry chemical, CO_2, water). These agents are discussed in more detail in Section 1.3.2.

Portable fire extinguishers are intended as a first line of defense to cope with fires of limited size. The selection and installation of extinguishers is independent of whether a building or area is equipped with

[4] Table 4 in Section 1.3 provides additional information about classifications of fire.

fixed fire protection equipment (NFPA 10: 2013). Handheld extinguishers are commonly used in more than fifty applications falling under the broad categories of commercial (including maritime), industrial, aviation/aerospace, and military uses.[5] Table 3, organizes some of the applications that use portable fire extinguishers to protect valuable or sensitive assets or areas in which contamination may be an issue.

Table 3. Streaming Agent Applications

Commercial (including maritime)	Industrial	Aviation/Aerospace	Military
• Cable trays • Computer rooms • Data centers • Telecommunications facilities • Electronic compartments • Ship control rooms • Transmission facilities • Utility vaults • Art galleries • Banking facilities • Libraries • Retail and wholesale facilities • Warehouses	• Process control facilities • Motor control rooms • Manufacturing plants • Clean rooms • Oil and gas facilities • Conventional and nuclear power plants • Hazardous materials storage areas	• Onboard aircraft • Control towers • Aircraft flight lines • Aircraft ramps • Aircraft rescue and firefighting vehicles • Spacecraft facilities	• Electronics facilities • Ship control rooms • Training • Aircraft flight lines

Portable fire extinguishers are classified in the United States by their UL rating, which is a relative measurement of the effectiveness of the extinguisher on specific fire classes. The UL rating system includes Class A, B, and C ratings and a numerical rating that represents the relative extinguishing effectiveness of the fire extinguisher. The Class A rating measures water equivalency where 1A equals 1.25 gallons of water. The Class B rating measures the equivalent amount of square footage that the extinguisher can cover and the Class C rating indicates whether or not it can be used on electrically energized items (UL 2004). This rating system provides guidance to understanding the different types of extinguishers and requirements for various end-uses.

According to available market reports, in 2014, the fire extinguisher manufacturing industry in the United States was estimated to have gross sales of $545 million and employed approximately 860 people (IBIS World 2014). Leading manufacturers of portable fire extinguishers in the United States are summarized below.

- Amerex Corporation
- Badger Fire Protection
- BFPE International
- Buckeye Fire Equipment Co.
- E-ONE
- H3R Aviation, Inc.
- H3R Performance, Inc.
- JL Industries
- Koatsu
- Larsen's
- PyroChem
- Reliable Fire & Security
- Sea-Fire
- TYCO (Ansul)
- UTC (Kidde)

[5] Handheld extinguishers are also used in the residential sector, however, units primarily use dry chemical as a streaming agent, rather than halons, HCFCs, or HFCs. Therefore, applications in the residential sector are not discussed further in this market characterization.

- FireBoy-Xintex
- Gielle
- Oshkosh Truck Corporation
- Potter Roemer Fire Pro

1.3 Sector Background

Historically, the fire suppression sector relied on halons as the extinguishing agent in both total flooding systems and streaming applications. In the United States, halon 1301 and halon 1211 were the only two halons extensively used in fire suppression, primarily in total flooding systems and streaming applications, respectively.[6] In response to the halon phaseout under the Montreal Protocol and as mandated by the CAA, fire suppression agent manufacturers transitioned to less intensive ozone-depleting HCFCs, non-ozone-depleting HFCs, as well as a variety of lower-GWP or no-GWP alternatives (e.g., inert gases, CO_2, powdered aerosols, foams, water) in the early 1990s.

As the industry made these transitions, further regulations limited the use of HCFCs as alternatives (e.g., HCFC-123, HCFC-124, HCFC blends), as required by Title VI of the CAA, to help the United States achieve and go beyond the Montreal Protocol phaseout targets. In particular, the nonessential products bans, implemented under Section 610 of the CAA, addressed several important emissive uses of ODS in the early 1990s, including the use of HCFCs in all "pressurized dispensers" (e.g., portable fire extinguishers). The use of HCFCs as a fire suppressant in portable fire extinguishers for non-residential applications was initially banned as part of the original 1993 rulemaking but was reconsidered for use in 1996. Thus, EPA allows the sale and distribution of HCFCs in portable fire extinguishers strictly for non-residential applications. The use of HCFCs continues to be permitted as a result of a House Resolution 1540 signed into law where Section 320, Fire Suppression Agents, amends section 605(a) of the CAA to allow HCFCs to continue to be used after 2015 in portable fire extinguishers for non-residential applications.[7] Despite this specific use exemption, HCFC-based fire extinguishing agents are subject to the U.S. HCFC phaseout schedule, which remains on track to completely phase out production and import of HCFC-22 and HCFC-142b by January 1, 2020, and ban the production and import of all other HCFCs, completing the phaseout by January 1, 2030.

Today, the entire halon alternative market is comprised of both clean agents and not-in-kind (NIK) technologies (i.e., non-gaseous agents, including powdered aerosols, foam, and water mist).[8] HFCs represent approximately 15 percent of the halon alternative market in the United States, with CO_2 and inert gases accounting for most of the remainder, although HCFCs, PFCs, fluoroketones (FKs), and iodinated fluorocarbons are also in use (EPA 2014a). HFC-227ea is commonly used today in this sector, with some use of HFC-23, HFC-125, and HFC-236fa. Although HFCs do not contribute to ozone depletion, these substances are powerful greenhouse gases thousands of times more potent per pound than CO_2 and their emissions contribute to climate change.

The successful adoption of halon alternatives in fire suppression is significantly reliant on the agent's effectiveness in a particular application, which is dependent upon the agent's chemical structure and the type of fire hazard to be extinguished. Alternatives to halons are now used in applications serving

[6] Halon 2402 was used in some very limited applications.
[7] HCFCs in total flooding systems and fixed streaming systems are not subject to the ban under CAA section 610(d) because these systems are not defined as pressurized dispensers.
[8] Clean agents are gaseous extinguishing agents that are electrically non-conductive and leave no residue. Typical applications for clean agents include explosion prevention, electrical and electronic hazards, subfloors and other concealed spaces, flammable and combustible liquids and gases, high-value assets, and telecommunications facilities.

certain fire classes, i.e., ordinary combustibles, flammable liquids, flammable gases, and electrical equipment. The different types of fires where halons are used are based on the physical and chemical nature of fuel involved and are shown in Table 4.

Table 4. Classifications of Fire Types in the United States Based on Fuel Hazard

Symbol	Fire Type Classification	Fuel
	Class A	Ordinary combustibles (e.g., wood, paper, plastics)
	Class B	Flammable liquids (e.g., gasoline, petroleum oil and paint) and flammable gases (e.g., propane, butane)
	Class C	Energized electrical equipment (e.g., motors, transformers, appliances)

Source: FEMA (2015)

Gaseous agents (e.g., halons, HCFCs, HFCs) extinguish fires using three main mechanisms (Wickham 2002):

1. *Chemical inhibition by halogen atoms* – Bromine, chlorine, and iodine atoms can act catalytically and react with free radicals from combustion gases multiple times, thereby reducing fire propagation at the flame front.

2. *Thermal physical effects* – The flame temperature decreases upon mixing of a non-reactive gas with a flammable gas, thereby decreasing the rate of combustion.

3. *Dilution physical effects* – The collision frequency of oxygen and fuel is reduced by adding another gas to the fuel-air mixture.

The primary mechanisms (i.e., chemical or physical) used by each agent are different (e.g., halon versus inert gases).

The remainder of this chapter provides an overview of the historically- and currently-used chemicals installed in fire suppression equipment in the United States, primarily for the applications within the main product categories: total flooding systems and streaming applications, as introduced in Section 1.2.

1.3.1 Total Flooding Agents

Historically, halon 1301 (bromotrifluoromethane, $CBrF_3$) was used as the primary gaseous agent in total flooding fire extinguishing systems. Clean total flooding agents (i.e., those that do not leave residue following system discharge such as halon) are ideally suited to protect areas containing highly valuable or sensitive assets, as well as areas where egress of personnel may be difficult. HCFCs and HFCs are clean extinguishing agents that are widely used as halon replacements, serving to protect high value assets in many applications following the production and import ban on halons in 1994. There is still continuing use of halon 1301 to maintain and service existing systems (e.g., oil processing, military) and in new installations on aircraft (e.g., engine nacelles/APUs, and airplane cargo compartments).

Table 5 summarizes the primary extinguishing agent, manufacturers, and the environmental characteristics, including ODP and GWP, for commercially available and technically proven halon, HCFC, and HFC total flooding agents.

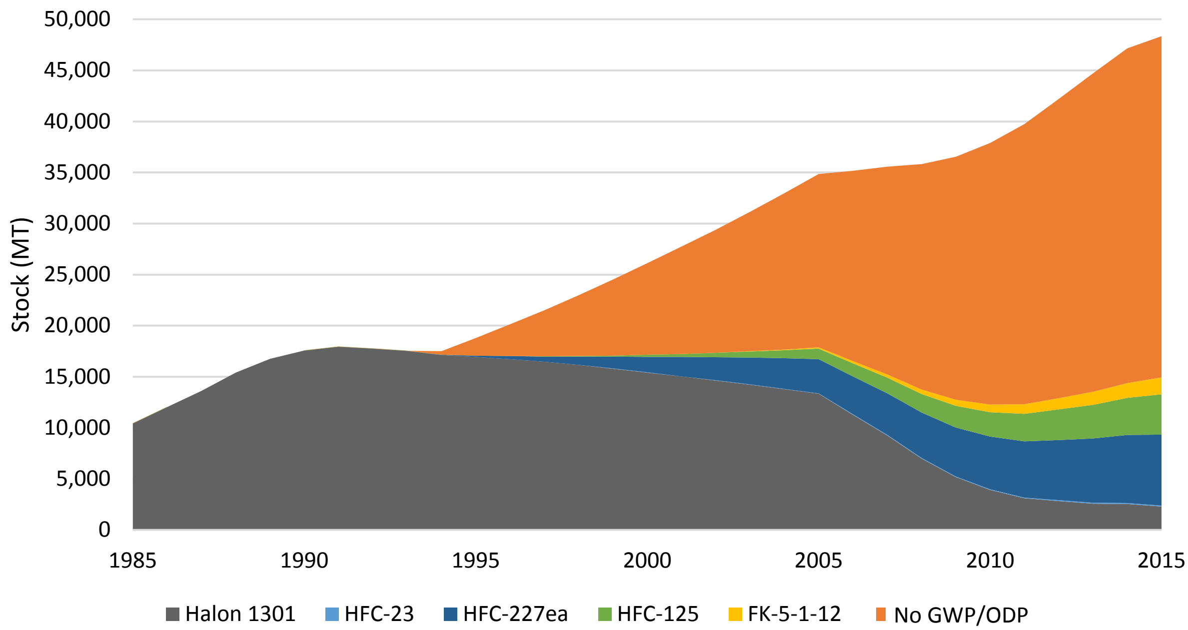
Table 5. Halon, HCFC, and HFC Total Flooding Agents

Total Flooding Agent	Trade Name	Manufacturer	ODP[a]	GWP[b]
Halon 1301[d]	Freon FE	DuPont and Great Lakes Chemical	10	7,140
HCFC Blend A[e]	NAF S-III	Safety Hi-Tech[f]	0.048	1,546
HCFC-124	FE-241	Chemours[c,e,f]	0.022	609
HFC Blend B[g]	Halotron II	American Pacific	0	1,598
HFC-23	FE-13	Chemours[c]	0	14,800
HFC-125	FE-25	Chemours[c]	0	3,500
HFC-227ea	FM-200	Chemours[c]	0	3,220
HFC-236fa	FE-36	Chemours[c]	0	9,810

Note: Rows highlighted in gray denote chemicals that have been subjected to a phaseout under the Montreal Protocol. See footnotes for more information.
[a] Montreal Protocol
[b] IPCC (2007)
[c] Chemours was formerly DuPont and the fire suppressant division of Great Lakes Chemical.
[d] The production of Halon 1301 and Halon 2402 was banned in the United States in 1994 in compliance with the Montreal Protocol. Ongoing halon use is limited to recycled halon.
[e] HCFC Blend A contains 82% HCFC-22, 9.5% HCFC-124, 4.75% HCFC-123, and 3.75% isopropenyl-1-methylcyclohexane.
[f] HCFCs are scheduled for phaseout under the Montreal Protocol. Starting in 2015, production and import of HCFCs (except in portable fire extinguishers for non-residential use and refrigeration and air conditioning equipment) are not allowed.
[g] HFC Blend B contains greater than 70% HFC-134a, less than 15% HFC-125, and less than 15% CO_2 (AMPAC 2007).

Currently, HFCs account for approximately 23 percent of the alternatives used to replace halon 1301, while HFC-227ea constitutes a majority of that total (EPA 2014a). As illustrated in Figure 1, the U.S. total flooding systems industry has made significant progress in adopting a variety of suppression agent alternatives to halon; as a result, a mix of agents are in use today with high-GWP HFCs occupying a substantial portion of the products on the market.

Figure 1. U.S. Total Flooding Agent Use from 1985 to 2015 (metric tons (MT))*



Source: EPA (2014a)
* "No GWP/ODP" includes NIK technologies with no ODP and low or no GWP including inert gases, powdered aerosols, foam, and water mist.

For example, the U.S. military selected HFCs as alternatives in some of its military weapons systems. Specifically, HFC-125 and HFC-227ea have been adopted in a number of military engine compartment, crew compartment, and engine nacelle/APU applications, as shown in Table 6.

Table 6. Military Weapons Fire Protection Applications of HFC-125 and HFC-227ea

U.S. Military Branch	HFC Agent	Weapon System
U.S. Air Force	HFC-125	• F-22 Raptor fighter • KC-46 (Boeing 767 derivative under development) • MV-22 Osprey assault transport
U.S. Army	HFC-227ea/Sodium Bicarbonate Dry Chemical	• Stryker combat vehicle crew and engine compartments • Autonomous Surface Vehicles (ASV) crew and engine compartments • Mine Resistant Ambush Protected (MRAP) crew and engine compartments • Up-Armored High Mobility Multipurpose Wheeled Vehicle (HMMWV) crew space • Small Emplacement Excavator (SEE) engine • M9 Armored Combat Earthmover (ACE) engine • Army watercraft engine spaces • Multiple Launch Rocket System engine • Field Artillery Ammunition Supply Vehicle (FAASV) engine
	HFC-125	• UH1 Huey helicopter

U.S. Military Branch	HFC Agent	Weapon System
U.S. Marine Corps		• AH1 Cobra helicopter • MV-22 Osprey assault transport • Light Armored Vehicles (LAVs) • Medium Tactical Vehicle Replacement (MTVR)
	HFC-227ea/Sodium Bicarbonate Dry Chemical	• Logistics Vehicle System Replacement (LVSR) crew compartments
U.S. Navy	HFC-125	Aircraft • F-22 Raptor fighter • F-18 E/F Super Hornet fighter • EA-18G Growler • Bell UH-1Y Venom • Bell AH-1Z Viper • E-2D Hawkeye • Sikorsky CH-53K King Stallion • MV-22 Osprey • CV-22 (U.S. Air Force Special Ops Command variant of MV-22) • P-8A (dry bay only) derivative of Boeing 737-800 • CH-60 helicopter
	HFC-227ea	Ships • Littoral Combat Ship (LCS) 1 • LCS 2 • Landing Helicopter Assault (LHA) 6 • Landing Helicopter Deck (LHD) 8 • Landing Platform/Dock (LPD) 17 • Aircraft carrier (nuclear propulsion) (CVN) 76-78 • DDG-1000 Zumwalt-Class Destroyer • DDG-51 Flight III Destroyer (proposed)

Sources: Wickham (2002), Hughes Associates and ICF Consulting (2004), JENSEN HUGHES, Inc. (2015)

1.3.2 Streaming Agents

Historically, halon 1211 (bromochlorodifluoromethane, $CBrClF_2$) was used as the primary clean agent in portable fire extinguishers. HCFC blends (e.g., Halotron I) and HFCs (largely HFC-236fa) replaced halon 1211 in various applications following the production and import ban of halons in 1994. However, the U.S. fire protection industry has made significant progress in adopting a variety of climate-friendly alternatives for streaming applications. In the mid-1990s, streaming agents with zero ODP and low or no GWP, including water, CO_2, and dry chemical, began to penetrate the market and currently occupy a large portion of available products. There is still some continuing use of halon 1211 to maintain and service existing handheld extinguishers, primarily for handheld extinguishers onboard aircraft.

Table 7, summarizes the extinguishing agent environmental characteristics including ODP and GWP, and primary manufacturer for commercially available and/or technically proven halon, HCFC, and HFC streaming fire protection agents. The only HCFC and HFC streaming agents currently commercially available in the United States are HCFC Blend B (Halotron I), HFC-236fa (FE-36), and HFC-227ea (FM-220). HCFC Blend B and HFC-236fa are in the same range of effectiveness as halon 1211.

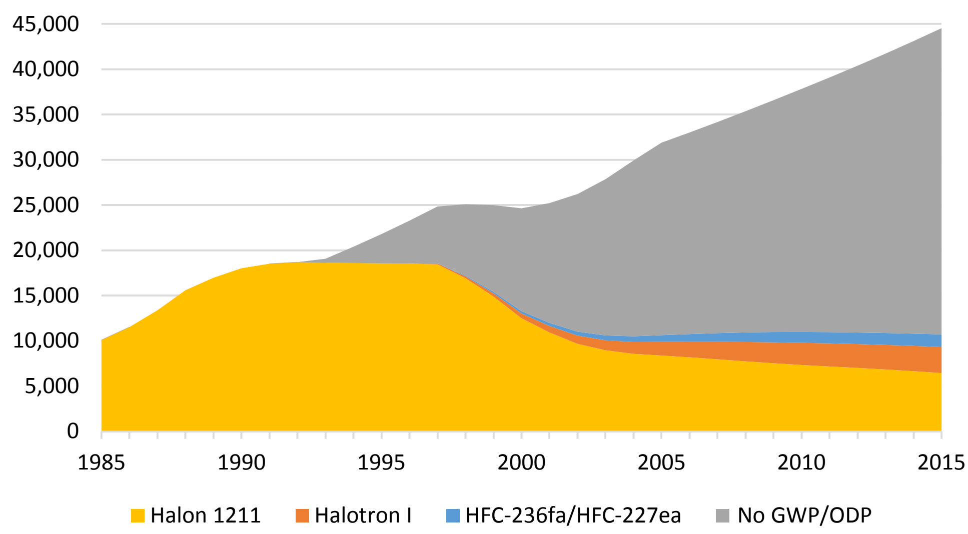
Table 7. Halon, HCFC, and HFC Streaming Agents

Streaming Agent	Trade Name	Manufacturer	ODP[a]	GWP[b]
Halon 1211[c]	FREON 12B1	DuPont	3	1,890
HCFC Blend B[e]	Halotron I	American Pacific[f]	0.02	222
HFC-236fa	FE-36	Chemours[d]	0	9,810
HFC-227ea	FM-200	Chemours[d]	0	3,220

Note: Rows highlighted in gray denote chemicals that have been subjected to a phaseout under the Montreal Protocol. See footnotes for more information.
[a] Montreal Protocol
[b] IPCC (2007)
[c] The production of Halon 1211 was banned in the United States in 1994 in compliance with the Montreal Protocol.
[d] Chemours was formerly DuPont and the fire suppressant division of Great Lakes Chemical.
[e] HCFC Blend B contains approximately 94% HCFC-123, 4% argon, and 2% CF_4.
[f] HCFCs are scheduled for phaseout under the Montreal Protocol. Starting in 2015, production and import of HCFCs (except HCFC-142b and HCFC-22) are not allowed.

Currently, HFCs (e.g., HFC-236fa) account for only three percent of the alternatives used to replace halon 1211 (EPA 2014a). As illustrated in Figure 2, the U.S. total flooding systems industry has made significant progress in adopting a variety of suppression agent alternatives to halon, largely streaming agents with zero ODP and low or no GWP, including water, CO_2, and dry chemical.

Figure 2. U.S. Streaming Agent Use from 1985 to 2015 (MT)*



Source: EPA (2014a)
* "No GWP/ODP" includes chemicals with no ODP and low GWP such as water, CO_2, and dry chemical.

1.4 Climate-Friendly Alternatives

Many climate-friendly alternatives have been found to be acceptable under EPA's SNAP program for use in fire suppression, including gas-powder blends, powders, and other NIK technologies (i.e., non-gaseous agents). As discussed in the previous section, the U.S. fire protection industry has made significant progress in adopting climate-friendly alternatives, largely in streaming applications, following the ban on halons in the early 1990s. Section 1.4 presents a closer look at each of the available classes of climate-friendly alternatives, organized by the two product categories: total flooding systems and streaming applications.

1.4.1 Total Flooding

This section summarizes information on climate-friendly total flooding agents that have been found acceptable for use or are undergoing review under EPA's SNAP program. Table 8 presents the GWP, SNAP-listing status, and primary manufacturers of each alternative.

Table 8. Climate-Friendly Total Flooding Agents

Total Flooding Agent	ODP[a]	GWP[b]	SNAP Listing Status	Manufacturers (Product)
FK-5-1-12 (Novec™ 1230)	0	<1	SNAP-listed (2002)	• 3M
CF_3I	0.008[c]	0.4	SNAP-listed (1996)	• Ajay North America, LLC
PBr_3[d]	0.01 – 0.08	0	SNAP-listed (2006)	• PhostrEx
2-BTP	0.0028	0.23 – 0.26[e]	Under SNAP review	• American Pacific
Inert Gas (IG) Blends	0	0	SNAP-listed (various years)	• Ansul Fire Protection (IG-541, Inergen) • LPG Fire (IG-01, IG-100, IG-55) • Minimax GmbH (IG-01) • Koatsu Company, Ltd. (IG-100) • Nohmi Bosai Ltd. (IG-100) • Kidde Danmark A/S (IG-55)
Inert Gas Generators	0	<1	SNAP-listed (2012)	• ATK (Nitrogen/Water Vapor Gas Generator, OS-10)
Carbon Dioxide	0	1	SNAP-listed (1994)	• Various
Water	0	0	SNAP-listed (1994)	• Various
Water Mist Systems	0	0	SNAP-listed (1995)	• Marioff Oy • Securiplex Technologies • Statewide Fire Protection

Total Flooding Agent	ODP[a]	GWP[b]	SNAP Listing Status	Manufacturers (Product)
Powdered Aerosols	0	0	SNAP-listed (various years)	• Amerex Defense (K-Ace) • ADI Technologies, Inc. (Powdered Aerosol A, SFE) • Dynamit Nobel GmbH (Powdered Aerosol C, Dynameco) • Pyrogen Technologies (Powdered Aerosol C, Pyrogen/Soyuz) • Fireaway, Inc. (Powdered Aerosol D, Aero K/Stat X) • FirePro Systems Limited (Powdered Aerosol E, FirePro) • Kidde Aerospace and Defense (Powdered Aerosol F, KSA®) • DSPA (Powdered Aerosol G, DSPA Fixed Generators) • Aerojet (Inert Gas/Powdered Aerosol Blend, FS 0140)

[a] WMO (2011), EPA (2002), EPA (2006), Orkin (2004)
[b] IPCC (2007), EPA (2002), EPA (2012b)
[c] At higher altitudes (i.e., 21,000 – 30,000 feet), the ODP of CF_3I is measured to be in the range of 0.07 to 0.25 (Li and Wuebbles 2006).
[d] PBr_3 is currently only used in one aircraft engine application.
[e] GWP range represents GWPs for 30°N to 60°N and 60°S to 60°N emissions scenarios for a 100-year time horizon. A tropospherically well-mixed approximation of the GWP is equal to 0.59. (Patten et al. 2012)

1.4.1.1 Halocarbon Agents

Climate-friendly halocarbon agents are technically proven alternatives for total flooding fire protection. These agents have similar characteristics to other clean agents (i.e., halons, HCFCs, and HFCs), without the environmental impact (i.e., no ODP and low GWP). FK-5-1-12, a fluoroketone and commercially known as Novec™ 1230, is a climate-friendly halocarbon currently available for use in total flooding systems in normally occupied spaces. Halogenated agents primarily function by removing heat and decreasing the flame temperature of a fire below that required for combustion (Robin 2009).

1.4.1.2 Inert Gas Clean Agents and Generators

Inert gas clean agents, typically consisting of nitrogen (N_2), argon (Ar), and CO_2, have zero ODP and GWP.[9] Four inert gas agents, IG-01 (argon), IG-55 (blend of 50 % nitrogen and 50% argon), IG-100 (nitrogen), and IG-541 (blend of 52% nitrogen, 40% argon, and 8% CO_2), are listed as acceptable for use in total flooding systems under EPA's SNAP program. However, only IG-01 and IG-541 are considered to be commercially viable in the U.S. market (Wickham 2002). These agents function physically by reducing the oxygen concentration in a confined space (UNEP 2014). Like halogen agents, inert gases are electrically non-conductive and leave no residue (i.e., clean). Although these agents are acceptable for use in occupied spaces, the risk of asphyxiation via hypoxia may exist.[10]

[9] Although CO_2 has a GWP of 1, it is not a large component of most commercialized inert gas blends (i.e., 8% of IG-541).
[10] Twelve percent oxygen in air is the NOAEL for hypoxia (ICF 1997).

Inert gas generators are pyrotechnic devices that use a solid material that oxidizes rapidly, producing large quantities of CO_2 and/or N_2 (UNEP 2014). OS-10, an N_2/water vapor gas generator, is listed as an acceptable substitute under EPA's SNAP program.

1.4.1.3 Carbon Dioxide

Carbon dioxide, which has a GWP of 1, has historically been extensively used for fire protection before (i.e., early 1990s) and after the phaseout of halons. Use conditions set by EPA's SNAP program require that CO_2 total flooding system designs must adhere to Occupational Safety and Health Administration (OSHA) 1910.162(b)(5)[11] and NFPA Standard 12.

In the early 20th century, CO_2 was the only practical gaseous fire extinguishing agent in commercial use (Wickham 2003). After the phaseout of halons, CO_2 total flooding systems were largely employed in engine rooms of all newly constructed commercial ships (Wickham 2002).

However, CO_2 can have significant adverse physiological effects at concentrations above 4 percent, which are required for effective total flooding. Safety precautions and engineering controls are now established for this alternative. Specifically, NFPA 12 includes restrictions on the use of CO_2 total flooding systems in normally occupied spaces (UNEP 2014).

1.4.1.4 Water Mist Technology

Water mist technology for fire protection generates and distributes very small mist droplets (i.e., less than 200 µm) to extinguish flames in a confined space, using both cooling effects and oxygen dilution as extinguishing mechanisms (UNEP 2014). Although not clean agent systems, they have negligible environmental impacts and toxicological and physiological hazards. Water mist systems are described in NFPA 750: Standard on Water Mist Fire Protection Systems. There are currently two types of water mist systems: single and dual fluid systems. Single fluid systems deliver water at 7 – 200 bar through spray nozzles while in dual systems, another gas (e.g., air, nitrogen) atomizes the water in the nozzle (UNEP 2014).

Technological advances in these systems include nozzle designs such as the use of air/water nozzles to generate even smaller droplets (e.g., 10 – 100 µm) and adjustable spray patterns. This alternative is currently employed in various applications including ship machinery spaces, combustion turbine enclosures, and flammable and combustible liquid storage spaces (UNEP 2014).

1.4.1.5 Fine Solid Particulate Technology

Fine solid particulate technologies (e.g., condensed powdered aerosol systems) generate and discharge solid aerosol particles and inert gases into the protected space upon activation, either automatically or manually. The pyrotechnic system charge forms aerosol and inert gases of a specified composition through a burning reaction. The inert gases deliver the solid aerosols that act directly on the flame to

[11] OSHA 1910.162(b)(5) requires that the employer shall provide a distinctive pre-discharge employee alarm capable of being perceived above ambient light or noise levels when agent design concentrations exceed the maximum safe level for employee exposure. A pre-discharge employee alarm for alerting employees before system discharge shall be provided on Halon 1211 and carbon dioxide systems with a design concentration of 4 percent or greater and for Halon 1301 systems with a design concentration of 10 percent or greater. The pre-discharge employee alarm shall provide employees time to safely exit the discharge area prior to system discharge. (OSHA 1974)

extinguish it (UNEP 2014). EPA's SNAP program has listed numerous powdered aerosols as acceptable for use in total flooding systems, as shown in Table 9.

Aerosol generators have been manufactured and commercialized for use in various applications including nuclear power station control rooms, automotive and ship engine compartments, and telecommunications and electronics cabinets (UNEP 2014). For example, the U.S. Army uses sodium bicarbonate dry chemical systems in engine compartments of various weapons systems (see Table 6).

1.4.2 Streaming

In the mid-1990s, streaming agents with zero ODP and low GWP, including water, CO_2, and dry chemical, began to penetrate the market and currently occupy a large portion of available products. This section summarizes information on climate-friendly streaming agents that have been found acceptable for use in portable fire extinguishers under EPA's SNAP program. Table 9, below, presents the ODP, GWP, SNAP-listing status, and primary manufacturers of each alternative.

Table 9. Climate-Friendly Streaming Agents

Streaming Agent	ODP[a]	GWP[b]	SNAP Listing Status	Manufacturer
FK-5-1-12 (Novec™ 1230)	0	<1	Acceptable, subject to narrowed use limits (2002)	• 3M
FK-6-1-14 (C7 Fluoroketone)	0	1	Acceptable, subject to use conditions (2012)	• 3M
CF_3I	0.008	0.4	Acceptable, subject to narrowed use limits (1996)	• Ajay North America, LLC
2-BTP	0.0028	0.23 – 0.26[c]	Proposed acceptable, subject to use conditions	• American Pacific
H Galden HFPEs[d]	0	2,790 – 6,230	Acceptable, subject to narrowed use limits (2003)	• Solvay
Dry Chemicals	0	0	Acceptable (1994)	• Various
Carbon Dioxide	0	1	Acceptable (1994)	• Various
Water	0	0	Acceptable (1994)	• Various

[a] WMO (2011), Orkin (2004), EPA (2002), EPA (2003)
[b] IPCC (2007), EPA (2002), EPA (2012a)
[c] GWP range represents GWPs for 30°N to 60°N and 60°S to 60°N emissions scenarios for a 100-year time horizon. A tropospherically well-mixed approximation of the GWP is equal to 0.59. (Patten et al. 2012)
[d] Hydrofluoropolyethers (HFPEs)

1.4.2.1 Halocarbon Agents

Climate-friendly halocarbon streaming agents (i.e., excluding HCFCs and HFCs) effectively extinguish Class A, B, and C fires without leaving any residue or causing damage in a protected space. EPA's SNAP program has listed two fluoroketones as acceptable for use in portable fire extinguishers, FK-5-1-12 (Novec™ 1230) and FK-6-1-14 (C7 Fluoroketone). U.S. Department of Defense (DoD) testing demonstrated the successful performance of the use of Novec™ 1230 in a wheeled flightline extinguisher (AFCEC 2014).

1.4.2.2 Carbon Dioxide

Carbon dioxide fire extinguishers store CO_2 as a liquefied compressed gas and are typically used on fires with flammable liquids and/or electrically energized equipment. CO_2 extinguishers do not leave residue on a protected area following release and are generally very cost effective (Wickham 2002).

1.4.2.3 Dry Chemical Agents

Dry chemical extinguishers, which are commonly used in many applications in the United States, exist in two types (UNEP 2014):

1. *Ordinary dry chemicals* have a formulation based on sodium or potassium bicarbonate and can be used on fires involving flammable liquids and gases (i.e., Class B) and electrical equipment (i.e., Class C).

2. *Multipurpose ("ABC") dry chemicals* have a formulation of ammonium phosphate and are suitable for use on fires involving ordinary combustibles (i.e., Class A) as well as Class B and C fires.

The measured particle size ranges from 25–95 µm with an average of 31 µm (Fire Protection Research Foundation 2010). Dry chemical extinguishers discharge a fine, powdery residue and should not be used to protect valuable or sensitive assets.

1.4.2.4 Water (Straight-Stream and Spray)

Water-based extinguishers are only suitable for use on Class A fires involving ordinary combustibles such as wood, paper, and fabrics. Water can be discharged as a fire suppression agent from the extinguisher via spray or straight stream.

2 U.S. Commercial Comfort Cooling Industry

2.1 Introduction

This market characterization focuses on comfort cooling in the commercial sector, and specifically only addresses chillers. Commercial comfort cooling refers to regulating the temperature and humidity in offices, hotels, hospitals, shopping centers, and other buildings. The U.S. commercial air conditioning industry historically has relied on chlorofluorocarbon (CFC) and HCFC refrigerants, and transitioned to HFCs (e.g., HFC-134a) in response to the phasing out of these ODS. Today, low-GWP alternatives (e.g., ammonia, CO_2, unsaturated HFCs) have entered or are expected to enter the U.S. commercial air conditioning market, facilitated by acceptability listings under EPA's SNAP program.

There are two major categories of chillers—vapor-compression and absorption chillers.[12] Vapor-compression chillers are further classified into two categories—centrifugal and positive displacement chillers. Centrifugal chillers are centralized air conditioning systems typically used in larger buildings (e.g., offices, hotels, shopping centers, and other large buildings). Positive displacement chillers are smaller and may be either water-cooled [13] or air-cooled.[14] There are four types of positive displacement chillers—1) reciprocating, 2) rotary-vane, 3) screw, and 4) scroll—each of which is named for the type of compressor employed.

The remainder of this document examines the chiller sector more closely, in terms of key market players, historical and current refrigerant use, and the availability of alternative, more climate-friendly refrigerants and technologies.

2.2 Market Characterization

Chillers are a form of stationary air-conditioning equipment that control heat and/or humidity for the comfort of occupants or for climate control of facilities, such as office and commercial buildings. The chiller industry is composed of two main end-uses: absorption chillers and vapor-compression chillers.

- **Absorption chillers** are designed to run on direct fired fuel or hot water/steam. Absorption chillers are further classified by the number of heat-input levels available and the type of fuel source (IPCC/TEAP 2005).
- **Vapor-compression chillers** are designed with an electric motor that runs a compressor and are further classified by the type of compression systems used: **centrifugal** or **positive displacement**. The latter classification can be further categorized into reciprocating, rotary-vane, screw, and scroll compressors (IPCC/TEAP 2005).

Table 10 summarizes these chiller end-uses according to the types found in the market, their cooling capacity[15] (in kilowatts (kW)), and refrigerants used.

[12] Absorption chillers have not historically used ODS refrigerants; therefore, these applications are not discussed in detail in this market characterization, except as they are considered to be alternatives for vapor compression chillers.

[13] Water-cooled chillers typically employ cooling towers to remove heat from the system.

[14] Air-cooled chillers employ refrigerant-to-air condenser coils and fans to remove heat from the system.

[15] The cooling capacity is the measure of a refrigeration system's ability to remove heat.

Table 10: Typical Chiller Capacity Ranges and Refrigerants

End-use	Chiller Type	Approximate Capacity Range (kW)	Typical Refrigerants
Absorption	Ammonia-water, air cooled	17 - 85	Ammonia (R-717)
	R-717-water, water cooled	17 - 85 700 - 3,500	R-717
	Water-lithium bromide – shell and coil	17 - 120	Water (R-718)
	Water-lithium bromide – shell and tube	140 -18,000	R-718
Vapor-Compression	Scroll, rotary, and reciprocating water-cooled	10 - 1,200	R-410A, HCFC-22, R-407C
	Screw, scroll, rotary, and reciprocating air-cooled	10 -1,800	HFC-134a, R-410A, HCFC-22, R-407C
	Screw water-cooled	100 -7,000	HFC-134a, HCFC-22, R-717 (secondary loop)
	Centrifugal air-cooled	200 - 7,000	HFC-134a
	Centrifugal water-cooled	200 - 21,000	HFC-134a, HCFC-123

Source: UNEP 2015a

Absorption chillers have been used in the commercial air conditioning industry since the 1950s. As presented in Table 10, ammonia/water and lithium bromide/water absorption chillers have historically been the most common refrigerant-absorber pairs, and so the Montreal Protocol and restrictions on the use of CFCs have had little impact on the design of absorption chillers (UNEP 2015a).

Because absorption chillers have not historically used ODS and do not currently use HFC refrigerants, absorption chillers are not addressed in detail in this market characterization (i.e., in terms of producers, charge size, and other activity data). However, they can be considered a viable alternative to vapor-compression chillers under certain circumstances, and are discussed further in Section 2.4.3 on alternatives – in particular in Table 16.

2.2.1 Vapor Compression Chillers

EPA's Vintaging Model estimates that there are approximately 616,000 vapor compression chillers installed in the United States in 2015 (U.S. EPA 2014a).[16] Approximately 80 percent of the U.S. chiller market (in terms of number of units) is assumed to be positive displacement chillers. About half of all vapor compression chillers are screw chillers and one-quarter are scroll chillers. Reciprocating chillers represent the smallest classification of chillers at just over five percent of the U.S. market. Centrifugal

[16] The Vintaging Model tracks rotary chillers and screw chillers as categories of vapor compression chillers, but does not specifically identify the subclass of rotary-vane chillers.

chillers make up the remaining 20 percent of the vapor compression market. Table 11 presents the estimated number of these chillers, by type, installed in the United States.

Table 11: Estimated 2015 Vapor Compression Chillers Stock in the United States

Chiller Type	2015 Stock (Units)
Vapor Compression (Total)	**616,010**
Centrifugal	122,210
Positive Displacement[a]	493,800
Screw	*307,840*
Scroll	*150,930*
Reciprocating	*35,030*

[a] The Vintaging Model tracks rotary chillers and screw chillers as categories of vapor compression chillers, but does not specifically identify the subclass of rotary-vane chillers.
Source: U.S. EPA 2014a

A vapor-compression chiller consists of a compressor with an electric motor, a liquid cooler (evaporator), a condenser, a refrigerant expansion device, and a control unit. Prior to the 1980s, centrifugal chillers were the most common type of vapor-compression chillers for applications requiring more than 700 kW cooling capacity, and reciprocating compressors were most common for smaller chillers. Starting in the mid-1980s, screw compressors became available in addition to reciprocating compressors in the cooling capacity ranges of 140-700 kW, as well as up to 2,275 kW to replace centrifugal chillers. Scroll compressors became available for smaller applications in the seven to over 90 kW range (IPCC/TEAP 2005). Example images of centrifugal and positive displacement chillers are provided in Figure 3 and Figure 4, respectively.

Figure 3: Example Images of Centrifugal Chillers (Johnson Controls 2015 and McQuay 2015)

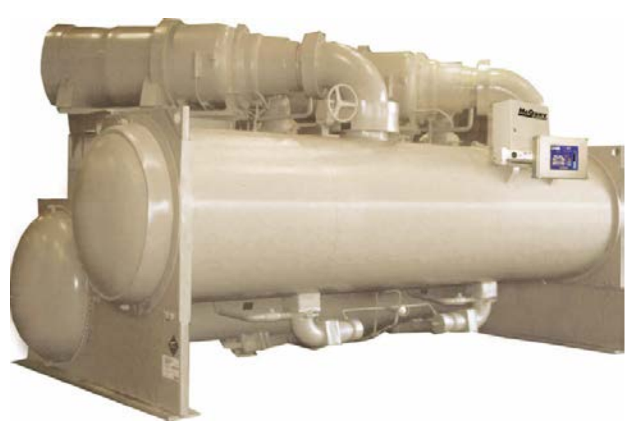


Figure 4: Example Images of Positive Displacement Chillers (Trane 2015a and Carrier 2015)

In general, the main consideration when determining the best compressor for a specific application is the size of the cooling capacity needed. Scroll, reciprocating, and small screw compressors have a typical cooling capacity between 50 and 750 kW, compared to large screw or centrifugal compressors which can serve between 750 and 10,000 kW (UNEP 2015d).

As a result, charge sizes for scroll, reciprocating or small screw compressors are much lower than that of large screw and centrifugal compressors and can range from 40-500 kilograms (kg) and 500-13,000 kg, respectively (UNEP 2015d). Table 12 shows the typical charge sizes for centrifugal and some types of positive displacement chillers, as modeled by EPA's Vintaging Model.

Table 12: Typical Chiller Charge Sizes

Chiller Type [a]	Typical Charge Size (kg)
Centrifugal	440-720
Positive Displacement: *Screw*	300
Positive Displacement: S*croll*	240
Positive Displacement: *Reciprocating*	315

[a] The Vintaging Model tracks rotary chillers and screw chillers as categories of vapor compression chillers, but does not specifically identify the subclass of rotary-vane chillers.

Source: U.S. EPA 2014a

Centrifugal and positive displacement chillers have average lifetimes that are estimated to be about 26 and 20 years, respectively (U.S. EPA 2014a), though chillers can be in service for up to 40 years (UNEP 2015a) . Although vapor-compression chillers have long lifetimes and large charge sizes, leak rates for these systems are low. The average annual leak rates, which includes operational leaks and leaks during servicing (i.e., due to loss of refrigerant from fugitive emissions) across all vapor-compression chillers, are estimated to be less than two percent for both ODS and HFC systems (U.S. EPA 2014a). The refrigerating circuit in most vapor-compression chillers is often pre-charged and factory sealed, leading to minimal leaks during installation and use (UNEP 2015d). Some larger chillers are built on-site and charged with refrigerant during installation.

2.2.1.1 Manufacturers

A selection of comfort cooling chiller manufacturers within the United States is listed in Table 13. The Department of Energy (DOE) identified domestic water- and evaporatively-cooled air conditioner manufacturers in a technical support document for a final rule on Commercial, Air Conditioning, and Water Heating Equipment (DOE 2011), including six centrifugal and positive displacement chiller manufacturers.[17] In addition to the DOE technical support document, additional U.S. manufacturers of centrifugal and positive displacement chillers were identified through an online search. Some of these companies manufacture the chillers as well as the compressors. The companies identified while developing this report do not necessarily represent an inclusive list of all companies manufacturing within the United States.

Table 13: Manufacturers of Compressors and Chillers

Manufacturer	Compressor	Chiller
American Chillers		X
Arctic Chiller Group		X
Bitzer	X	
Cooling Technology, Inc.		X
Daikin Applied	X	X
Danfoss	X	
Emerson Electric	X	
EVAPCO, Inc.		X
Ingersoll Rand	X	X
Johnson Controls	X	X
NAPPS		X
Thermal Care	X	X
United Technologies	X	X

2.2.1.2 Industry Standards

Vapor compression chillers are subject to several industry standards implemented by the Air-Conditioning, Heating, & Refrigeration Institute (AHRI) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). AHRI 550/590: *Performance Rating of Water-Chilling and Heat Pump Water-Heating Packages Using the Vapor Compression Cycle* standard establishes standard rating conditions for chillers. ASHRAE 90.1: *Energy Standard for Buildings except*

[17] DOE identified the following eight manufacturers of water- and evaporatively-cooled air conditioners: Aaon, Inc., Allied Thermal Systems, Carrier Corp. (United Technologies Corporation), Lennox International, Inc., Engineered Air, Thermoplus Air, Inc., Trane Inc. (Ingersoll Rand), and York International Corp. (Johnson Controls, Inc.). Six of these manufacturers (excluding Allied Thermal Systems and ThermoPlus Air) manufacture centrifugal and positive displacement chillers.

Low-Rise Residential Buildings serves as a benchmark for commercial building energy codes as well as a key basis for energy codes and standards around the world.

In 2013, ASHRAE released updates to Standard 90.1 providing new minimum requirements for the energy-efficient design of most buildings, whether they are new buildings with new systems, new portions of buildings with new systems, or existing buildings with new systems (ASHRAE 2013). These standards require a modest improvement to the full-load efficiency of chillers but will require a substantial margin of difference in improvement to the part-load efficiency of chillers (The Air-Conditioning, Heating and Refrigeration News 2014).

Additionally, chillers installed at U.S. federal buildings are subject to standards apart from the residential and commercial sector. The Federal Energy Management Program (FEMP) provides guidance on the efficiency requirements for air-cooled electric chillers (DOE 2015). Chillers are subject to standards for full- and part-load optimization in terms of Energy Efficiency Ratio (EER)[18] and Integrated Part Load Value (IPLV)[19] specified by the capacity of the chiller. Chillers smaller than 150 tons, for instance, must have a full-load EER of greater than or equal to 10.40 in applications optimized for full-load and 9.56 for applications optimized for part-load, while the minimum IPLV requirements for such units are 12.5 and 15.39, respectively (DOE 2015).

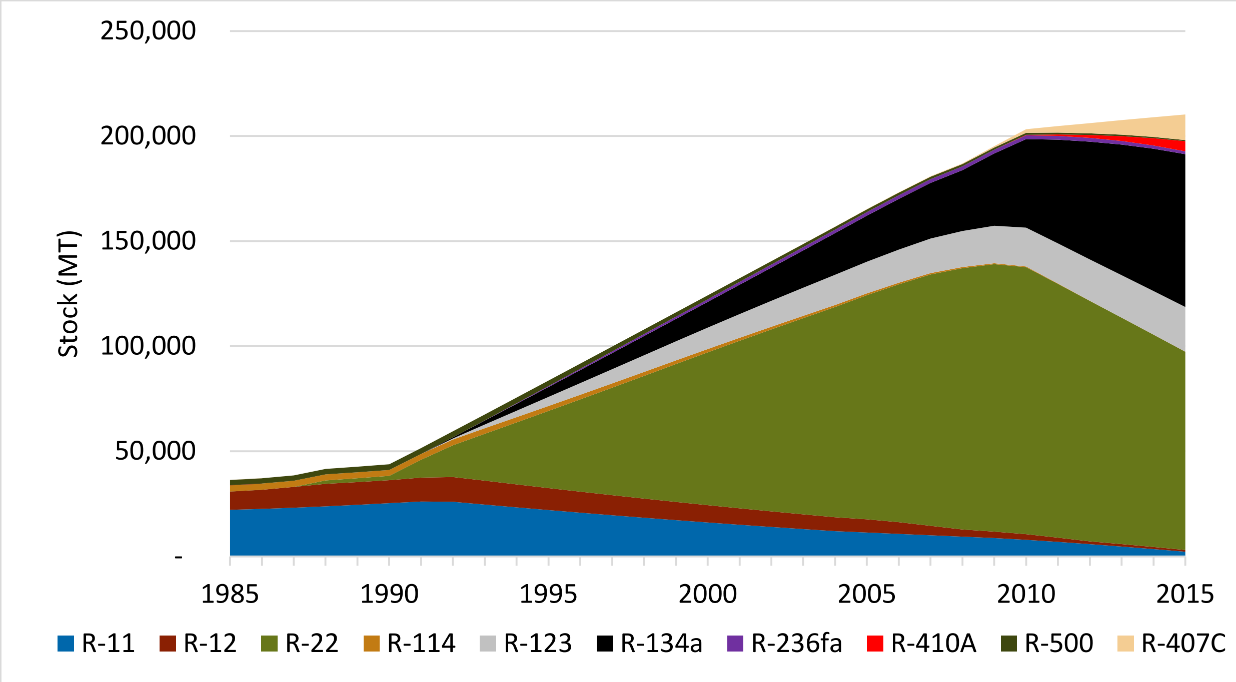
2.3 Sector Background

Vapor-compression chillers have historically used CFC-11, CFC-12, and HCFC-22 as refrigerants (U.S. EPA 2014a). Once the U.S. ODS phaseout regulations came into effect, CFC-11 and CFC-12 were replaced by HCFC-123, HCFC-22, and HFC-134a. In the early 2000's, HFC blends—namely R-407C and R-410A—began gaining market share to replace HCFC-22. ODS chillers, particularly HCFC-22, HCFC-123, and even some CFC-11 and CFC-12 systems, are still present in the market due to the long lifetime of chillers. As shown in Figure 5 below, refrigerant stock in vapor-compression chillers (i.e., the amount of refrigerant charge in chillers installed in the United States) is largely HCFC-22 and HFC-134a.

[18] EER is the ratio of net cooling capacity (or heat removed in British thermal units (BTU) per hour) to the total input rate of electric power applied in watts. The units of EER are BTU/Wh. A higher EER value indicates a more efficient system.

[19] IPLV is an efficiency metric calculated using AHRI Standard 550/590 test conditions at load capacities of 25%, 50%, 75%, and 100%. It is intended to provide comparative information about a chiller used under variable load conditions.

Figure 5: Fluorinated Refrigerant Stock in Vapor-compression Chillers in the United States from 1985-2015 (MT)



Source: U.S. EPA 2014a

The remainder of this section provides an overview of the historically- and currently-used refrigerants installed in centrifugal and positive displacement chillers in the United States.

2.3.1 Centrifugal Chillers

Prior to the implementation of the Montreal Protocol, the most common refrigerant used in centrifugal chillers was CFC-11 but there were also centrifugal chillers using CFC-12, CFC-114, R-500, and HCFC-22 as refrigerants (UNEP 2004). By 1993, the use of CFC-11, CFC-12, CFC-114, and R-500 in new chillers was phased out with the Montreal Protocol and CAA while HCFC-22 was used through the late 1990s. To replace the CFCs, HCFC-123, HFC-236fa, and HFC-134a were used as alternatives starting in 1993 and up through the mid-2000s (UNEP 2004). Table 14 shows the estimated distribution of refrigerants used in centrifugal chiller units in the United States today.

Table 14: Centrifugal Chiller Estimated Stock

Chiller Type	Refrigerant	Estimated 2015 Stock (Units)
Centrifugal	CFC-11	4,380
	CFC-12	1,140
	R-500	570
	HCFC-22	9,370
	HCFC-123	47,620

Chiller Type	Refrigerant	Estimated 2015 Stock (Units)
	HFC-134a	57,190
	HFC-236fa	1,940
	Total	**122,210**

Source: U.S. EPA 2014a

2.3.2 Positive Displacement Chillers

All positive displacement chillers (e.g., reciprocating, rotary-vane, screw, and scroll chillers) have employed a variety of refrigerants both prior to and after the implementation of the Montreal Protocol. Prior to implementation of the Montreal Protocol, HCFC-22 was the primary refrigerant offered in reciprocating, screw, and scroll chillers. CFC-12 was offered in some small reciprocating systems (under 100 kW), but HCFC-22 was used for the majority of small and large reciprocating chillers (UNEP 2004). Once HCFC requirements were in place under the Montreal Protocol and the CAA, HCFC-22 began being replaced largely by R-407C and R-410A. HFC-134a also gained a share of the scroll and screw compressor market and was introduced to a small extent in reciprocating chillers (UNEP 2004). Table 15 presents the estimated distribution of refrigerants by chiller type and the estimated number of these appliances in use in the United States today.

Table 15: Positive Displacement Chiller Stock Estimates

Chiller Type [a]	Refrigerant	Estimated 2015 Stock (Units)
Screw	HCFC-22	197,460
	HFC-134a	72,040
	R-410A	10,920
	R-407C	27,420
	Total	**307,840**
Scroll	HCFC-22	96,820
	HFC-134a	35,320
	R-410A	5,350
	R-407C	13,440
	Total	**150,930**
Reciprocating	HCFC-22	22,620
	HFC-134a	8,110
	R-410A	1,220
	R-407C	3,080
	Total	**35,030**

[a] The Vintaging Model does not specifically track rotary-vane chillers.
Source: U.S. EPA 2014a

2.4 Climate-Friendly Alternatives

Although not a significant portion of the market today, climate-friendly alternatives (e.g., unsaturated HFCs [often blended with saturated HFCs], ammonia, and CO_2) are available for use or are expected to be available for use in the near-term for all types of vapor compression chillers.

Regarding refrigerant choice, assuming that a chiller is located in either a machinery room or outdoors, manufacturers have a wide range of lower-GWP options for refrigerants as there are few restrictions on the refrigerant charge in these locations (UNEP 2015d); however, some may require additional safety precautions and technician training. These safety precautions and training can translate into higher costs when compared with the systems they replace (UNEP 2015d).

As discussed in Section 2.2, energy efficiency is another important consideration in regards to choosing an alternative refrigerant or technology for chillers. The energy efficiency of an alternative refrigerant when used in a chiller should be equal to or better than the refrigerant being replaced (UNEP 2015a), and chillers will need to maintain compliance with relevant energy efficiency standards.

The remainder of this section summarizes information on refrigerant alternatives and technologies for chillers, which is also summarized in Table 16, including both alternative refrigerants and alternative technologies (i.e., absorption chillers).

Table 16: Overview of Climate-Friendly Alternatives and SNAP Listing Status

Alternative		GWP[a]	SNAP Listing Status	Chiller Use Status
Unsaturated Halocarbons and Blends	Hydrofluoro-olefin (HFO)-1234ze(E)	6	• Acceptable (2012)	• Alternative for use in reciprocating, scroll, screw and centrifugal compressors
	Trans-1-chloro-3,3,3-trifluoro-prop-1-ene(R-1233zd(E))	4.7 to 7	• Acceptable (2014)	• Alternative for use in low-pressure centrifugal systems
	HFO-1336mzz(Z)	~9	• Under SNAP review	• Under development
	R-513A	630	• Acceptable (2015)	• Alternative in medium-pressure chillers and for use in new and retrofit systems replacing HFC-134a
	R-450A	601	• Acceptable (2014)	• Alternative in medium-pressure chillers and for use in new and retrofit systems replacing HFC-134a
R-717 (ammonia)		0	• Acceptable (1996)	• Alternative in vapor-compression and absorption chillers
Absorption Chillers	Ammonia/water	0	• Acceptable (1996)	• Used in absorption chillers, alternative technology for centrifugal chillers
	Lithium Bromide/water	0	• Acceptable (1996)	• Used in absorption chillers, alternative technology for centrifugal chillers
R-744 (CO_2)		1	• Under SNAP review	• Air-cooled CO_2 chillers have been used in Northern Europe
Hydrocarbons and Hydrocarbon Blends	R-290	3	• Not EPA SNAP approved	• Has been used as an HFC alternative in small and medium sized chillers in Europe.
	R-1270	2	• Proposed unacceptable	• Has been used as an HFC alternative in small and medium sized chillers in Europe.
	R-441A	<5	• Not EPA SNAP approved	• Commercially available as an HFC alternative in small and medium sized chillers in Europe.

Source: U.S. EPA 2015a; UNEP 2015d

[a]IPCC 2007 and UNEP 2015a

2.4.1 HFO/HFC Blends

The use of unsaturated HFCs, or HFOs, and related compounds in chillers is growing with several HFOs and HFO/HFC blends available or currently under development. HFO-1234ze(E) is available for reciprocating, rotary-vane, scroll, screw, and centrifugal compressors and is approved[20] by EPA's SNAP program. System modifications are required to compensate for HFO-1234ze(E)'s lower capacity than HFC-134a; however, it has comparable or higher energy efficiency across a range of applications and conditions (Honeywell 2012). In addition, due to its physical properties including its low-flammability, only minor changes are necessary to transition a system from HFC-134a to HFO-1234ze(E). A potential barrier to the adoption of HFO-1234ze(E) chillers is that these systems may be of slightly higher cost than HFC-134a (UNEP 2015d). In addition, training will be necessary for technicians operating these chillers due to the mild flammability of HFO-1234ze(E).

R-1233zd(E) is SNAP-approved to replace HCFC-123 in low pressure centrifugal chillers (Honeywell 2015b). This refrigerant is non-flammable and it is becoming commercially available in the United States. R-1233zd(E) is currently being used in large-capacity centrifugal chillers in Europe, the Middle East, and Japan that are up to 10 percent more energy efficient than other commercially available centrifugal chillers (BusinessWire 2015). R-1233zd(E), as well as HFO-1336mzz(Z), which is still under development and under SNAP review, are expected to be competitive with HCFC-123 and offer alternatives as HCFC-123 is phased out (Honeywell 2015b).

R-513A and R-450A are refrigerant blends of HFC-134a/HFO-1234yf and HFC-134a/HFO-1234ze, respectively and both blends are suitable for replacing HFC-134a (Chemours 2015a, Honeywell 2015a). Beginning in 2015, R-513A air-cooled chillers became commercially available in North America and Latin America (BusinessWire 2015, Trane 2015b).

2.4.2 Ammonia

Ammonia (R-717) has been used as a refrigerant since the early 1900s and is listed as an acceptable substitute by EPA's SNAP program in both vapor compression and absorption chillers. Despite the advent of fluorocarbon refrigerants, ammonia remained a popular refrigerant throughout the 20th century due to its low cost and good thermodynamic properties. In addition to these characteristics, ammonia has no ODP and no GWP (The Linde Group 2015a). Ammonia is most suitable for use in medium and large screw compressors, but is more commonly used in industrial chillers than for air-conditioning (UNEP 2015c). There is some use of ammonia in screw chillers in northern Europe (IPCC/TEAP 2005) as well as the United States and elsewhere.

Ammonia chillers are considerably more expensive than those designed for other refrigerants and operation of ammonia chillers requires additional training for technicians due to the high toxicity of the refrigerant; however, there are already well established training courses for technicians in the United States and many other countries where ammonia is more commonly used as a refrigerant (UNEP 2015d).

[20] Within this market characterization report, we use "approve" to indicate a SNAP listing of acceptable or acceptable subject to use conditions.

2.4.3 Absorption Chillers

Absorption chillers can be considered a viable alternative to vapor-compression chillers under certain circumstances. The most common refrigerant-absorber pairs in absorption chillers are ammonia/water and lithium bromide/water, both of which are listed as acceptable alternatives under the SNAP program (U.S. EPA 2015a). The energy source for absorption chillers is heat provided by steam, hot water, or a fuel burner. Compared to vapor compression chillers, absorption systems have a higher initial cost and lower operating efficiency, and they are not very common in the United States; however, they can be a cost-effective alternatives to vapor compression chillers in certain situations, such as when waste heat or steam is available to power the chiller or where the cost of electricity makes gas-fired absorption a lower-cost alternative (UNEP 2004).

2.4.4 Carbon Dioxide

Carbon dioxide (R-744) has regained popularity as an environmentally friendly refrigerant because it has zero ODP, a GWP of 1, low toxicity, and is not flammable. In addition, equipment using R-744 can experience lower energy usage (The Linde Group 2015a). R-744 air-cooled chillers have been introduced in northern Europe. This refrigerant is not EPA SNAP approved for this use at the time this document was produced; however, R-744 is under review for certain applications for use with chillers.

2.4.5 Hydrocarbons

R-290 (propane), R-1270 (propylene), and other hydrocarbons have been successfully used as HFC alternatives in small and medium sized chillers in Europe (The Linde Group 2013). Hydrocarbon blends (including R-441A, a blend of ethane, propane, butane, and isobutane) may also be in operation outside of the U.S. These refrigerants are not currently EPA SNAP approved for this use. The SNAP program is proposing R-1270 to be unacceptable for use in chillers.

3 U.S. Cold Storage Industry

3.1 Introduction

The U.S. cold storage industry consists of refrigerated warehousing and storage facilities that are used to preserve meat, produce, dairy products, and other perishable goods prior to their distribution and sale.[21] Historically, cold storage facilities relied on refrigeration systems that contain ammonia or ozone depleting substances (ODS), such as CFCs and HCFCs—specifically, CFC-12, HCFC-22 and R-502 (a CFC/HCFC blend). In response to the global phaseout of ODS under the Montreal Protocol, some manufacturers transitioned from ODS to HFC refrigerants, with a large portion of the market moving to or continuing to rely on ammonia. Increasingly, advanced ammonia technologies, including low charge packaged ammonia systems, ammonia/CO_2 cascade systems, and ammonia secondary loop systems are gaining market share as alternatives to conventional cold storage systems. Other climate-friendly alternatives, such as HFC/HFO blends with lower GWPs, are EPA SNAP approved for use in cold storage systems, but have not yet been widely adopted by the market.

The remainder of this report characterizes the U.S. cold storage industry in terms of market size, facility operators, refrigeration systems types, system manufacturers, historical and current refrigerant use, and the availability of climate-friendly alternative refrigerants.[22]

3.2 Market Characterization

In the United States, the majority of cold storage warehouses are used to store refrigerated and frozen food (approximately 88 percent), with food manufacturers, wholesalers, and retailers representing 33 percent, 33 percent, and 22 percent of the demand for storage space, respectively (JLL 2014). The remaining capacity (roughly 12 percent) is mainly used to store pharmaceutical, floral, and fur products (JLL 2014). The remainder of this section discusses the types of cold storage refrigeration systems, manufacturers of these systems, types of facility operators, and total cold storage capacity in the United States. Relevant standards that impact cold storage facilities and their refrigeration systems are also presented.

3.2.1 Cold Storage Refrigeration Systems

To effectively preserve goods, cold storage facilities must maintain specific operating temperatures. Cold storage facilities usually operate at two temperature levels: frozen (below -18°C) and chilled (above 0°C) (UNEP 2015a). Most frozen produce is stored between -22°C and -26°C, although some products require lower temperatures—for example, ice cream is stored between -26°C and -29°C while some types of sushi are kept at -60°C. Chilled produce is typically kept between 0°C and 4°C with some produce, such as fruit, bakery products and vegetables, being stored between 8°C and 12°C (UNEP 2015a). Pharmaceutical products also typically require specific storage temperatures, with the optimum temperature for refrigerated vaccines, for example, being between 2°C and 8°C (Shafaat et al. 2013).

[21] Cold storage, as characterized for the purposes of this report, excludes food processing activities (e.g., air blast freezing) and other industrial process refrigeration.

[22] Although the cold storage industry also relies on insulating foam that commonly use HFCs, insulating foams found in cold storage are not discussed as part of this market characterization report.

For most cut flowers, ideal temperatures range from roughly 0°C to 2°C (Reid and Nell 2004), while the optimal storage temperature for furs is between 1°C to 7°C (Furcare.com 2015).

The refrigeration systems used in cold storage facilities are commonly categorized into two system types: central plant systems and packaged systems. Central plant systems are large, custom built systems that are made up of separately manufactured components, while packaged systems are manufactured to contain all system components within a single factory-packaged unit. These system types are described further in the sections below.

3.2.1.1 Central Plant Systems

Central plants are custom-built refrigeration systems that are typically used in large refrigerated warehouses with cooling capacities that range from 20 to 5,000 kW (UNEP 2015c).[23] Central plant systems deliver cool air to the refrigerated space through evaporators, which are typically suspended from the ceiling in the refrigerated space (EIA 2012). The evaporators are connected through a piping network to multiple compressors that are located in a central machine room, and a condenser, which is typically mounted outside near the compressor (Cole 2004). Central plant systems can have a direct or indirect (secondary loop) design. Direct systems circulate a primary refrigerant throughout the refrigerated space. In an indirect system, a primary refrigerant cools a secondary refrigerant in the machine room, and the secondary refrigerant is then circulated throughout the refrigerated space. Example images of central plant evaporators, compressors, and condensers are presented in Figures 6-8.

Figure 6: Ceiling-mounted Cold Storage Room Evaporators (TRJ Refrigeration 2015; UNEP 2015c)

[23] The cooling capacity is the measure of a refrigeration system's ability to remove heat.

Figure 7: Central Plant Compressors in a Machine Room (Cole 2004)

Figure 8: Three Evaporative Condensers outside a Cold Storage Facility (Cole 2004)

3.2.1.2 Packaged Systems

Packaged systems (also known as unitary systems) are self-contained systems that combine an evaporator, compressor, and condenser in one frame. Packaged systems are commonly installed on the roof of a refrigerated warehouse above the air cooling units that are within the refrigerated space (Cole 2004). The evaporator is located inside the refrigerated space of a walk-in facility while the condensing unit, which is usually protected by weather resistant housing, is located outside (EIA 2012). Packaged systems are most commonly used in small refrigerated warehouses that have a capacity of 20 to 750 kW (Emerson Climate 2014). Figure 9 presents example images of two packaged units installed in a refrigerated warehouse.

Figure 9: Packaged Units on the Roof and Ceiling of a Refrigerated Warehouse (Cole 2004)

3.2.1.3 System Manufacturers

A non-comprehensive list of manufacturers of central plant and packaged systems in the United States is provided below, as identified largely through the Global Cold Chain Alliance directory.[24]

- Alta Refrigeration
- American Industrial Refrigeration
- AMS Mechanical Systems
- Azane, Inc.
- Baltimore Air Coil
- Bitzer U.S., Inc.
- Cimco, Refrigeration
- Colmac Coil
- Emerson Climate Technologies
- Evapco
- Gartner Refrigeration & MFG, Inc.
- Guntner U.S., LLC
- Heatcraft Refrigeration Products
- Hill Phoenix
- Hussmann Corporation
- Ingersoll Rand
- Innovative Refrigeration Systems, Inc.
- Johnson Controls
- Krack Corporation
- NXTCOLD LLC
- M&M Refrigeration, Inc.
- Mayekawa U.S.A., Inc.
- Mollenberg-Betz, Inc.
- Republic Refrigeration, Inc.
- S&S Refrigeration Company
- Service Refrigeration, LLC
- TRJ Refrigeration
- Uni-Temp Refrigeration, Inc.
- Zero Zone

[24] The Global Cold Chain Alliance directory is available online at: https://gcca.connext.io/#/search. Other system manufacturers were identified through EIA 2012 and an online search.

3.2.1.4 Standards

Relevant standards for the design and operation of cold storage refrigeration systems are listed below:

- ASHRAE Standard 15-2013 – Safety Standard for Refrigeration Systems
- ASHRAE Standard 34-2013 – Designation and Classification of Refrigerants
- ANSI/ASHRAE/IES 90.1-2013 – Energy Standard for Buildings Except Low-Rise Residential Buildings
- California Energy Commission – 2008 Building Energy Efficiency Standards for Residential and Nonresidential Buildings – Section 126
- ANSI/International Institute of Ammonia Refrigeration (IIAR) Standard 2-2008 (Addendum B) – American National Standard for Equipment, Design, & Installation of Closed Circuit Ammonia Mechanical Refrigerating Systems
- ANSI/IIAR Standard 3-2012 – American National Standard for Ammonia Refrigeration Valves

In addition to the standards listed above, ASHRAE published *Design Essentials for Refrigerated Storage Facilities* in 2005 to share best practices in the design of refrigerated warehouses. Furthermore, ASHRAE Technical Committee 10.5 is tasked with addressing the application of packaged and customized refrigeration systems for cold storage applications. The committee meets semi-annually to develop guidelines and approve standards related to cold storage refrigeration systems.

3.2.2 U.S. Cold Storage Facility Types and Operators

Cold storage facilities are often characterized as either public or private/semi private. Table 17 defines the facility types and the types of operators that commonly manage these facilities.

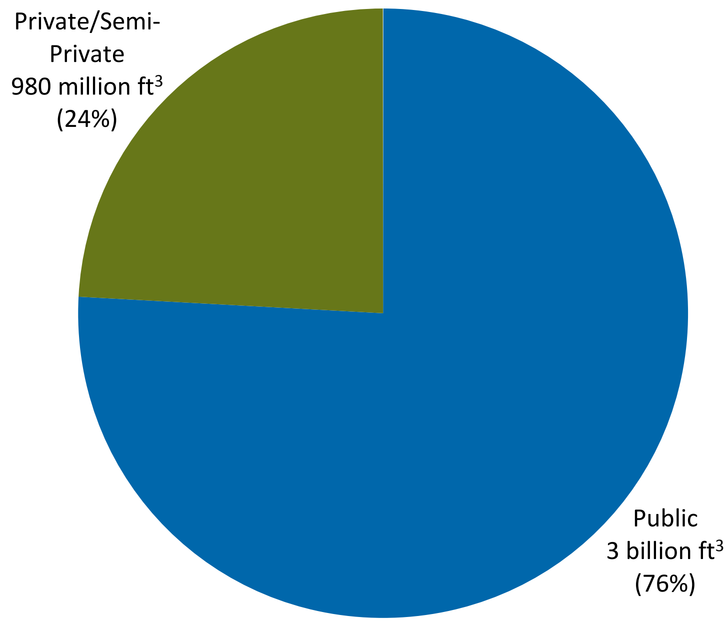
Table 17: Types of Cold Storage Facilities and Operators

Facility Type	Definition	Type of Operators
Public	Public cold storage warehouses store goods from various vendors, and are typically operated by one refrigerated warehouse logistics provider.	• Refrigerated warehouse providers • Third party logistics (3PL) providers[a]
Private and Semi-Private	In private/semi-private cold storage warehouses, the operator owns the goods that are stored. Private storage facilities typically exist to facilitate an operator's role—often that of a producer, processor or manufacturer of refrigerated food products. Semi-private facilities store an operator's products in addition to offering storage space to outside clients.	• Food manufacturers • Wholesale distributors • Retailers

[a]3PL provide both storage and transportation services

In total, there are more than 600 facility operators in the United States (JLL 2014). In 2013, public refrigerated warehouses accounted for 76 percent of U.S. cold storage capacity with more than three billion cubic feet of storage space, while private refrigerated warehouses comprised 24 percent of the U.S. cold storage capacity with approximately 980 million cubic feet of storage space (USDA 2014). Figure 10 graphically presents the breakout of cold storage capacity by facility type in the United States in 2013.

Figure 10: Gross Capacity of Refrigerated Storage by Facility Type, 2013

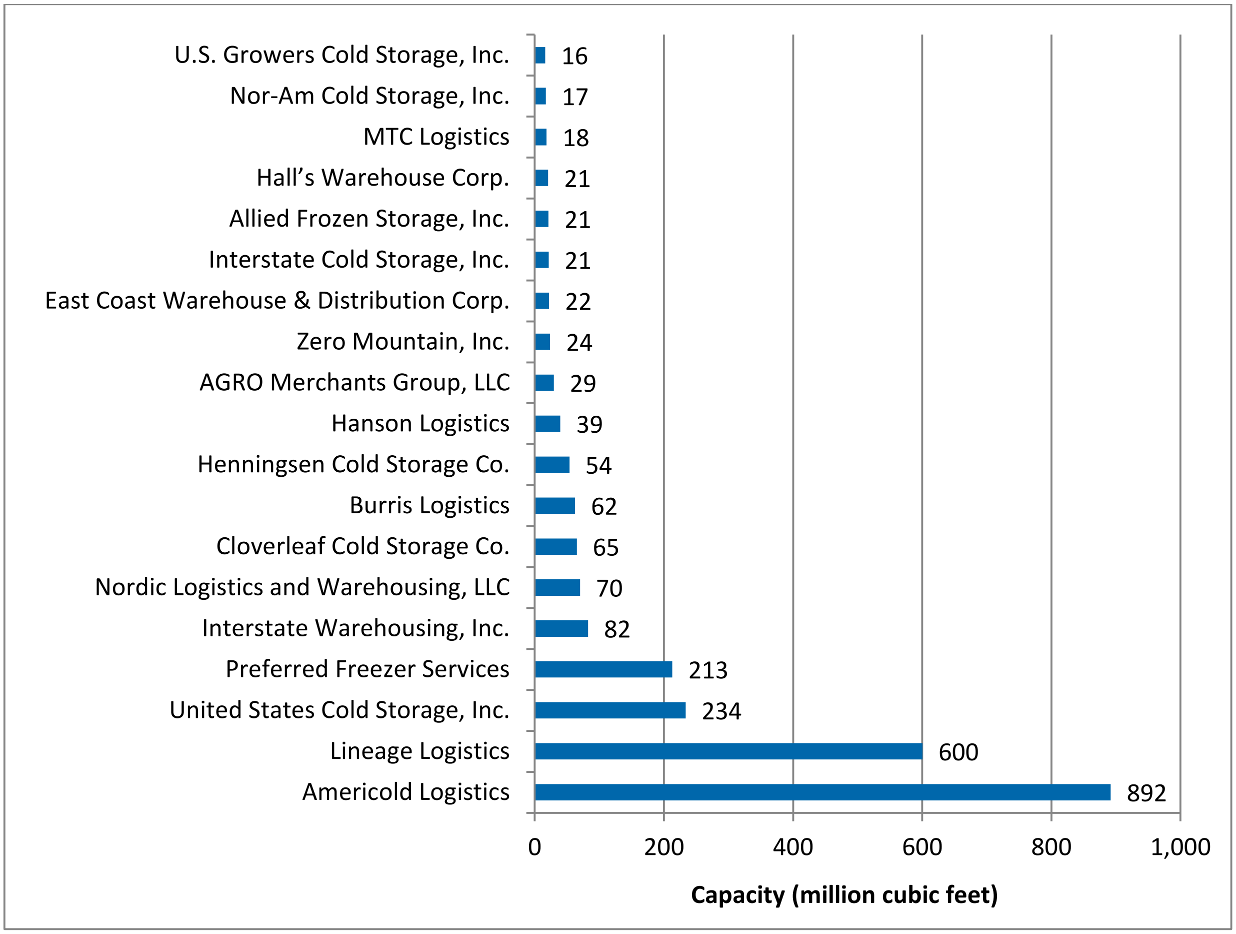


Source: USDA 2014

Refrigerated warehouse providers and 3PL providers make up the public refrigerated warehouse industry. In addition to operating facilities that house goods from a variety of customers, these providers also operate dedicated facilities under long-term contracts with their customers. Forward warehouses (stand-alone warehouses that are independent of the manufacturing site), in particular, are also commonly outsourced to 3PL providers (Harps 2003). Figure 11 presents the largest public refrigerated warehousing and logistics providers in the United States and their total storage capacity.

While many wholesale distributors, food manufacturers, and retailers use the services offered by 3PL and other public cold storage facility operators, some operate private cold storage facilities in-house. For example, United Natural Foods, Inc. (UNFI), the largest distributor of organic and natural products in North America, owns and operates 33 distribution centers, including the nation's first Leadership in Energy & Environmental Design (LEED) Gold certified refrigerated warehouse (UNFI 2014a; UNFI 2014b).

Figure 11. Largest Public Refrigerated Warehousing and Logistics Providers in the United States[a]

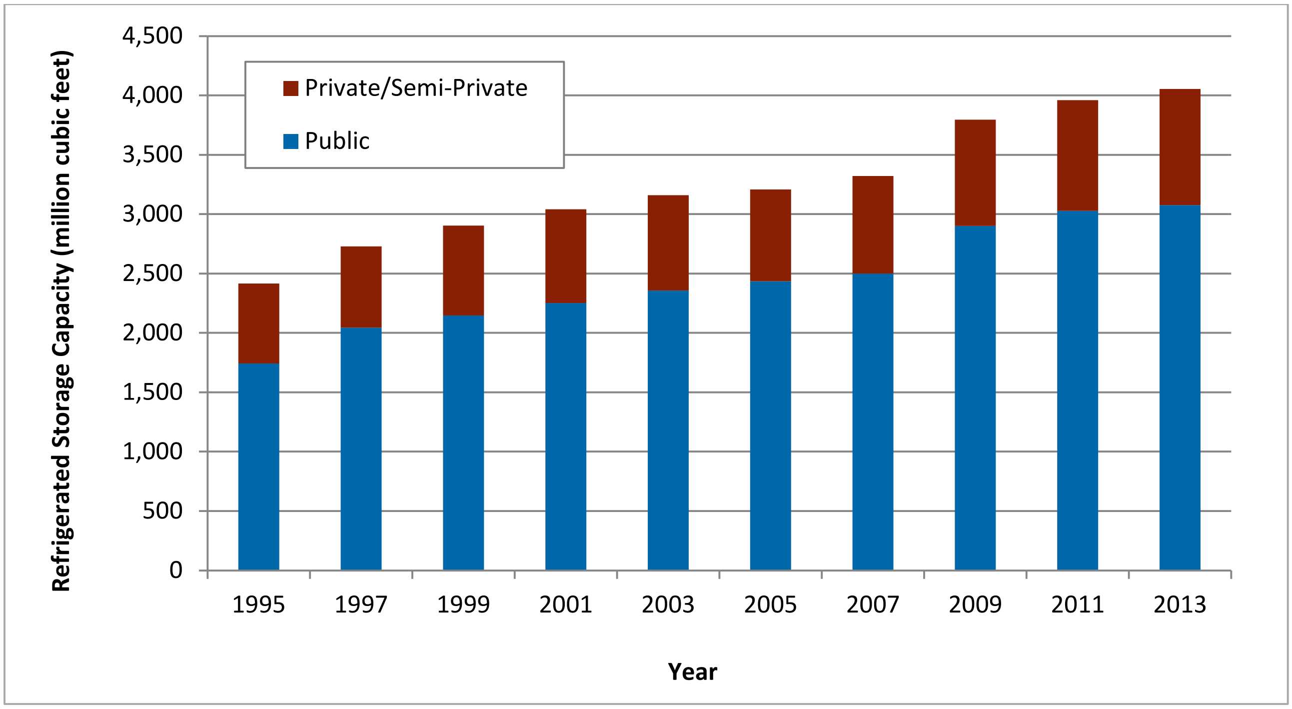


[a]Americold Logistics provides a total capacity of roughly 908 million cubic feet, 16 million cubic feet of which are located in Canada.
Sources: IARW (2015); Colliers International (2011); Cushman & Wakefield (2013); U.S. Securities and Exchange Commission (2010).

3.2.3 Cold Storage Capacity in the United States

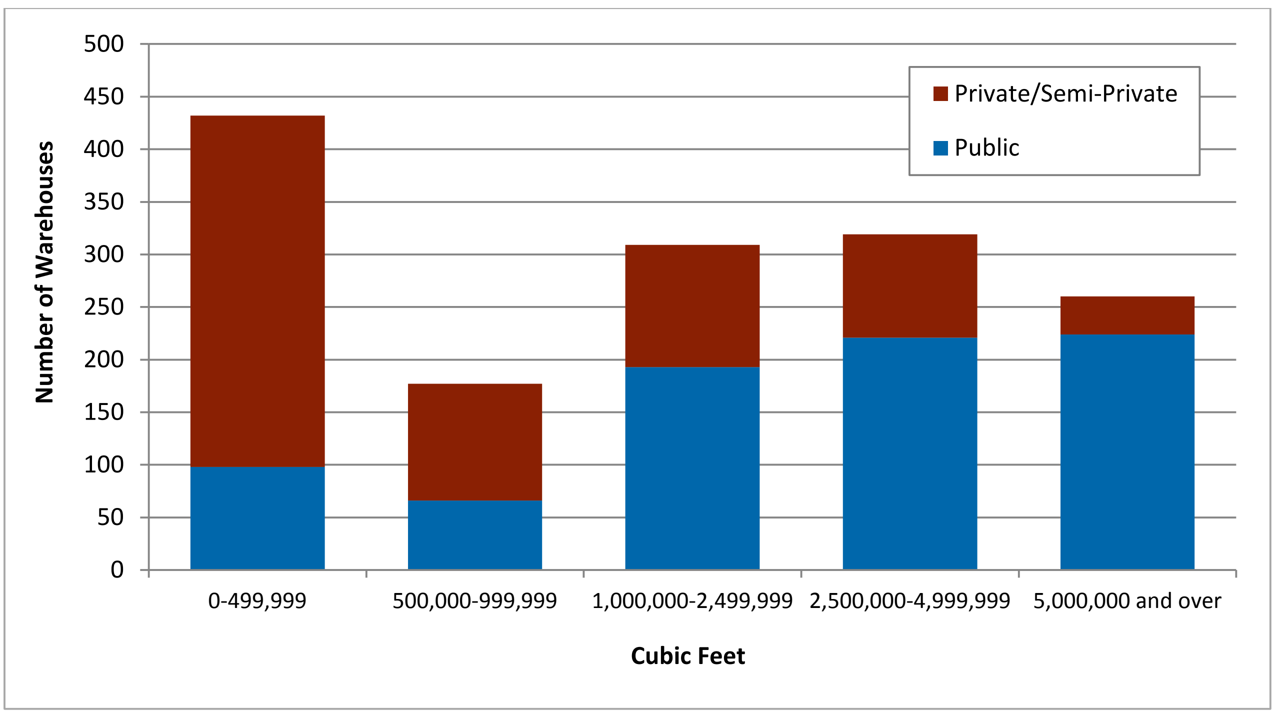
According to a 2013 survey conducted by the United States Department of Agriculture (USDA), there are roughly 1,500 cold storage warehouses in the United States with a gross refrigerated storage capacity of more than four billion cubic feet (USDA 2014). Since 1995, storage capacity in the United States has increased by an average of roughly four percent each year. Figure 12 presents the gross refrigerated storage capacity in the United States by year and facility type. Figure 13 summarizes the number of warehouses in 2013 in the United States by size group.

Figure 12: Gross Capacity of Refrigerated Storage by Year (1995-2013) and Facility Type



Source: USDA 2014

Figure 13: Number of Cold Storage Warehouses in 2013 by Size Group and Facility Type



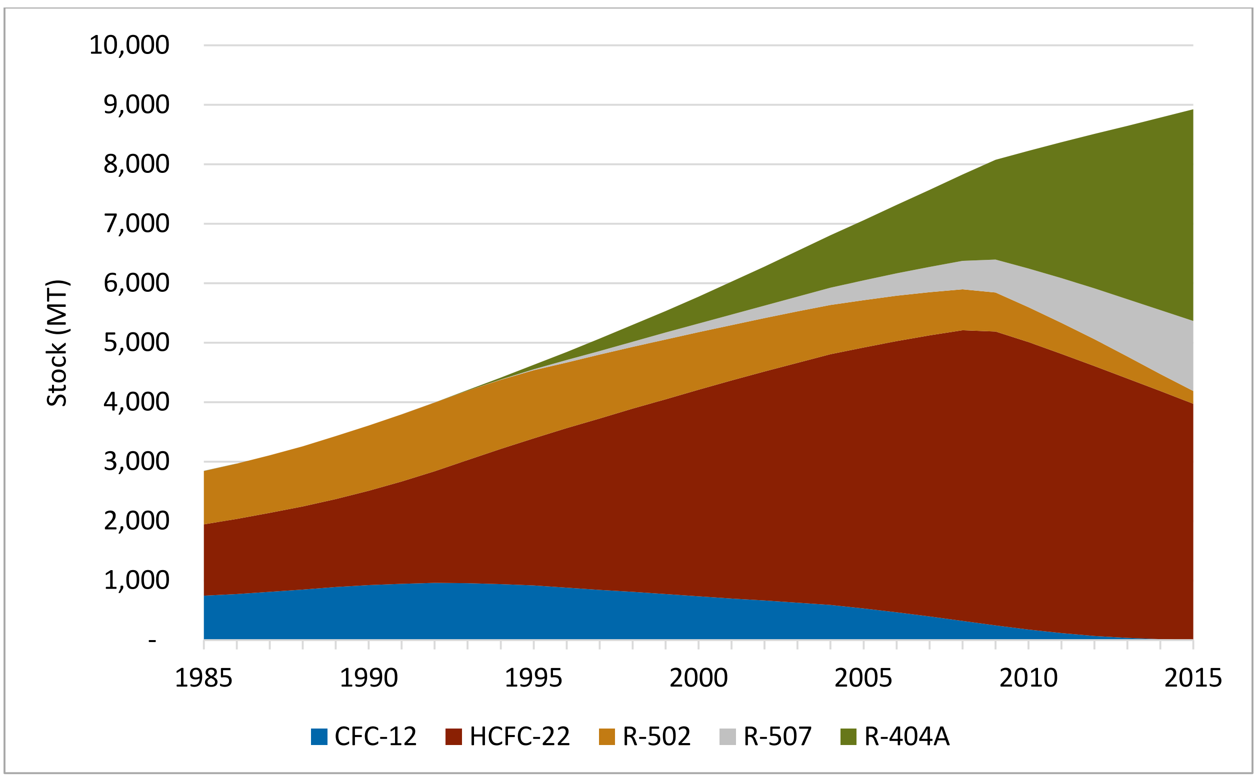
Source: USDA 2014

3.3 Sector Background

In the late 1800s, ammonia (R-717) was first adopted in the United States for use in cold storage applications. Following the introduction of CFC and HCFC refrigerants in the 1930s, part of the cold storage market transitioned to ODS—namely CFC-12, R-502, and HCFC-22—to avoid the safety concerns associated with ammonia. However, unlike other refrigeration applications, a significant portion of the cold storage market in the United States continued to use ammonia due to both the low cost of ammonia refrigerant and the high energy efficiency of ammonia systems (UNEP 2015a). In response to the global phaseout of ODS under the Montreal Protocol, in the 1990s many manufactures began the transition from CFCs to HCFC-22, and then from HCFC-22 to HFCs—primarily R-404A and R-507, which have GWPs of 3,922 and 3,985, respectively (UNEP 2015a). Some traditional ODS users transitioned to ammonia, as well.

Today, ammonia continues to be the most commonly used refrigerant in large central plant cold storage systems, while HCFCs and HFCs continue to be used largely in smaller packaged systems. Specifically, it is estimated that approximately 90 percent of the U.S. cold storage market today uses ammonia (Accelerate America 2015). For the portion of the market that does not use ammonia, HCFC-22 represents the largest existing stock of refrigerant, followed closely by R-404A. Figure 14 presents the estimated stock of fluorinated refrigerants from 1985 to 2015 used in cold storage applications in the United States.

Figure 14: Fluorinated Refrigerant Stock in U.S. Cold Storage (MT)*



Source: EPA (2014)
*The stock of ammonia, which represents roughly 90 percent of the cold storage market, is not reflected in the graph.

3.4 Climate-Friendly Alternatives

As discussed in the section above, ammonia (R-717) has been and continues to be the most widely used climate-friendly alternative in cold storage applications in the United States, particularly in large refrigerated warehouses. With the introduction of advanced system designs—such as low charge packaged ammonia systems and ammonia/CO_2 cascade systems—ammonia is expected to continue to gain market share. Other alternatives, including CO_2 (R-744) and HFC/HFO blends are also viable alternatives for use in cold storage facilities. Table 18 summarizes the current status of climate-friendly alternatives in cold storage applications in the United States, including each alternative's GWP and SNAP-listing status. Each alternative is discussed in more detail in the sections that follow.

Table 18. Climate-Friendly Alternatives in Cold Storage

Climate-Friendly Alternative	GWP[a]	Status of Use
Ammonia (R-717)	0	• Acceptable under SNAP (1996) • Used in 90 percent of the U.S. cold storage industry • Alternative designs also available
CO_2 (R-744)	1	• Acceptable under SNAP (2009) • Used in cascade designs with ammonia
HFC/HFO Blends	<631	• R-450A (blend of HFO-1234ze(E)/HFC-134a) acceptable under SNAP (2014) • R-513A (blend of HFO-1234yf/HFC-134a) acceptable under SNAP (2015) • R-448A and R-449A under SNAP review • Other blends under development

[a]Source: UNEP 2015c

3.4.1 Ammonia

Ammonia (R-717) is the most common alternative to ODS in cold storage systems and has consistently been used in large cold storage facilities throughout the United States (UNEP 2015a). Conventional central plant systems that use ammonia can have a refrigerant charge as high as 20,000 to 40,000 pounds (Accelerate America 2015).[25] Ammonia is inexpensive and has excellent heat transfer characteristics (IARW 2014). At the same time, ammonia is more toxic than common fluorinated refrigerants and slightly flammable, and can be dangerous if not used properly. Due to safety concerns and regulations, some cold storage operators are hesitant to adopt ammonia-based systems. In addition, ammonia is less popular for use in smaller applications that currently rely on ODS- or HFC-based packaged systems. In recent years, however, advanced system designs—including low charge

[25] Systems that exceed 10,000 pounds of ammonia refrigerant are subject to regulations set forth by EPA and OSHA. These regulations mandate a range of compulsory measures including registration with local authorities, periodic inspection, strict requirements on reporting of any emissions and preparation of an offsite consequence analysis and emergency response plan (including regular drills) (IARW 2015; Pearson 2010).

packaged ammonia systems, ammonia/CO_2 cascade systems and ammonia secondary loop systems—have been introduced into the market and are gaining market share, as discussed further below.

3.4.1.1 Low Charge Packaged Ammonia Systems

In recent years, a number of manufacturers have introduced systems that use ammonia refrigerant in small, packaged units. Unlike conventional ammonia systems, the low charge packaged systems do not require the use of a machine room, eliminate the large scale vessels required for holding ammonia refrigerant, and minimize distribution piping throughout the cold storage facility (IAWR 2014). They also reduce the charge size of ammonia by an estimated 80 to 98 percent (IAWR 2014). These systems, in particular, have great potential to replace smaller systems that currently use HCFC or HFC refrigerants.

3.4.1.2 Ammonia/CO_2 Cascade Systems

As an alternate design to conventional ammonia central plant systems, many operators have begun to adopt ammonia/CO_2 cascade systems, which use CO_2 as the low stage refrigerant in a cascade design. These systems, which are most favorable for use in low temperature applications, can reduce the charge size by an estimate 70 to 90 percent compared to an ammonia-only system (Shecco 2013; IAWR 2014). For example, in 2005, U.S. Cold Storage installed its first ammonia/CO_2 cascade system at their facility in Bethlehem, PA. Since then, U.S. Cold Storage has installed more than ten ammonia/CO_2 systems in the United States (Accelerate America 2015). In addition to reducing the charge size of ammonia to between 5,000 and 8,000 pounds, their ammonia/CO_2 systems on average are roughly six percent more efficient than a conventional central plant ammonia system (Accelerate America 2015).

3.4.1.3 Ammonia Secondary Loop Systems

While ammonia/CO_2 cascade designs are the most popular advanced system design for use in large cold storage applications, secondary loop systems—where ammonia (or another primary refrigerant) is contained to the machine room and a secondary fluid such as CO_2 or brine/glycol is circulated to the evaporators in the refrigerated space—are also feasible. These systems have similar benefits in terms of charge reduction to an ammonia/CO_2 cascade system, achieving a reduction of an estimated 70 percent relative to an ammonia-only system (IAWR 2014). It is also possible to implement a hybrid design that uses both a secondary loop and cascade system.

3.4.2 Carbon Dioxide

Due to the low critical temperature of CO_2, it cannot be used in the same way as other industrial refrigerants (UNEP 2015a). While CO_2 is approved for use as a primary refrigerant under SNAP in transcritical systems, there are no compressors currently on the market that provide the necessary high operating pressures to run an industrial-sized CO_2 transcritical system (UNEP 2015a). Therefore, CO_2 transcritical systems may be adopted by some smaller cold storage facilities in the United States, while in larger applications the use of CO_2 will likely be limited to cascade and other indirect system designs.

3.4.3 HFC/HFO Blends

Unsaturated HFCs (i.e., HFOs) blended with saturated HFCs, namely R-450A and R-513A, are approved for use in cold storage under EPA's SNAP program but are not believed to have been adopted by the cold storage industry yet. R-450A is a blend of HFO-1234ze(E)/HFC-134a and R-513A is a blend of HFO-

1234yf/HFC-134a. The HFO/HFC blends R-448A and R-449A are currently under review by the SNAP program for use in cold storage warehouses. R-448A is a blend of HFC-32, HFC-125, HFC-134a, HFO-1234yf, and HFO-1234ze(E), and R-449A is a blend of HFC-32, HFC-125, HFC-134a, and HFO-1234yf. Due to costs and the viability of other climate-friendly alternatives, it is not expected that these refrigerants and others that are under development will gain significant market share in cold storage applications in the United States (UNEP 2015a).

4 U.S. Refrigerated Food Processing and Dispensing Equipment

4.1 Introduction

The refrigerated food processing and dispensing equipment industry consists of self-contained units that cool and dispense food and beverages via a nozzle. This equipment is typically found in small retail food facilities, including convenience stores, restaurants, cafeterias, hotels, schools, hospitals, and snack and beverage bars. The refrigerated food processing and dispensing equipment industry historically relied on ODS, including CFC-12 and HCFC-22, but transitioned to HFC-134a and R-404A—both of which are powerful greenhouse gases—for medium- and low-temperature applications, respectively, in response to the phaseout of ODS under the Montreal Protocol. Today, there are several low-GWP alternative refrigerants (e.g., hydrocarbons, carbon dioxide, R-448A, R-449A, R-450A, and R-513A) that may become available for use in refrigerated food processing and dispensing equipment. The remainder of this chapter characterizes the refrigerated food processing and dispensing equipment industry in terms of equipment type, system manufacturers, historical and current refrigerant use, and the availability of climate-friendly alternatives.

4.2 Market Characterization

Refrigerated food processing and dispensing equipment comprise three main product categories: soft serve/ice cream machines, chilled beverage dispensers, and frozen beverage dispensers. Soft serve/ice cream dispensers serve ice cream, soft-serve, frozen yogurt/custard, sorbet, gelato, and Italian ice; chilled beverage dispensers serve cold drinks including, but not limited to, fountain drinks, iced coffee and tea, juice, and milk; and frozen beverage dispensers typically serve "slushies," shakes, and cocktails. Example images of refrigerated food processing and dispensing equipment are provided in Figure 15.

Figure 15: Example Images of Refrigerated Food Processing and Dispensing Equipment (Avantco 2015; Stoelting 2015; Taylor Company 2015)

Chilled Beverage Dispenser | Frozen Beverage Dispenser | Soft Serve/Ice Cream Dispenser

This equipment can be either air- or water-cooled and has the potential to employ various types of compressors (Alpine 2014, Electro Freeze 2015). Major components of the refrigerated food processing and dispensing systems include: electric motors, compressors, a liquid cooler, and refrigerant expansion valves. Charge sizes are estimated to range 0.1 to 1 kg (Alpine 2014). Manufacturers of refrigerated food processing and dispensing equipment, as identified through an internet search are summarized below in Table 19.

Table 19: Manufacturers of Refrigerated Food Processing and Dispensing Equipment*

Company	Soft Service/Ice Cream Machines	Chilled Beverage Dispensers	Frozen Beverage Dispensers
Alpine Freezer	X		
Avantco Equipment		X	
Bunn		X	X
Central Restaurant Products		X	X
Cornelius		X	X
Electro Freeze	X	X	X
Elmeco		X	X
Emery Thompson Machine & Supply Co.	X		
Eurodib		X	
Grindmaster Cecilware		X	X
MegaLane	X		
Omega		X	X
SaniServ	X		X
Spaceman	X		X
Stoelting	X		X
Taylor Company	X		X

* The companies listed do not necessarily represent an inclusive list of all manufacturers of refrigerated food processing and dispensing equipment in the United States.

4.3 Sector Background

Historically, the refrigerated food processing and dispensing equipment industry relied on ODS refrigerants, including CFC-12 and HCFC-22. In response to the phaseout of ODS under the Montreal Protocol, the refrigerated food processing and dispensing equipment industry adopted HFC-134a and R-404A in medium- and low-temperature applications, respectively. Both HFC-134a and R-404A are potent GHGs with GWPs of 1,430 and 3,920, respectively (EPA 2015e).

4.4 Climate-Friendly Alternatives

Several alternative refrigerants with lower GWPs have the potential for use in refrigerated food processing and dispensing equipment. These alternatives include hydrocarbons (e.g., R-600a and R-290), carbon dioxide (R-744), and HFO/HFC blends (e.g., R-448A, R-449A, R-450A, and R-513A). Table 20 below provides an overview of climate-friendly alternatives and their listing status under EPA's SNAP program. Each alternative is discussed in more detail in the sections that follow.

Table 20: Climate-Friendly Alternative Refrigerants

Alternative		GWP	SNAP Listing Status
Hydrocarbons	R-600a	~4	Not EPA SNAP approved
	R-290	3.3	Not EPA SNAP approved
Carbon Dioxide	R-744	1	Acceptable (2009)
HFO/HFC Blends	R-450A	601	Acceptable (2014)
	R-448A	1,390	Not EPA SNAP approved
	R-449A	1,400	Not EPA SNAP approved
	R-513A	630	Under SNAP review

Sources: EPA 2009b, EPA 2011, EPA 2014c, and EPA 2015d

4.4.1 Hydrocarbons

Hydrocarbons, such as R-600a and R-290, are a potentially viable alternative refrigerant for HFC-134a and R-404A in refrigerated food processing and dispensing equipment but are not currently SNAP-approved for this end-use (The Linde Group 2015b, EPA 2015b). Hydrocarbon refrigerants have no ODP, low GWPs, but are also highly flammable (ANSI/ASHRAE Standard 34 Safety Group A3) (The Linde Group 2015b). Hydrocarbon refrigerants can also produce higher energy efficiency in some equipment types (The Linde Group 2015a). Supplement SB to the UL Standard for Commercial Refrigerators and Freezers, UL 471, dated November 24, 2010 applies to hydrocarbon refrigerants in refrigerated food processing and dispensing equipment. These refrigerants are not currently EPA SNAP approved for this use.

4.4.2 Carbon Dioxide

Carbon dioxide (R-744) has regained popularity as an environmentally friendly refrigerant because it has zero ODP, a GWP of 1, low toxicity, and is not flammable. In addition, equipment using R-744 can experience lower energy usage (The Linde Group 2015a). This refrigerant was EPA SNAP approved for use in new retail food refrigeration in 2009 (EPA 2009b).

4.4.3 HFC/HFO Blends

Other potentially viable alternatives for refrigerated food processing and dispensing equipment are HFO/HFC blends, such as R-450A and R-513A in medium-temperature systems, and R-448A and R-449A, which could be used in both low- and medium-temperature refrigeration applications (Honeywell 2015c, Chemours 2015b, Honeywell 2015a, Chemours 2015a). R-450A, a blend of HFC-134a and HFO-1234ze(E), is compatible with new and retrofit equipment using HFC-134a, has a GWP nearly 60% lower than HFC-134a, and was approved by EPA's SNAP program across all retail food refrigeration systems in 2014 (EPA 2014c, Honeywell 2015a). R-513A, a blend of HFC-134a and HFO-1234yf, is compatible for new and retrofit equipment using HFC-134a, with a GWP more than 55% less than HFC-134a and was approved by EPA's SNAP program in a number of types of retail food refrigeration systems in 2015, but not yet for refrigerated food processing and dispensing equipment (EPA 2015d, Chemours 2015a). R-450A and R-513A are also non-flammable, and offer a similar performance and energy efficiency to HFC-134a (Honeywell 2015a; Chemours 2015a). R-448A, a blend of HFC-32, HFC-125, HFC-134a, HFO-1234ze(E), and HFO-1234yf, is considered a near drop-in replacement for R-404A, with a GWP almost 70% lower than R-404A (Honeywell 2015c). Similarly, R-449A, a blend of HFC-32, HFC-125, HFC-134a, and HFO-1234yf, is compatible for new and retrofit equipment using R-404A and has a GWP almost 65% lower than R-404A (Chemours 2015b). Both are non-flammable (ANSI/ASHRAE Standard 34 Safety Group A1) with increases in efficiency of 5-10% compared to R-404A (Honeywell 2015c, The Linde Group 2015c). R-448A and R-449A have not been EPA SNAP approved for this end-use.

5 U.S. Household Refrigeration Industry

5.1 Introduction

The U.S. household refrigeration industry includes household refrigerators and freezers that are intended primarily for residential use. Note, however, that some of this equipment may also be used outside the home, for example, in an office building break room or college dormitory. The U.S. household refrigeration industry historically relied on CFC-12 refrigerant, which depletes the stratospheric ozone layer and contributes to climate change. In response to the global phaseout of ODS, the industry transitioned to HFC-134a in the mid-1990s. Although HFC-134a does not contribute to ozone depletion, it is a powerful greenhouse gas (GHG), and its emissions contribute to climate change. Today, low-GWP alternative refrigerants (e.g., hydrocarbons, HFOs, and HFO/HFC blends) have entered or are expected to enter the U.S. household refrigeration market, facilitated by acceptability listings under EPA's SNAP program.

The remainder of this chapter characterizes the U.S. household refrigeration industry in terms of key market players, historical and current refrigerant use, and the availability of climate-friendly alternatives.

5.2 Market Characterization

This section provides an overview of household refrigeration equipment, the current market, and key manufacturers.

5.2.1 Overview of U.S. Household Refrigeration Equipment

Household refrigerators and freezers comprise three main product categories: refrigerators, freezers, and refrigerator-freezers, with a combined refrigerator-freezer in a single unit being the most common. A small fraction of household refrigeration equipment is made up of small refrigerated household appliances such as chilled kitchen drawers, wine coolers, and mini-fridges. The descriptions provided in the following sections do not distinguish between product categories since the equipment is very similar in design across categories. Example images of household refrigeration equipment are provided in Figure 16.

Figure 16. Example Images of Household Refrigeration Equipment (Maytag 2015; Whirlpool 2015; Kenmore 2015; GE 2015)

Side-by-side refrigerator | Top freezer refrigerator | Upright freezer | Wine/beverage cooler

Most household refrigeration equipment are factory-produced, electrically-driven, hermetically-sealed systems that use a vapor compression refrigeration cycle (UNEP 2015b). Major components of each system include an evaporator, a compressor with an electric motor, a condenser, and an expansion valve. Household refrigerators and freezers typically contain between 0.1 and 0.3 kg of refrigerant.[26] Refrigerant charge sizes have decreased over the years in the United States, but are typically larger than those in Europe and Japan (U.S. EPA 2010). Table 21 summarizes key characteristics for currently manufactured household refrigerators and freezers for sale and distribution in interstate commerce.

Table 21. Summary of U.S. Household Refrigerator and Freezer Characteristics

Parameter	Typical Characteristics
Typical cooling capacity[a]	0.1 to 0.5 kW
Refrigerants used	HFC-134a
Refrigeration circuit design	Hermetically sealed vapor compression
Manufacture/installation	Factory built
Typical annual leakage rate	<5%, with an average of 0.6%
Main source of emissions	Losses at end-of-life
Typical size of refrigerated space	15 to 22 cubic feet

[26] Although this industry also relies on insulating foam that commonly use HFCs, insulating foams found in household refrigerators and freezers are not discussed as part of this market characterization report.

Parameter	Typical Characteristics
Average lifetime	14 years

[a]The cooling capacity is the measure of a refrigeration system's ability to remove heat.
Source: EPA 2014a; UNEP 2015b; EIA 2013

In 2014, an estimated 164 million household refrigerators and freezers were in operation in the United States (EPA 2014a). Approximately 10.8 million new units enter the U.S. market annually (EPA 2014a).[27] According to a recent U.S. residential energy consumption survey, 113.4 million U.S. households use a refrigerator, 77% of which use one refrigerator and 23% of which use two or more refrigerators (EIA 2013). As shown in Table 22, the most-used refrigerator types in U.S. households are the two-door configuration with a freezer on top, followed by the two-door configuration with the refrigerator and freezer side-by-side.

Table 22. Refrigerator Types in U.S. Households

Type of Refrigerator[a]	Total U.S. Homes (millions)	Percent
Single Door	9.3	8%
2 Doors (Top Freezer)	55.8	49%
2 Doors (Bottom Freezer)	7.7	7%
2 Doors (Side-By-Side)	38.5	34%
3 or More Doors	0.9	1%
Half-Size/Other	1.3	1%
Total	113.5	100%

[a]For homes with more than one refrigerator, the most-used one is shown and the others are excluded.
Source: EIA 2013

Known household refrigeration equipment manufacturers with a presence in the United States market are listed below. The largest appliance manufacturers are Whirlpool, General Electric (GE) and Kenmore (Bloomberg 2014). The companies below were identified through a literature review while developing this report, and this is not necessarily an inclusive list of all companies producing and/or selling refrigerated appliances within the United States.

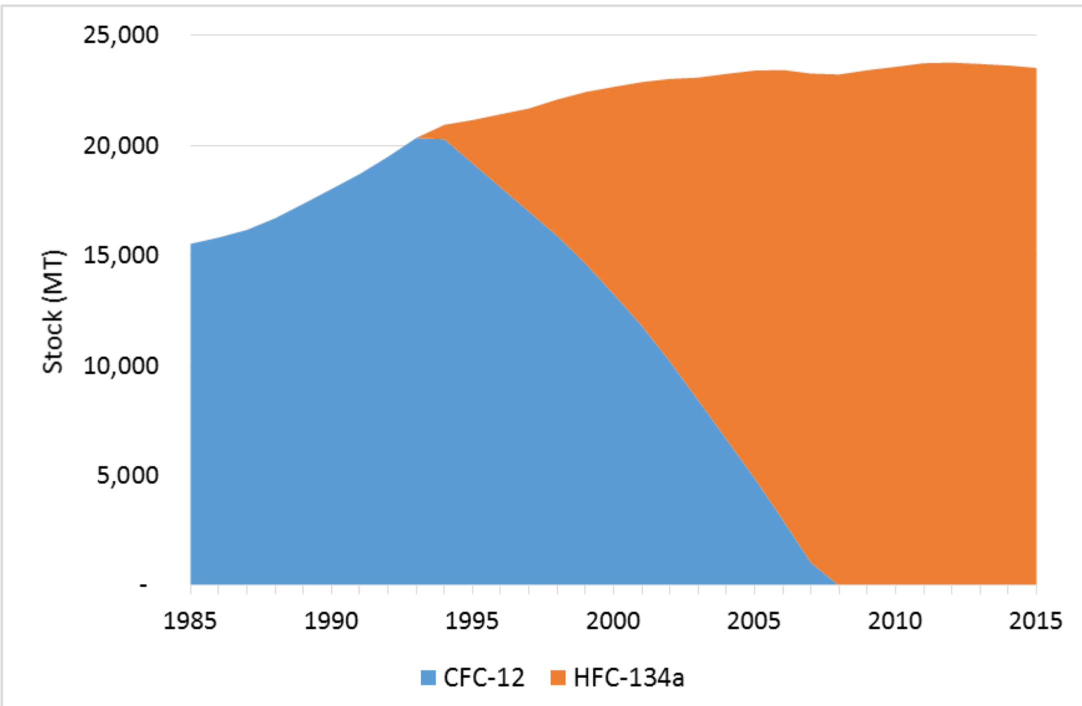
- AGA Ranges LLC
- Amana
- Avanti
- Bosch
- Dacor
- Danby
- Electrolux
- Fagor America, Inc.
- Frigidaire
- General Electric
- Haier
- Kenmore
- KitchenAid
- Liebherr
- LG
- Middleby
- Miele
- Maytag
- Norcold
- Panasonic
- Perlick
- Samsung
- Sub-Zero
- Summit
- Whirlpool

[27] Based on previous industry research and analysis, it is estimated that approximately 70 percent of the annual demand for household refrigerators and freezers in the United States is met by imports (EPA 2009a, U.S. Census Bureau 2007).

5.3 Sector Background

CFC-12 was introduced as a refrigerant in the early 1930s as a replacement for the flammable and/or toxic natural refrigerants that were commonly used at the time (UNEP 2015a). CFC-12 was a popular refrigerant through the 1980s until the Montreal Protocol came into effect, banning its use due to its high ODP. As a replacement for CFC-12, the household refrigeration industry transitioned to the non-ozone depleting alternative HFC-134a in the mid-1990s. However, like its predecessor, HFC-134a is a potent GHG. HFC-134a, which has a GWP of 1,430 (IPCC 2007), is the predominant refrigerant used today in U.S. refrigerator-freezers, as illustrated in Figure 17. HCFCs have not been used as refrigerants in this end-use.

Figure 17. Refrigerant Stock in U.S. Household Refrigeration from 1985 to 2015 (MT)[a]



[a]EPA's Vintaging Model does not model CFC refrigerants after 2007; however, data from EPA's Responsible Appliance Disposal (RAD) program indicate that some CFC-12 refrigerators are still being decommissioned.
Source: EPA 2014a

5.4 Climate-Friendly Alternatives

Several alternative refrigerants with lower GWPs have been found to be acceptable under EPA's SNAP program for use in household refrigerators and freezers. These alternatives have no ODP and include ammonia absorption, hydrocarbons, HFOs, and HFO/HFC blends. The remainder of this section summarizes information on refrigerant alternatives for the U.S. household refrigeration industry. Table 23 provides an overview of climate-friendly alternatives and their listing status under EPA's SNAP program.

Table 23. Climate-Friendly Alternative Refrigerants in U.S. Household Refrigeration

Alternative		GWP[a]	SNAP Listing Status
Hydrocarbons and hydrocarbon blends	R-290	3	Acceptable subject to use conditions (2015)
	R-600a	~4	Acceptable subject to use conditions (2011)
	R-441A	<5	Acceptable subject to use conditions (2011)
HFOs and HFO/HFC Blends	R-450A	601	Acceptable (2014)
	R-513A	631	Acceptable (2015)
	HFO-1234yf	4	Not EPA SNAP approved
	HFO-1234ze(E)	6	Not EPA SNAP approved
Low-GWP Saturated HFCs	HFC-152a	124	Acceptable (1994)
Ammonia absorption		0	Acceptable (1995)

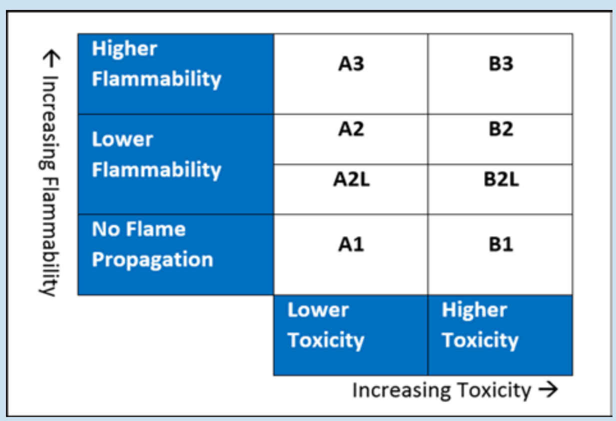
[a]Sources: EPA 2011, EPA 2012a, EPA 2014c, EPA 2015d, and IPCC 2007

5.4.1 Hydrocarbons and Hydrocarbon Blends

Hydrocarbons and hydrocarbon blends, including R-290, R-600a, and R-441A, are SNAP-approved alternative refrigerants subject to use conditions. Due to their flammability, these refrigerants may only be used in new household refrigerators and freezers that are specifically designed for and clearly identified to contain these refrigerants. Further, these refrigerants may only be used in household refrigerators and freezers that meet all requirements listed in Supplement SA to the 10th edition of the UL Standard for Household Refrigerators and Freezers, UL 250, dated August 25, 2000. As mandated in UL 250, the maximum charge size is limited to 57 grams in any refrigerator or freezer (UL 2015).

ANSI/ASHRAE Standards 34 and 15 assign a safety group classification to refrigerants based on their toxicity and flammability and establish procedures for operating systems using those refrigerants (see Figure 18). Using these safety group classifications, R-290, R-600a, and R-441A are in the A3 Safety Group. Meeting these standards leads to additional costs for safety features such as proper ventilation and leak prevention resulting in manufacturers opting to continue to produce equipment using HFC-134a (UNEP 2015a).

Figure 18. Refrigerant Safety Group Classification



Source: EPA 2015e

Although the United States has been slow to adopt hydrocarbons in household refrigerators, they have been widely used in other countries for many years (UNEP 2015a). Globally, R-600a is now the predominant refrigerant for new household refrigeration appliances and suitable components are widely available (UNEP 2015b). Currently, there are an estimated 500 million refrigerators and freezers using R-600a worldwide (UNEP 2015b). By 2020, an estimated 75 percent of new household refrigerator production will use R-600a (UNEP 2015a). Hydrocarbon refrigerants have been widely used in the market in Europe and Asia (GE 2010). Many global manufacturers offer hydrocarbon-based units outside of the U.S. while selling predominantly HFC-134a units in the U.S.

Following the SNAP listing of R-600a as an acceptable alternative in household refrigerators and freezers, GE introduced a refrigerator line in the United States containing R-600a refrigerant (GE 2010). Since then, the use of hydrocarbon refrigerants in these appliances has begun to penetrate the market in the United States.

In addition to their zero ODP and low GWP, hydrocarbons have other benefits. For instance, R-600a is approximately five percent more efficient than HFC-134a, equipment using R-600a has a lower annual running cost and lifetime cost, and R-600a reduces the noise level of the unit (UNEP 2015a).

5.4.2 HFO/HFC Blends

SNAP-approved HFO/HFC blends include R-450A and R-513A, which have no ODP and lower GWPs in comparison to HFC-134a. R-450A is a non-flammable blend of HFO-1234ze and HFC-134a that was EPA SNAP listed in 2014 for use in household refrigerators and freezers in new and retrofit equipment (EPA 2014c). R-513A is a non-flammable blend of HFO-1234yf and HFC-134a that was EPA SNAP listed in 2015 for household refrigerators and freezers in both new and retrofit equipment (EPA 2015d).

HFO-1234yf and HFO-1234ze are two low-GWP unsaturated HFCs that could become viable for use in household refrigeration pending additional research and development. HFO-1234yf has a lower flammability than R-600a (ASHRAE 2L), and has the potential for a comparable efficiency to HFC-134a. However, costs for equipment using HFO-1234yf are expected to be slightly higher that HFC-134a equipment due to the refrigerant's flammability and investment requirements for product development (UNEP 2015a). This alternative has not been EPA SNAP approved for this end-use.

HFO-1234ze is a refrigerant in the early exploration phase for household refrigeration. Like HFO-1234yf, this refrigerant has a lower flammability than R-600a, but higher than HFC-134a, but it is not likely that this refrigerant will replace R-600a or HFC-134a in the near future (UNEP 2015a). Components optimized for HFO-1234yf or HFO-1234ze in household refrigerators and freezers are not yet widely available (UNEP 2015b). This alternative has not been EPA SNAP approved for this end-use.

5.4.3 Low-GWP Saturated HFCs

Based in part on a flammability risk assessment, SNAP listed HFC-152a as acceptable for new household refrigerator-freezers in the original 1994 rule. Due to the fact that HFC-152a is flammable, manufacturers investigating this refrigerant should follow precautions similar to those listed above for hydrocarbons, including labeling and conformance to safety standards. HFC-152a has not been pursued by household refrigerator-freezer manufacturers as a refrigerant for this end-use, and so is not discussed in any more detail here.

5.4.4 Ammonia Absorption

Ammonia absorption is a NIK alternative household refrigeration technology with a zero ODP and a zero GWP. In absorption chillers, water acts as the absorbent while ammonia acts as the refrigerant for new and existing systems. The technology has been used for years in hotels; college dormitories; hotel min-bar units; mobile, off-network applications including campers and mobile homes; and other small spaces (UNEP 2015a). The advantage of this technology is low noise, while drawbacks include low efficiency and a very high discharge temperature (Pearson 2003). Barriers to adoption include ammonia's incompatibility with copper and a lack of technicians trained to handle ammonia refrigeration systems (ASHRAE 2014). ASHRAE Standards 34 and 15 classify ammonia as a B2L refrigerant with a higher toxicity and low flammability (ASHRAE 2013).

6 References

Accelerate America. 2015. North American Edition. April 2015. Available online at: http://publication.shecco.com/upload/file/org/142980014170226_472862.pdf.

The Air-Conditioning, Heating and Refrigeration News. 2014. Many HVAC Contractors Unaware of Pending Chiller Standards. Available online at: http://www.achrnews.com/articles/126864-many-hvac-contractors-unaware-of-pending-chiller-standards.

Air Force Civil Engineer Center (AFCEC). 2014. Evaluation of the Amerex Model 775 Wheeled Extinguisher with Novec™ 1230. November 2014.

Alpine. 2014. Soft Serve Machines. Available online at: http://www.alpinefreezer.com/soft-serve-machines/.

American Pacific (AMPAC). 2007. Halotron™ II Material Safety Data Sheet (MSDS). Available online at: http://www.halotron.com/pdf/halotron_two_msds.pdf.

American Pacific (AMPAC). 2015. Halotron® Clean Fire Extinguishing Agents. Available online at: http://www.halotron.com/index.php.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). 2013. Standard 90.1. Available online at: www.ashrae.org/resources--publications/bookstore/standard-90-1.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). 2014. ASHRAE Position Document on Ammonia as a Refrigerant. Available online at: https://www.ashrae.org/about-ashrae/position-documents.

Americold Logistics. 2015. Americold Facilities. Available online at: http://www.americold.com/facilities.aspx.

Armstrong & Associates. 2013. Trends in 3PL/Customer Relationships. Available online at: https://www21.corecommerce.com/~peerlessmedia/files/Customers_of_3PLs_2013.pdf.

Avantco. 2015. RBD33 Triple 3 Gallon Bowl Refrigerated Beverage Dispenser. Available online at: http://www.avantcoequipment.com/product/2587.

Bloomberg Business. 2014. Samsung Wants to be the World's Biggest Appliance Maker by 2015. Available online at: http://www.bloomberg.com/bw/articles/2014-01-09/samsung-wants-to-be-the-worlds-biggest-appliance-maker-by-2015.

BusinessWire. 2015. Ingersoll Rand Introduces the EcoWise™ Portfolio of Products as Step to Achieve its Global Climate Commitment. January 26, 2015. Available online at: http://www.businesswire.com/news/home/20150126005175/en/Ingersoll-Rand-Introduces-EcoWise%E2%84%A2-Portfolio-Products-Step#.VduMIJeK0Xs.

California Energy Commission. 2013. Greenguide for Sustainable Energy Efficient Refrigerated Storage Facilities. Available online at: http://www.energy.ca.gov/2013publications/CEC-500-2013-145/CEC-500-2013-145.pdf.

Carrier. 2015. Aquaforce® 30XA Air-Cooled Liquid Chiller with R-134a Refrigerant. Available online at: http://www.carrier.com/commercial/en/us/products/chillers/chillers/30xa/.

Center for Land Use Interpretation (CLUI). 2014. Refrigerated Nation: The Landscape of Perishable Food in America. Available online at: http://clui.org/newsletter/winter-2014/refrigerated-nation.

Chemours. 2015a. Opteon ™ XP10 Refrigerants. Available online at: https://www.chemours.com/Refrigerants/en_US/products/Opteon/Stationary_Refrigeration/assets/downloads/Opteon_XP10_prodinfo.pdf.

Chemours. 2015b. DuPont TM Opteon® Refrigerants. Available online at: https://www.chemours.com/Refrigerants/en_US/assets/downloads/k26492_Opteon_refrigerants.pdf.

Cole, R. 2004. Cold Storage Warehouses – An Engineering Overview. Available online at: http://seagrant.uaf.edu/map/workshops/cold-storage/Cole-sm.pdf.

Colliers International. 2011. Market Report: Metro Vancouver, BC. Available online at: http://www.colliersteams.com/prod/ccbrkr.nsf/publish/FF2BA46516D38561852578240061173 4/$File/Q4-10+Industrial+Rpt_PO11024_Email.pdf.

Cushman & Wakefield, Ltd. 2013. Marketbeat Industrial Snapshot: Vancouver, BC. Available online at: http://www.cushmanwakefield.com/~/media/marketbeat/2014/01/Vancouver_AMERICAS_MarketBeat_Industrial_Q42013.pdf.

Electro Freeze. 2015. Equipment. Available online at: http://www.electrofreeze.com/Equipment.aspx.

Emerson Climate. 2014. Cold storage warehouse improves efficiency with ammonia/pumped CO_2 system. Available online at: www.emersonclimate.com/Documents/Vilter/Product_Brochures/Cold-Storage-2013VM-15-R1-C.pdf.

Environmental Investigation Agency (EIA). 2012. HFC-free technologies area available in the U.S. market for the supermarket-retail refrigeration sector. Available online at: http://eia-global.org/images/uploads/HFC-Free_Tech_Available_in_the_US.pdf.

Federal Aviation Administration (FAA). 2015. Advisory Circular: Air Cargo Operations. Available online at: http://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_120-85A.pdf.

Fire Equipment Manufacturers' Association (FEMA). 2015. Portable Fire Extinguishers. Available online at: http://femalifesafety.org/about.html.

Fire Protection Research Foundation. 2010. Measuring Impact of Fire Extinguisher Agents on Cultural Resource Materials. Prepared by Hughes Associates, Inc. February 2010. Available online at: http://www.nfpa.org/~/media/files/research/research%20foundation/research%20foundation%20reports/suppression/extinguishentsculturalresourcecollections.pdf.

Furcare.com. 2015. Fur Storage. Available online at: http://www.furcare.org/fur-storage/.

General Electric (GE). 2010. GE Brings Cleaner Home Refrigeration to the U.S. in 2010. Available online at: http://pressroom.geappliances.com/news/ge-brings-cleaner-home-refrigeration-179750.

General Electric (GE). 2015. GE Refrigerators. Available online at: http://www.geappliances.com/ge/refrigerators.htm.

Global Cold Chain Alliance (GCCA). 2015. Global Cold Chain Alliance Directory. Available online at: https://gcca.connext.io/#/search. Accessed September 25, 2015.

Gottlieb, Mark S. 2006. Refrigerated Warehousing: An Industry Study. Available online at: http://www.msgcpa.com/files/Refrigerated%20Warehousing.pdf.

Hansen Harps, L. 2003. Fast Food: SCM Feeds the Need. Available online at: http://www.inboundlogistics.com/cms/article/fast-food-scm-feeds-the-need/.

Honeywell. 2012. Solstice ™ ze (HFO-1234ze) Refrigerant. Available online at: http://www.honeywell-refrigerants.com/india/?document=solstice-ze-hfo-1234ze-brochure-2012&download=1.

Honeywell. 2015a. Solstice® N13 (R-450). Available online at: http://www.honeywell-refrigerants.com/europe/product/solstice-n13/.

Honeywell. 2015b. Solstice® zd. Available online at: http://www.honeywell-refrigerants.com/americas/product/solstice-zd/.

Honeywell. 2015c. Honeywell Solstice® N40 (R-448A) Refrigerant. Available online at: http://www.honeywell-refrigerants.com/americas/?document=solstice-n40-data-sheet&download=1.

Hughes Associates, Inc. and ICF Consulting. 2004. Review of the Transition Away from Halons in U.S. Civil Aviation Applications. September 2004. Available online at: http://www.epa.gov/ozone/snap/fire/FinalCivilAviationReport_21_Sept04.pdf.

IBIS World. 2014. Fire Extinguisher Manufacturing in the US: Market Research Report. Available online at: http://www.ibisworld.com/industry/fire-extinguisher-manufacturing.html.

ICF International. 1997. Physiological Effects of Alternative Fire Protection Agents - Hypoxic Atmospheres Conference. Stephanie Skaggs prepared the proceedings of the conference held May 22, 1997 in New London, CT.

International Association of Refrigerated Warehouses (IARW). 2014. Low Ammonia Charge Refrigeration Systems for Cold Storage. Available online at: www.danfoss.us/workarea/downloadasset.aspx?id=17179919178.

International Association of Refrigerated Warehouses (IARW). 2015. IARW North American Top 25 List of Refrigerated Warehousing and Logistics Providers. Available online at: www.gcca.org/resources/industry-topics/cold-chain-market-research-trends/iarw-top-25-list-of-largest-refrigerated-warehousing-and-logistics-companies/iarw-north-american-top-25/.

Intergovernmental Panel on Climate Change (IPCC)/ Technical and Economical Assessment Panel (TEAP). 2005. IPCC/TEAP Special Report: Safeguarding the Ozone Layer and the Global Climate System. Chapter 5: Residential and Commercial Air Conditioning and Heating. Aguiar Peixoto, R. Available online at: www.ipcc.ch/publications_and_data/_safeguarding_the_ozone_layer.htm.

Intergovernmental Panel on Climate Change (IPCC). 2007. Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland. 2007. Changes in Atmospheric Constituents and in Radiative Forcing. *In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

JBS USA. 2013. JBS Opens Modern Beef Distribution Center in Grand Island, Nebraska. Available online at: http://jbssa.com/about/news/2013/10-01/#.VeW_0_lViko.

JENSEN HUGHES, Inc. 2015. Personal communication with Dan Verdonik of Jensen Hughes, Inc. August 11, 2015.

Johnson Controls. 2015. York® Water-Cooled Centrifugal Chillers. Available online at: http://www.johnsoncontrols.com/content/us/en/products/building_efficiency/products-and-systems/integrated_hvac_systems/Industrial___Commercial_HVAC_Equipment/chiller_systems/hvac_chillers/water_cooled_centrifugal.html.

Jones Lange LaSalle (JLL). 2014. Perspectives on cold storage investment opportunities. Available online at: http://www.us.jll.com/united-states/en-us/Research/cold-storage-investment-perspectives-jll-nov2014.pdf?9c8bf36c-a6b5-4432-87e5-5149186c1c26.

Kenmore. 2015. Refrigerators & Freezers. Available online at: www.kenmore.com/kitchen-refrigerators-freezers/b-1040176?intcmp=ken_globalnav_refrigerators_freezers_image_081814.

Li, Y. and D.J. Wuebbles. 2006. Potential impacts of CF_3I on ozone as a replacement for CF_3Br in aircraft applications. Atmospheric Chemistry and Physics, 6, 4559–4568.

The Linde Group. 2013. Hydrocarbon refrigerants. Available online at: http://www.linde-gas.com/internet.global.lindegas.global/en/images/Hydrocarbon%20Refrigerants%20Leaflet17_108810.pdf.

The Linde Group. 2015a. Natural Refrigerants. Available online at: http://www.linde-gas.com/en/products_and_supply/refrigerants/natural_refrigerants/index.html.

The Linde Group. 2015b. R600A Refrigerant Grade Isobutane. Available online at: http://www.linde-gas.com/internet.global.lindegas.global/en/images/R600a%20Refrigerant%20Grade%20Isobutane%20Brochure17_110860.pdf.

The Linde Group. 2015c. R449A – Opteon® XP40. Available online at: http://www.linde-gas.com/internet.global.lindegas.global/en/images/BAMPG_Refrigerants_R449A17_140677.pdf.

The Linde Group. 2015d. R290 Refrigerant Grade Propane. Available online at: http://www.linde-gas.com/internet.global.lindegas.global/en/images/R290%20Refrigerants%20Grade%20Propane%20Brochure17_110859.pdf

Maytag. 2015. Refrigerators. Available online at: http://www.maytag.com/kitchen-1/refrigeration-2/side--by--side-3/102120031/.

McQuay International. 2015. Fact Sheet: McQuay's Positive Approach to HFC Refrigerants in Centrifugal Chillers. Available online at: http://www.georgia.daikinmcquay.com/McQuay/DesignSolutions/RefrigerantResourceCenter.

National Fire Protection Association (NFPA). 2013. NFPA 10: Standard for Portable Fire Extinguishers.

Occupational Safety & Health Administration (OHSA). 1974. Standard 1910: Occupational Safety and Health Standards. 39 FR 23502, June 27, 1974. Available online at: https://www.osha.gov/.

Orkin, V. L. 2004. Photochemical Properties of 2-bromo-3,3,3-trfluoropropene and semi-empirical kinetic estimates of its Global Impacts on the Atmosphere. Prepared by the National Institute of Standards and Technology Physical and Chemical Properties Division for American Pacific Corporation. July 2004.

Partridge, A. 2012. An Appetite for Refrigerated Warehousing Improvement. Available online at: http://www.inboundlogistics.com/cms/article/an-appetite-for-refrigerated-warehousing-improvement/.

Patten, K. O., V. G. Khamaganov, V. L. Orkin, S. L. Baughcum, and D. J. Wuebbles. 2012. Correction to "OH reaction rate constant, IR absorption spectrum, ozone depletion potentials and global warming potentials of 2-bromo-3,3,3-trifluoropropene," J. Geophys. Res., 117, D22301.

Pearson, Andy, "Ammonia as a Replacement for Medium Sized Modular R-22 Systems" (2010). International Refrigeration and Air Conditioning Conference. Paper 1112. Available online at: http://docs.lib.purdue.edu/iracc/1112.

Pearson, S.F. 2003. New Natural and Alternative Refrigerants. Available online at: http://www2.epa.gov/sites/production/files/documents/New_Natural_and_Alternative_Refrigerants.pdf.

Reid, M.S. and T.A. Nell. 2004. Three C's of Floral Success – 'Cooling'. Available online at: http://hort.ifas.ufl.edu/flowerpostharvest/pubs/Cooling.pdf.

Robin, L. Mark. 2011. A Short History of Clean Fire Suppression Agents. Fire Detection and Suppression. FS-World.com Fire and Safety Magazine. Spring 2011 Edition. Available online at: https://www.chemours.com/FE/en_US/assets/downloads/pdf/Chemours_Reprint_FSWorld_Spring2011.pdf.

Shafaat, K., A. Hussain, B. Kumar, R. ul Hasan, P. Prabbat, V. K. Yadav. 2013. An Overview: Storage of Pharmaceutical Products. *World Journal of Pharmacy and Pharmaceutical Sciences*. 2(5): 2499-2515.

Shecco. 2013. Examples of NH3/CO_2 secondary systems for cold store operators. Available online at: http://www.shecco.com/files/news/guide_nh3-final.pdf.

Stoelting. 2015. Counter-top Frozen Beverage Dispenser. Available online at: http://stoeltingfoodservice.com/Stoelting-Counter-top-Frozen-Beverage-Dispenser-A118.htm.

Taylor Company. 2015. Model C723 Soft Serve Freezer. Available online at: http://www.taylor-company.com/product-details/soft-serve_landr_frozen-yogurt/multi_flavor/model-c723.

Trane. 2015a. Cold Generator™ Scroll Chillers. Available online at: http://www.trane.com/commercial/north-america/us/en/products-systems/equipment/chillers/water-cooled-chiller/scroll-water.html.

Trane. 2015b. Trane® Sintesis™ Air-cooled Chillers. Available online at: http://www.trane.com/content/dam/Trane/Commercial/global/products-systems/equipment/chillers/air-cooled/TRANE_Sintesis_Brochure.pdf.

TRJ Refrigeration. 2015. Industrial Refrigeration. Accessed September 1, 2015. Available online at: http://www.trj-inc.com/indusrefrig.html.

Underwriters Laboratories (UL). 2004. UL 711: Rating and Fire Testing of Fire Extinguishers.

United Laboratories (UL). 2014. UL 471 Standard for Commercial Refrigerators and Freezers. Available online at: http://ulstandards.ul.com/standard/?id=471_10.

Underwriters Laboratories (UL). 2015. UL 250 Household Refrigerators and Freezers. Available online at: http://ulstandards.ul.com/standard/?id=250.

United Nations Environment Programme (UNEP). 2004. Report of the Technology and Economic Assessment Panel (TEAP) Chiller Task Force. Nairobi, Kenya. Available online at: http://montreal-protocol.org/Assessment_Panels/TEAP/Reports/Other_Task_Force/teap_chiller_report_May2004.pdf.

United Nations Environment Programme (UNEP). 2012. Report of the Technology and Economic Assessment Panel, Additional Information on Alternatives to Ozone Depleting Substances. Available online at: http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports/teap-task-force-XXIII-9-report-may2012.pdf.

United Nations Environment Programme (UNEP). 2014. Report of the Halons Technical Options Committee. December 2014. Fire Protection Alternatives to Halons. Technical Note #1 – Revision 4. Available online at: http://ozone.unep.org/Assessment_Panels/TEAP/Reports/HTOC/Technical%20Note%201-%20Revision%204%20-%20Fire%20Protection%20Alternatives%20To%20Halon%20-%202014.pdf.

United Nations Environment Programme (UNEP). 2015a. 2014 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee. Available online at:

http://conf.montreal-protocol.org/meeting/oewg/oewg-35/presession/Background%20Documents%20are%20available%20in%20English%20only/RTOC-Assessment-Report-2014.pdf.

United Nations Environment Programme (UNEP). 2015b. Fact Sheet 3: Domestic Refrigeration. UNEP Ozone Secretariat Workshop on HFC management: technical issues. Bangkok, 20 and 21 April 2015. Available online at: http://conf.montreal-protocol.org/meeting/workshops/hfc_management-02/presession/English/FS%203%20Domestic%20Refrigeration%20final.pdf.

United Nations Environment Programme (UNEP). 2015c. Fact Sheet 5: Industrial Refrigeration. Available online at: http://conf.montreal-protocol.org/meeting/workshops/hfc_management-02/presession/English/FS%205%20Industrial%20Refrigeration%20final.pdf.

United Nations Environment Programme (UNEP). 2015d. Fact Sheet 10: Water chillers for air-conditioning. Available online at: http://conf.montreal-protocol.org/meeting/workshops/hfc_management-02/presession/English/FS%2010%20Water%20chillers%20for%20air-conditioning%20final.pdf.

United Natural Foods, Inc. (UNFI). 2014a. Distribution Centers. Accessed September 1, 2015. Available online at: https://www.unfi.com/Pages/default.aspx.

United Natural Foods, Inc. (UNFI). 2014b. LEED Certified Projects. Accessed September 1, 2015. Available online at: https://www.unfi.com/Sustainability/Pages/LEEDProjects.aspx.

U.S. Census Bureau. 2007. U.S. International Trade Commission (USITC) Data Web. Available online at: http://dataweb.usitc.gov.

United States Department of Agriculture (USDA). 2014. Capacity of Refrigerated Warehouses 2013 Summary. Available online at: http://usda.mannlib.cornell.edu/usda/current/CapaRefrWa/CapaRefrWa-01-24-2014.pdf.

U.S. Department of Energy (DOE). 2011. Commercial Heating, Air Conditioning, and Water Heating Equipment (i.e., ASHRAE Equipment) Final Rule Rulemaking Technical Support Document. Chapter 2. Available online at: http://www.regulations.gov/#!documentDetail;D=EERE-2011-BT-STD-0029-0039.

U.S. Department of Energy (DOE). 2015. Covered Product Category: Air-Cooled Electric Chillers. Available online at: http://energy.gov/eere/femp/covered-product-category-air-cooled-electric-chillers.

U.S. Energy Information Administration (EIA). 2013. Residential Energy Consumption Survey (RECS). 2009 RECS Survey Data: Housing characteristics tables. Available online at: http://www.eia.gov/consumption/residential/data/2009/.

U.S. Environmental Protection Agency (EPA). 1995. Protection of Stratospheric Ozone; Acceptable Substitutes for the Significant New Alternatives Policy (SNAP) Program. Notice of acceptability. Vol. 60, No. 145. Available online at: http://www.gpo.gov/fdsys/pkg/FR-1995-07-28/pdf/95-18617.pdf.

U.S. Environmental Protection Agency (EPA). 2002. Protection of Stratospheric Ozone: Listing of Substitutes for Ozone-Depleting Substances. 67 FR 77931. December 20, 2002. Available online at: http://www.gpo.gov/fdsys/pkg/FR-2002-12-20/pdf/02-32130.pdf.

U.S. Environmental Protection Agency (EPA). 2003. Protection of Stratospheric Ozone: Listing of Substitutes for Ozone-Depleting Substances. 68 FR 4004. September 27, 2006. Available online at: http://www.gpo.gov/fdsys/pkg/FR-2003-01-27/pdf/03-1623.pdf.

U.S. Environmental Protection Agency (EPA). 2006. Protection of Stratospheric Ozone: Listing of Substitutes for Ozone-Depleting Substances—Fire Suppression and Explosion Protection. 71 FR 56359. January 27, 2003. Available online at: **Error! Hyperlink reference not valid.**.

U.S. Environmental Protection Agency (EPA). 2009a. Vintaging Model. Version 4.3, dated 02-26-09.

U.S. Environmental Protection Agency (EPA). 2009b. Protection of Stratospheric Ozone: Notice 24 for Significant New Alternatives Policy Program. 74 FR No. 188. September 30, 2009. Available online at: http://www.gpo.gov/fdsys/pkg/FR-2012-09-19/pdf/2012-23138.pdf.

U.S. Environmental Protection Agency (EPA). 2010. Transitioning to Low-GWP Alternatives in Domestic Refrigeration. Available online at: http://www.epa.gov/ozone/downloads/EPA_HFC_DomRef.pdf.

U.S. Environmental Protection Agency (EPA). 2011. Protection of Stratospheric Ozone: Listing of Substitutes for Ozone-Depleting Substances—Hydrocarbon Refrigerants. Final Rule. Vol. 76, No. 244. Available online at: **Error! Hyperlink reference not valid.**http://www.gpo.gov/fdsys/pkg/FR-2011-12-20/pdf/2011-32175.pdf.

U.S. Environmental Protection Agency (EPA). 2012a. Protection of Stratospheric Ozone: Determination 27 for Significant New Alternatives Policy Program. 77 FR 47768. August 10, 2012. Available online at: http://www.gpo.gov/fdsys/pkg/FR-2012-08-10/pdf/2012-19688.pdf.

U.S. Environmental Protection Agency (EPA). 2012b. Protection of Stratospheric Ozone: Listing of Substitutes for Ozone Depleting Substances—Fire Suppression and Explosion Protection. 77 FR 58035. September 19, 2012. Available online at: http://www.gpo.gov/fdsys/pkg/FR-2012-09-19/pdf/2012-23138.pdf.

U.S. Environmental Protection Agency (EPA). 2014a. EPA Vintaging Model. VM IO file_V4.4_10.13.14.xlsx.

U.S. Environmental Protection Agency (EPA). 2014b. Global Warming Potentials and Ozone Depletion Potentials of Some Ozone-Depleting Substances and Alternatives Listed by the SNAP Program. Available online at: http://www.epa.gov/ozone/snap/subsgwps.html.

U.S. Environmental Protection Agency (EPA). 2014c. Protection of Stratospheric Ozone: Determination 29 for Significant New Alternatives Policy Program. Vol. 79, No. 203. Available online at: http://www.gpo.gov/fdsys/pkg/FR-2014-10-21/pdf/2014-24989.pdf.

U.S. Environmental Protection Agency (EPA). 2015a. Acceptable Substitutes for Centrifugal Chillers. Available online at: http://www.epa.gov/snap/acceptable-substitutes-centrifugal-chillers.

U.S. Environmental Protection Agency (EPA). 2015b. Acceptable Substitutes in Stand-Alone Units. Available online at: http://www2.epa.gov/snap/acceptable-substitutes-stand-alone-units.

U.S. Environmental Protection Agency (EPA). 2015c. Acceptable Substitutes in Household Refrigerators and Freezers. Available online at: http://www.epa.gov/ozone/snap/refrigerants/lists/fridge.html.

U.S. Environmental Protection Agency (EPA). 2015d. Protection of Stratospheric Ozone: Determination 30 for Significant New Alternatives Policy Program. Vol. 80, No. 136. Available online at: http://www.gpo.gov/fdsys/pkg/FR-2015-07-16/pdf/2015-17469.pdf.

U.S. Environmental Protection Agency (EPA). 2015e. Protection of Stratospheric Ozone: Listing of Substitutes for Refrigeration and Air Conditioning and Revision of the Venting Prohibition for Certain Refrigerant Substitutes. Vol. 80; No. 69. Available online at: http://www.gpo.gov/fdsys/pkg/FR-2015-04-10/pdf/2015-07895.pdf.

U.S. Securities and Exchange Commission. 2010. Amendment No. 8 to Form S-11 for Registration under the Securities Act of 1933 of Securities of Certain Real Estate Companies. Americold Realty Trust. Registration No. 333-163703. Available online at: www.sec.gov/Archives/edgar/data/1455863/000104746910004799/a2198481zs-11a.htm.

Watson, M., Cacioppi, P., Jayaraman, J., and Lewis, S. 2012. The Value of Supply Chain Network Design. Available online at: http://www.ftpress.com/articles/article.aspx?p=1941208&seqNum=3.

Whirlpool. 2015. Refrigerators. Available online at: http://www.whirlpool.com/kitchen-1/refrigeration-2/refrigerators-3/102110023/.

Wickham, Robert T. 2002. Status of Industry Efforts to Replace Halon Fire Extinguishing Agents. March 16, 2002. Available online at: http://www.epa.gov/ozone/snap/fire/status.pdf.

Wickham, Robert T. 2003. Review of the Use of Carbon Dioxide Total Flooding Fire Extinguishing Systems. Available online at: http://www.epa.gov/ozone/snap/fire/co2/co2report2.pdf.

WMO (World Meteorological Organization). 2011. Scientific Assessment of Ozone Depletion: 2010, Global Ozone Research and Monitoring Project-Report No. 52, 516 pp., Geneva, Switzerland.