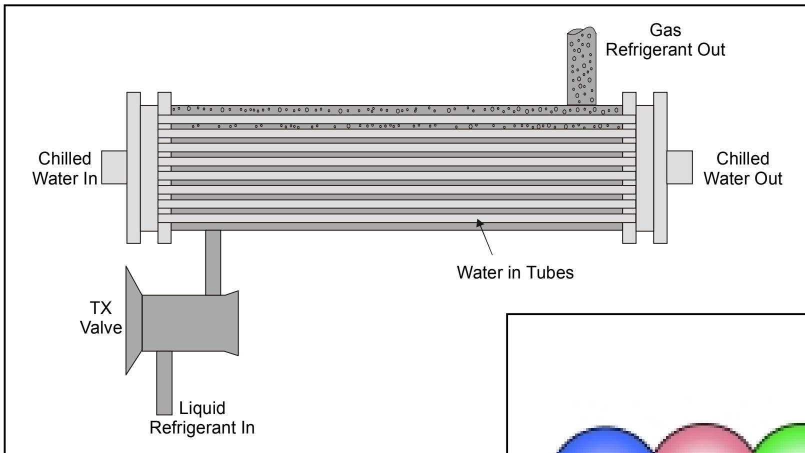
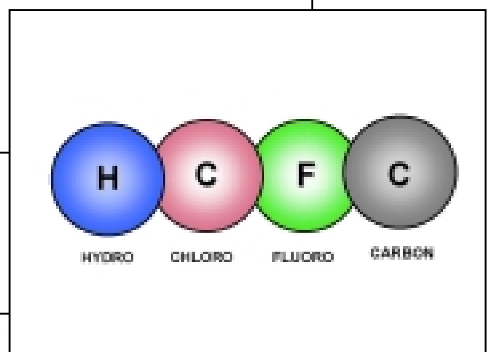
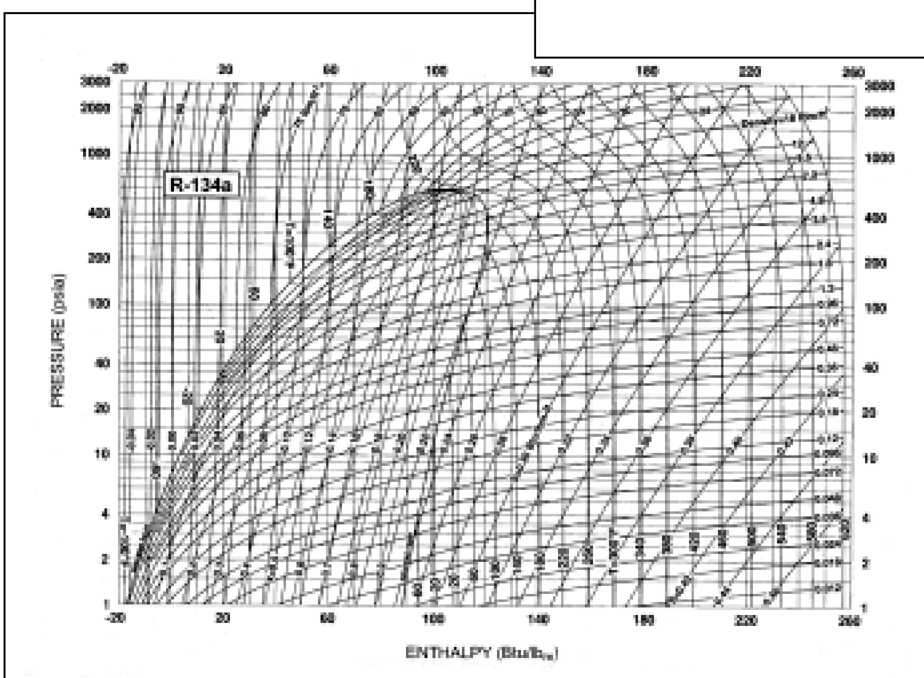
Refrigerants







	Lower Toxicity	Higher Toxicity
Higher Flammability	A3	B3
Lower Flammability	A2	B2
No Flame Propagation	A1	B1

Contents

Introduction

In the mid nineteen-eighties the world recognized that CFC refrigerants, once considered safe for people as well as the planet, were in fact severely damaging the Earth's ecology. Refrigerants suddenly went from being rarely discussed during the design of a building to becoming a major consideration for the consulting engineer.

There was much confusion and speculation at that time, as refrigerants became a strong marketing point for HVAC equipment manufacturers. It was often difficult for decision-makers to get clear answers to their questions.

Although the CFC issue is, for most part, behind us, significant issues concerning persist. The purpose of this guide is to provide detailed refrigerant background information to increase understanding of how refrigerants can affect our business and personal lives.

While this guide was prepared by McQuay International, which clearly has a stake in refrigerant applications, there are many footnotes and an extensive bibliography drawing from many renowned, non-partisan sources.

What Is A Refrigerant?

At the end of the last millennium, there were many “Top Ten” lists made, including one listing the greatest invention of the twentieth century. Along with space flight and computers, refrigeration made the top ten because without refrigeration, food preservation would not be possible. In addition, there could not be high rise office buildings or modern health care facilities.

Webster’s dictionary defines refrigerants as “a substance used in a refrigerating cycle or directly such as ice for cooling”. A person from outside the HVAC industry might describe a refrigerant as some kind of fluid used in an air conditioner. Many within the HVAC industry would immediately think of CFCs (Chlorofluorocarbons).

All these definitions are accurate, but refrigerants are much more than that. Water is the refrigerant used in absorption chillers. Carbon Dioxide (CO_2) and Ammonia (NH_3) are known as “natural” refrigerants. Flammable substances such as propane and isobutane are also used as refrigerants. To this group, CFCs, HCFCs and HFCs can be added. ASHRAE Standard 34, Designation and Safety Classification of Refrigerants, lists over 100 refrigerants, although many of these are not used on a regular commercial HVAC basis.

Refrigerants are chemical substances. Some substances known as refrigerants (e.g. R-141b) are used in diverse applications such as a foam blowing agent, which has little to do with “cooling spaces”.

Refrigerant History

Mechanical refrigeration has been around since the mid-nineteenth century. The first practical machine was built by Jacob Perkins in 1834[1]. It was based on using ether as a refrigerant in a vapor compression circuit. Carbon Dioxide (CO_2) was first used as a refrigerant in 1866 and Ammonia (NH_3) in 1873. Other chemicals used as vapor compression refrigerants included chymgene (petrol ether and naphtha), sulfur dioxide (R-764) and methyl ether. Their applications were limited to industrial processes. Most food preservation was accomplished by using blocks of ice collected during the winter and stored or manufactured through an industrial process.

By the beginning of the twentieth century, refrigeration systems were being used to provide air conditioning in major building projects. The Milam Building in San Antonio, Texas was the first high-rise office building to be completely air conditioned[2].

In 1926, Thomas Midgely developed the first CFC (Chlorofluorocarbons), R-12. CFCs were non-flammable, non-toxic (when compared to Sulfur Dioxide) and efficient. Commercial production began in 1931 and quickly found a home in refrigeration. Willis Carrier developed the first centrifugal chiller for commercial use and the era of refrigeration and air conditioning began.

For technical reasons that will be discussed later, several refrigerants became very popular in air conditioning including CFC-11, CFC-12, CFC-113, CFC-114 and HCFC-22. While the fledgling air conditioning industry grew into a multi billion dollar industry, very little changed on the refrigerant front. By 1963, these refrigerants represented 98% of the organic fluorine industry.

By the mid 1970s, concerns began to surface about the thinning of the ozone layer and whether CFCs may be in part responsible. This led to the ratification of the Montreal Protocol in 1987 that required the phase out of CFCs and HCFCs. New solutions were developed with HFCs taking on a major role as refrigerants. HCFCs continued to be used as interim solutions and at the time of writing this document were beginning to be phased out.

In the 1990s global warming arose as the new threat to the well being of the planet. While there are many contributors to global warming, refrigerants were again included in the discussion because air conditioning and refrigeration are significant energy users (about 1/3 of the energy in the USA is consumed in the operation of buildings) and many refrigerants are themselves greenhouse gases.

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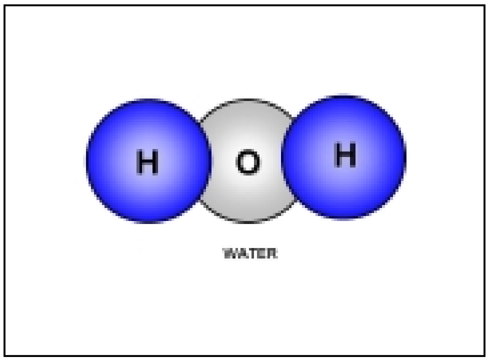
[1] Thevenot, R. 1979. *A History of Refrigeration Throughout the World.* International Institute of Refrigeration (IIR)

[2] Pauken, M. May 1999. *Sleeping Soundly on Summer Nights.* ASHRAE Journal

Common Refrigerants

Although there are many substances classified as refrigerants by ASHRAE Standard 34, only a handful are used for commercial air conditioning. Following is quick a rundown of the common refrigerant groups that are either in use or have been used in the past. Table 1 provides technical data on common refrigerants.

Water, R-718

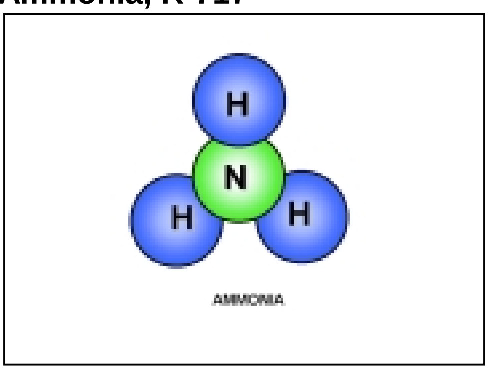


Most refrigeration processes use either an absorption cycle or a vapor compression cycle. Commercial absorption cycles typically use water as the refrigerant with a salt solution such as Lithium Bromide as the absorbent.

Water is non toxic, non-flammable, abundant etc. It is a natural refrigerant. The challenge for absorption chillers is that even a double-effect absorption cycle only has a COP (Coefficient Of Performance) slightly greater than 1 (Centrifugal chillers have COPs greater than 5). From a life cycle analysis point of view, absorption chillers require a thorough investigation to determine whether they offer a financially viable solution. Software programs such as McQuay's Energy Analyzer™ can be used for this analysis.

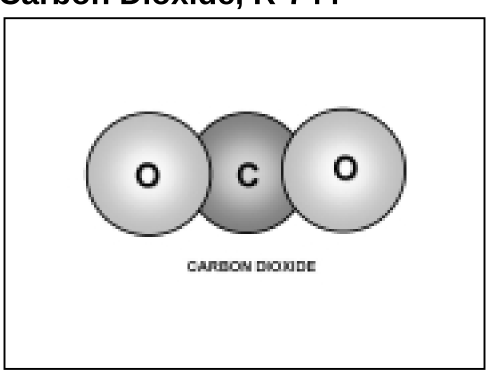
From an environmental point of view, the use of water as a refrigerant generally, is very good. The low COP might indicate that larger amount of fossil fuels will be required to operate an absorption chiller over a centrifugal chiller. This is not guaranteed however, since absorption chillers use fossil fuels directly, while electric chillers operate on electricity, a secondary energy source. The choice of which to use will be affected by how the electricity is actually generated.

Ammonia, R-717



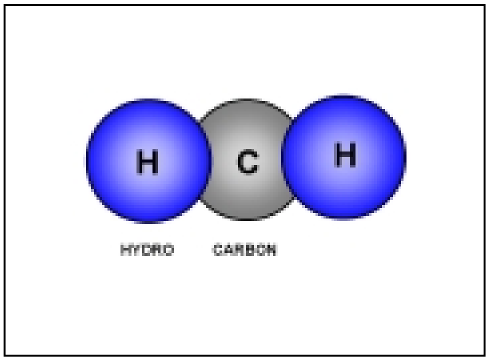
Ammonia (NH_3) is a natural refrigerant and considered to be one of the most efficient. It is one of the only "original" refrigerants still in use today. It is used in vapor compression processes, typically with positive displacement compressors. ASHRAE Standard 34 classifies it as a B2 refrigerant (higher toxicity – lower flammability). ASHRAE Standard 15 requires special safety considerations for Ammonia refrigeration plants. Ammonia is mostly used in industrial applications, although there are many large commercial air conditioning installations that utilize it as well.

Carbon Dioxide, R-744



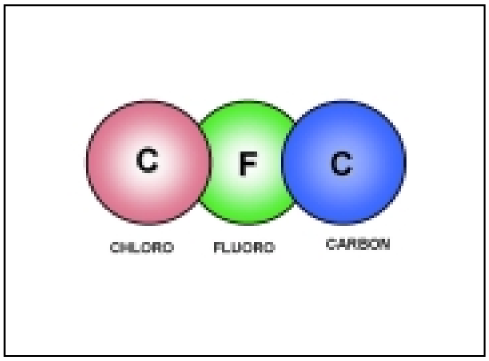
Carbon dioxide (CO_2) is a natural refrigerant. Its use was phased out at the turn of the century, but new research aimed at using it again is currently under way. It is used in vapor compression processes with positive displacement compressors. The required condensing pressure is over 900 psig at 90°F, which is a challenge. Also, the critical point is very low and efficiency is poor. Still, there may be applications, such as cascade refrigeration, where CO_2 will be useful.

Hydrocarbons



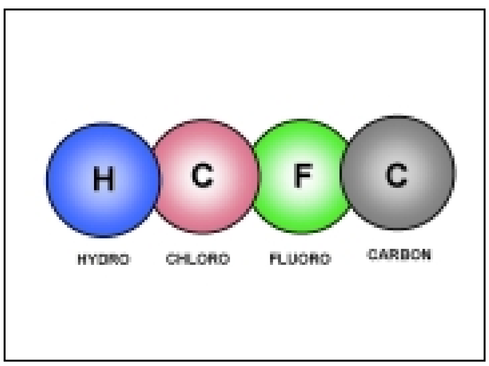
Propane (R-290) and isobutane (R-600a), among other hydrocarbons, can be used as refrigerants in the vapor compression process. In Northern Europe, about 35% of refrigerators are based on hydrocarbons. They can have low toxicity and good efficiency but they are highly flammable. The latter issue has severely limited their use in North America where current safety codes restrict their use.

Chlorofluorocarbons (CFCs)



There are many Chlorofluorocarbons (CFCs) but the most common ones for air conditioning are R-11, R-12, R-113 and R-114. CFCs were in popular use up to the mid-eighties. Production of CFCs was phased out by the Montreal Protocol in developed countries in 1995. They're still being manufactured and used in developing countries (but are scheduled for phase out soon). They are used in vapor compression processes with all types of compressors. The common CFCs are stable, safe (by refrigerant standards), non-flammable and efficient. Unfortunately, they also have damaged the ozone layer.

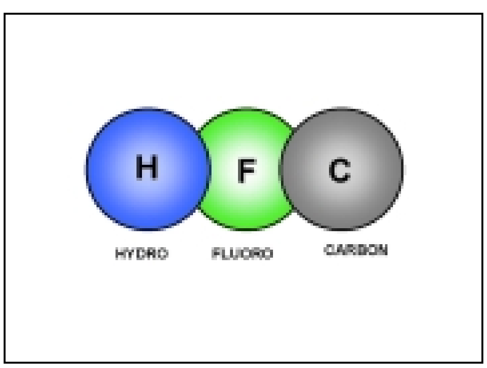
Hydrochlorofluorocarbons (HCFCs)



Hydrochlorofluorocarbons (HCFCs) have been around almost as long as CFCs. HCFC-22 is the most widely used refrigerant in the world. HCFC-123 is the interim replacement for CFC-11. They are used in vapor compression processes will all types of compressors. HCFC-22 is efficient and classified as A1 (lower toxicity – no flame propagation). HCFC-123 is efficient and classified as B1 (higher toxicity – no flame propagation).

Like CFCs, these refrigerants are being phased out as required by the Montreal Protocol. Production has been capped and soon will be ratcheted down in developed countries. Developing countries also have a phase-out schedule but on an extended timeline.

Hydrofluorocarbons (HFCs)



Hydrofluorocarbons (HFCs) are relatively new refrigerants whose prominence arose with the phase out of CFCs. HFCs have no ozone depletion potential (ODP=0). HFC-134a is the replacement for CFC-12 and R-500. They are used in vapor compression processes with all types of compressors. The common HFCs are efficient and classified as A1 (lower toxicity – no flame propagation).

Table 1 - Refrigerant Properties

General Information

Refrigerant Number[a]	Chemical Name[a]	Chemical Formula[a]	Molecular Mass[a]	Safety Group[a]	Atmospheric Lifetime[b] (Yrs)	ODP[c]	GWP
11	trichlorofluoromethane	CCl_3F	137.4	A1	50	1	3800
12	dichlorodifluoromethane	CCl_2F_2	120.9	A1	102	1	8100
22	chlorodifuoromethane	$CHClF_2$	86.5	A1	12.1	.055	1500
32	difluoromethane	CH_2F_2	52	A2	5.6	0	650
123	2,2-dichloro-1,1,1-trifluoroethane	$CHCl_2CF_3$	153	B1	1.4	.02	90
125	Pentafluoroethane	CHF_2CF_3	120	A1	32.6	0	2800
134a	1,1,1,2-tetrafluoroethane	CF_3CH_2F	102	A1	14.6	0	1300
245fa	1,1,2,2,3-Pentafluoropropane	$CHF_2\ CH_2\ CF_3$	134.05	B1	8.8	0	820
290	Propane	$CH_3CH_2CH_3$	44	A3	<1[h]	0	~0
404a	R-125/143a/134a (44/52/4)			A1			3260[h]
407C	R-32/125/134a (23/25/52)			A1		0	1530
410A	R-32/125 (50/50)			A1		0	1730
500	R-12/152a (73.8/26.2)			A1		.74	6010
507a	R-125/143a (50/50)			A1			
600	Butane	$CH_3CH_2CH_2CH_3$	58.1	A3	<1[h]	0	~0
717	Ammonia	NH_3	17	B2	N/A	0	0
718	Water	H_2O	18	A1	N/A	0	<1
744	Carbon dioxide	CO_2	44	A1	N/A	0	1

Operational Information

Refrigerant Number[a]	Normal Boiling Point (°F)[a]	Velocity of [e]Sound (ft/s) @ 40 °F	Critical Point[g]		Bubble[g] (°F) @ psi	Dew[g] (°F) @ psi	Glide (°F)	Viscosity Lb_m/ft*h[g] @ 40 °F Liq.	Specific Heat at Btu/ib•°R @ 40°F Liq.	Thermal Cond.[g] Btu/h*ft*°F @ 40°F Liq.
			Temp (°F)	Press. (psi)						
11	74.67	443	388.33	639.27				1.304	.2059	.0548
12	-21.55	448	233.55	599.89				.574	.2253	.0429
22	-41.46	535	205.06	723.74				.503	.2825	.0537
32	-60.97	688	172.59	838.61				.361	.3106	.0872
123	82.08	414	362.63	531.1				1.292	.2379	.0476
125	-54.64	409	150.83	526.34				.457	.3044	.0397
134a	-14.93	482	213.91	588.75				.620	.2194	.0521
245fa	58.82	436.2	309.2	527.1				1.296	.3121	.0506
290	-43.75	723	206.06	616.07				.291	.6077	.0600
404a	-51.66b	473	162.5	548.18	38.8 @ 100	39.8 @ 100	1.0	.405	.3349	.0438
407C	-46.82b	519	186.9	672.2	37.0 @ 90	47.8 @ 90	10.8	.479	.3403	.0582
410A	-60.83b	553	158.4	694.87	42.9 @ 140	43.2 @ 140	0.3	.380	.3652	.0652
500	-28.31	490	222.0	641.9				.557	.2579	.0480
507a	-52.79	457	159.34	538.79				.401	.3331	.0432
600	31.04	659	305.62	550.56				.469	.5588	.0665
717	-27.99	1319	270.05	1643.71				.392	1.1094	.3155
718	211.95	1352	705.1	3200.1				3.738	1.0555	.3293
744	-109[f]	687	87.76	1069.99				.222	.6460	.0607

[a] ASHRAE, 1997. *ANSI/ASHRAE Standard 34-1997,Designation and Safety Classification of Refrigerants.* Atlanta, Ga.: ASHRAE

[b] 1995 IPCC Report: HFCs Table 2.9;CFCs and HCFCs Table 2.2(Houghton et al. 1996).

[c] Ozone Secretariat UNEP (1996).

[h] ARTI Refrigerant Database, based on WMO and IPCC assessments, August 1998. GWP shown are for 100 year integrated time horizon.

[e] NIST *Standard Reference Database* 23, Version 6.01 (NIST 1996).

[g] 2001 ASHRAE Fundamentals Handbook chapter 20.

[f] Sublimes.

What Makes A Good Refrigerant?

General

At first glance properties such as lower toxicity, no flame propagation, efficiency, and cost effectiveness come to mind. Certainly these are important characteristics and ones that are well advertised. But selecting a refrigerant for use in a refrigeration or air conditioning process goes far beyond just these properties. For example, "efficiency" can mean many different things and can therefore cause misunderstanding and confusion.

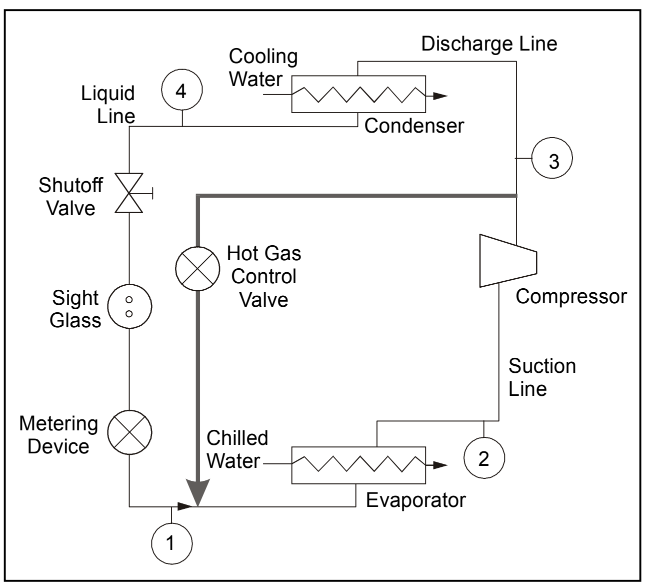
This section will delve into many aspects of what makes a good refrigerant. Most refrigerants are used in a vapor compression cycle. A basic understanding of that cycle will help one to better appreciate the complex issue of refrigerants.

The Vapor Compression Refrigeration Cycle

With the exception of absorption chillers, most commercial air conditioning systems are based on the vapor compression cycle. The process can be used to collect heat from air (an air conditioner) or from water (a chiller). It can reject the heat into air (air-cooled) or water (water-cooled). The process can even be applied as a heater by moving heat from cold fluid (outdoor air) to a warm fluid (indoor air). This is referred to as a heat pump.

A water-cooled chiller will be used as an example. The chiller utilizes the vapor compression cycle to chill water and reject the heat collected from the chilled water plus the heat from the compressor to a second water loop cooled by a cooling tower. Figure 1 shows the basic refrigeration circuit. It consists of the following four main components:

Figure 1-Basic Refrigeration Circuit



Evaporator

The evaporator is a heat exchanger that removes the building heat from the chilled water, lowering the water temperature in the process. The heat is used to boil the refrigerant, changing it from a liquid to a gas.

Compressor

The compressor assembly is made up of a prime mover (typically an electric motor) and a compressor. The compressor raises the pressure and temperature of the refrigerant gas.

Condenser

Like the evaporator, the condenser is a heat exchanger. In this case, it removes heat from the refrigerant causing it to condense from a gas to a liquid. The heat raises the water temperature. The condenser water then carries the heat to the cooling tower where the heat is rejected to the atmosphere.

Expansion Device

After the refrigerant condenses to a liquid, it passes through a pressure-reducing device. This can be as simple as an orifice plate or as complicated as an electronic modulating thermal expansion valve.

Pressure-Enthalpy Diagram

The Pressure-Enthalpy (P-H) diagram is another way of looking at the refrigeration cycle. It has the advantage of graphically showing the process, the cooling effect and the work required to make it happen.

Figure 2-Refrigeration Circuit, P-H Diagram

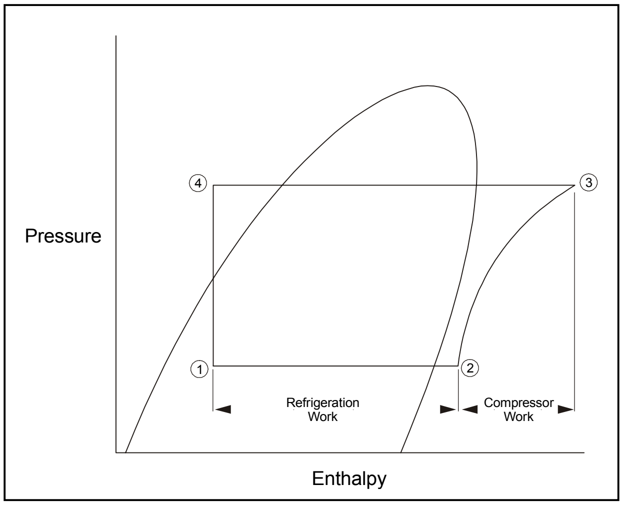


Figure 2 shows the Pressure-Enthalpy (P-H) diagram for the same refrigeration circuit shown in Figure 1. The process for each of the components is indicated. The evaporator process is from point 1 to point 2. As the refrigerant changes from a liquid to gas, the pressure (and temperature) stays constant. The heat is being absorbed as a phase change (latent energy). The refrigeration effect is the change in enthalpy from 1 to 2, simply expressed as Btu/lb. of refrigerant circulated.

The line from 2 to 3 represents the compression process. The work is the change in enthalpy from point 2 to point 3 times the flow of refrigerant. Simply, Btu/lb. times the lb./min equals compressor power. Compressors end up with the work of compression as heat in the refrigerant. The vertical aspect of the curve shows the rise in refrigerant pressure (and temperature) from 2 to 3.

The next process takes place in the condenser. The first section (outside the refrigerant dome) is the desuperheating process. Once the refrigerant is saturated, condensation occurs and the refrigerant changes from a gas to a liquid. Like the evaporator, the line is horizontal indicating constant pressure (or temperature).

The final process is the expansion device. This appears as a vertical line from point 4 to point 1, indicating the pressure (and temperature) drop that occurs as the refrigerant passes through the Thermal Expansion (TX) valve.

Figure 3-Heat Exchanger Performance

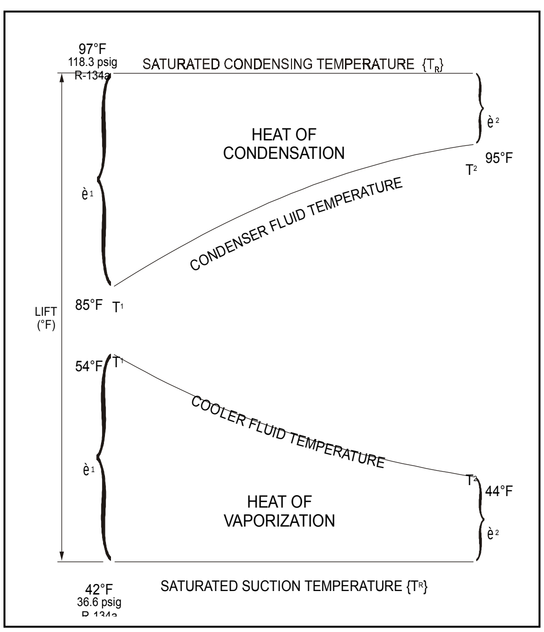


Figure 3 shows the heat transfer process for both the condenser and the evaporator. Using the ARI design conditions, typical temperatures are shown. Looking at the condenser, the refrigerant temperature remains constant at 97°F. The refrigerant is changing from a gas to a liquid and is releasing its latent heat of condensation. At the same time the tower water enters the condenser at 85°F and is gaining sensible heat as its temperature rises to approximately 95°F.

The evaporator behaves similarly. In this case, the evaporator refrigerant temperature remains constant at 42°F. The refrigerant is changing from a liquid to a gas while absorbing its *latent heat of vaporization.* The chilled water entering the evaporator at 54°F is releasing sensible heat and its temperature is dropping to 44°F.

The pressure in either the evaporator or condenser will be the saturation pressure for the given temperature. These can be found on temperature-pressure charts. For HFC-134a, the condenser pressure at 97°F is 118.3 psig. The evaporator pressure at 42°F is 36.6 psig.

Refrigerant Properties

Following is a list of key properties of refrigerants that are considered in the design of a refrigeration system. The positive and negative nature of these properties is shown with examples.

Toxicity

Toxicity and flammability are the two key parameters used by ASHRAE to indicate the safety level of a refrigerant. ASHRAE Standard 34 has adopted a matrix as shown in Figure 4 that indicates the relative levels of these two parameters.

Figure 4-STD 34 Refrigerant Safety Classification

	Lower Toxicity	Higher Toxicity
Higher Flammability	A3	B3
Lower Flammability	A2	B2
No Flame Propagation	A1	B1

Class A signifies refrigerants for which toxicity has not been identified at concentrations less than or equal to 400 ppm by volume, based on date used to determine Threshold Limit Value – Time Weighted Average (TLV-TWA) or consistent indices.
Class B signifies refrigerants for which there is evidence of toxicity at concentrations below 400 ppm by volume, based on date used to determine Threshold Limit Value – Time Weighted Average (TLV-TWA) or consistent indices.
Class 1 indicates refrigerants that do not show flame propagation when tested in air at 14.7 psia and 70°F.

Class 2 signifies refrigerants having a lower flammability limit (LFL) of more than 0.00625 lb/ft³ at 14.7 psia and 70°F and the heat of combustion (HOC) less than 8174 Btu/Lb.

Class 3 refrigerants are highly flammable. They have a lower flammability limit (LFL) of less than 0.00625 lb/ft³ at 14.7 psia or 70°F or the heat of combustion greater than or equal to 8174 Btu/Lb.

Toxicity of a substance is a relative matter. Almost anything can be toxic in some dosage. It not so much an issue of whether something is bad for you, as at what concentration it will do bodily harm.

Reactivity (the opposite of stability) will be discussed in a moment as it pertains to atmospheric concerns. In terms of toxicity, often more reactive substances have increased toxicity. The undesirable balance is to have a substance that is stable enough to enter the body but then reactive enough to cause harm. Atmospheric stability (an issue for the environment) is not necessarily tied to this process.

ASHRAE Standard 34 classifies refrigerants into either class A or class B. Figure 4 includes the definitions for Class A and B.

Acute Toxicity

Acute toxicity refers to short term, often high concentration level exposure to a substance. For instance, being in a mechanical room when a refrigeration circuit breaks and releases large amounts of refrigerant into the space.

Chronic Toxicity

Chronic toxicity refers to long-term repeated exposure to a substance. For instance, the kind of exposure a service technician might experience over a lifetime of working on refrigeration equipment. These values tend to be time weighted since a technician is not likely to spend repeated full days exposed to refrigerants. Acute toxicity levels are always higher than the chronic toxicity levels for a given substance. For this reason, most safety levels are based on chronic (conservative) toxicity levels, although the overall goal is to reduce both acute and chronic exposure risks.

Threshold Limit Value (TLV)

The TLV is the airborne concentration of a substance and represents conditions under which it is believed that nearly all workers may be repeatedly exposed day after day without adverse health effects. In simple terms it is the maximum allowable concentration that will avoid chronic toxicity problems. The values are based on the best available information from industrial experience and experimental testing.

There is a wide variation in individual susceptibility to substances so some people may experience discomfort at levels below the TLV. A pre-existing condition in an individual may cause a more aggravated response to exposure. Smoking may also aggravate an individual's response.

Individuals may also be hyper-susceptible to some substances due to genetic factors, age, personal habit (smoking, alcohol or other drugs) medication or previous exposure. In these cases, the TLV may not provide an adequate indicator and an occupational physician should be consulted to determine whether any additional protection may be desireable.[3]

PAFT

PAFT is the Program for Alternative Fluorocarbon Toxicity Testing. It is a co-operative effort sponsored by refrigerant manufacturers to accelerate the testing of fluorocarbon based (HFC) substances. These tests involve more than 100 tests, which can take up to six years and cost in excess of $5 million.

PAFT tests cover acute toxicity, chronic toxicity, carcinogicity (cancer causing), genotoxicity (effects on genetic material), teratology (effects on the reproductive system and birth defects), ecotoxicity (effects on living organisms in the environment) among others[4].

Research from PAFT is used to help set the safety classifications and toxicity levels for many refrigerants recently introduced to the market place including R-123, R-134a, R-141b, R-124, R-125 and R-32. R-32, R-125 and R-134a are used to produce R-410A and R-407C.

> **Safety Consideration**
>
> *Consider two refrigerants in common use today, Ammonia (R-717) and R-22. Standard 34 lists Ammonia as a B2 refrigerant and R-22 as an A1 refrigerant..*
>
> *A quick review would indicate that Ammonia has higher toxicity than R-22, which is certainly true. However, R-22 is both a gas and heavier than air at atmospheric conditions. It is also odorless. It has killed because an unsuspecting occupant entered an enclosed low-lying space where the air had been displaced by R-22 leaked from a refrigeration system. Ammonia on the other hand has a strong odor, which can provide early warning to occupants.*
> *Any refrigerant can be used safely with proper procedures and any refrigerant can do harm if used improperly.*

Other Safety Considerations

Many refrigerants are used under considerable pressure (the average home air conditioner is operating at over 250 psig) which, if released in an uncontrolled manner, can be a threat. Possible splashing of liquid refrigerant, particularly into the eyes, is another concern. The low temperatures can cause frostbite if exposed to a leak. The flammability of a refrigerant also poses a potential threat.

What is Safe?

There is no clear-cut winner. Refrigerants have proven to be lethal in ways other than poisoning occupants. Many refrigerants are gaseous at atmospheric pressure and heavier than air. This means that the refrigerant will displace air in low-lying areas such as a basement mechanical room. An unsuspecting person entering such a space will suffocate rather than be poisoned. MSDS (Material Safety Data Sheets) offer an excellent source of information on the properties of a refrigerant. Appendix 1 R-134a MSDS Sheet shows a typical MSDS document.

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[3] *1990-91 Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices*. American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio, 1990

[4] PAFT 1993.*PAFT Toxicology Summaries.* Bristol, United Kingdom: Program For Alternative Fluorocarbon Toxicity Testing.

Flammability

Flammability is another key parameter in evaluating the safety level of a refrigerant. It is the second parameter that ASHRAE uses in Standard 34 when classifying refrigerant safety. Like toxicity, flammability is not as simple to evaluate as it may first appear. Most would consider water (R-718) to be non-flammable while Propane (R-290) is flammable. However, there are many substances that will burn given the right circumstances. What is required to make a substance combust also varies. Paper can be made to burn at room temperature by exposing it to open flame in standard air. Paper will also spontaneously combust at 451°F without the presence of open flame.

Standard 34 classifies refrigerants into three flammability classes.

- Class 1 indicates refrigerants that do not show flame propagation when tested in air at 14.7 psia and 70°F.
- Class 2 signifies refrigerants having a lower flammability limit (LFL) of more than 0.00625 lb/ft³ at 14.7 psia and 70°F and the heat of combustion (HOC) less than 8174 Btu/Lb.
- Class 3 refrigerants are highly flammable. They have a lower flammability limit (LFL) of less than 0.00625 lb/ft³ at 14.7 psia or 70°F and the heat of combustion greater than or equal to 8174 Btu/Lb.[5]

Lower Flammability Limit (LFL)

The LFL of a refrigerant is the minimum homogeneous concentration in air that will propagate a flame. It is typically given as a percentage by volume. The test is based at 77°F and 14.7 psia. To convert from a volume percentage to a density multiply the percentage by 0.0000257*(molecular mass) to obtain lb/ft³. The actual test method is described *in Concentration Limits of Flammability of Chemicals*, ANSI/ASTM Standard E681-85, American Society of Testing and Materials, Philadelphia, Pa., 1984.

Heat Of Combustion (HOC)

The HOC is the heat released when a refrigerant is combusted in air and is expressed in Btu/lb. The number is positive when heat is released (exothermic) and negative when heat is required (endothermic).

Flammability and Blends

Blends create some interesting situations with regards to flammability. First, ASHRAE Standard 34 requires that each component of a blend already be a classified refrigerant. It is possible to have a Class 1 refrigerant blend, which has a class 2 substance as one of its constituents. For example, R-32 is classified as an A2 refrigerant and is used in both R-407C and R-410A, both of which are classified as A1 refrigerants.

> **Flammability Consideration**
>
> *Consider a refrigerator using propane (R-290) as a refrigerant. The refrigerator has a charge of approximately 0.5 lb in a kitchen that is 8 ft x 8 ft x 8 ft high. Propane is a gas at atmospheric pressure but is heavier than air. If a leak forms, the propane will diffuse throughout the space as a gas but will have heavier concentrations near the floor. The LFL for propane is 2.1%. To reach a flammable concentration in this example, 1.2 lb of propane would have to be released, which is more than twice what is in the refrigerator. However, the concentration will be higher near the floor, quite possibly high enough to cause an explosion if ignited.*
>
> *The point here is that flammability is not clear cut. Even with a flammable refrigerant such as propane, a hazardous situation is not certain.*

Refrigerant developers will test for the *critical flammability ratio,* which is the maximum amount of flammable component that a mixture can contain and still be non-flammable regardless of the amount of air. As long as the refrigerant has a low enough critical flammability ratio, it will be class 1 refrigerant.

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[5] ASHRAE, 1997. *ANSI/ASHRAE Standard 34-1997,Designation and Safety Classification of Refrigerants.* Atlanta, Ga.: ASHRAE

Humidity, pressure and temperature will affect the flammability of a refrigerant. The flammability testing carried out for Standard 34 is based at 14.7 psia and 70°F. It is possible to have refrigerants become flammable at higher temperatures and pressures.

Efficiency

Of all the properties of refrigerants, efficiency is the most misunderstood and most abused. To most people efficiency means "how much energy do I have to provide to get a fixed amount of cooling"?

$$COP = \frac{\text{Useful refrigerating effect}}{\text{Net energy supplied from external sources}}$$

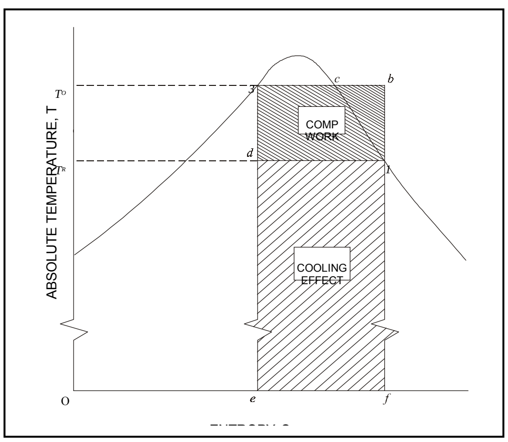
The more efficient the system, the less energy required to do the same amount of cooling. The issue is that ***efficiency is a system property not a refrigerant property!*** Many parameters control how efficient a refrigeration system is, many of which have little to do with refrigerants. The list includes motor efficiency, compressor efficiency (both at full and part load), heat exchanger design and materials, operating conditions etc. The refrigerant can affect the system efficiency in many ways including transfer properties (how easy is it to pump), heat transfer properties, acoustic velocity and so on.

Efficiency Consideration

Efficiency is a difficult parameter to comprehend. Carnot efficiency is the ultimate, but doesn't even take into account the refrigerant. Ideal cycles allow comparisons but again, these cycles cannot be obtained in the real world. Modeling real world efficiencies means taking into account heat transfer and transport properties and refrigeration system design. Refer to *System Example page 29* *for an in-depth discussion on system efficiency.*

Carnot Cycle

Figure 5 - Carnot Cycle



The Carnot cycle is a theoretical cycle that is completely reversible. Figure 5 shows the Carnot cycle. The efficiency based on the Carnot cycle is;

$$COP = T_R / (T_O - T_R)$$

Notice refrigerant is not part of the equation. It is possible to build refrigerant models and calculate the theoretical performance, but that requires making engineering decisions on the design of the system, the efficiency of the components etc so that any "apples to apples" comparison of refrigerants is not applicable. Different refrigerants will achieve optimal performance with different refrigeration system design. Using any one system design for analysis is unlikely to show competing refrigerants at their best performance.

Heat Transfer Properties

The main purpose of refrigeration is to move heat from where it is not wanted to where it is wanted (or at least not a problem). Heat transfer is key to this process. It is possible for a refrigerant to have run of the mill theoretical efficiency yet be an excellent performer because of its strong heat transfer performance. Good heat transfer allows close approaches in the heat exchangers. This in turn means smaller lifts for the compressor and improved efficiency.

Many factors affect heat transfer. Several have to do with the refrigeration system itself such as piping design and material and flow rates (Reynolds numbers). Three key properties of the refrigerant also affect the overall heat transfer capability of the system. These are viscosity (μ), specific heat (c_p) and thermal conductivity (k). The factors are used to calculate Prandtl numbers ($Pr= \mu \cdot c_p/k$) which are used in the design of the heat exchangers. The goal is to work with substances that can carry a lot of energy (high specific heats) and can transfer the energy easily (high thermal conductivity). It is also desirable to have low viscosity to enhance turbulence and reduce the work required to move the fluid.

Ozone Depletion Potential (ODP)

ODP is an index of a substance's ability to destroy atmospheric ozone[6]. Table 1 lists the ODP for many common refrigerants. Note that R-11 and R-12 have the highest potential (1.0). While the ODP of a refrigerant does not affect its performance as a refrigerant, it is a key parameter. All refrigerants with any ODP either have been or will be phased out as required by the Montreal Protocol. Any new refrigerant/product development must be based on refrigerants with no ODP.

Global Warming Potential (GWP)

GWP is an index of a substance's ability to be a greenhouse gas. This is covered in detail in the chapter on Climate Change. The GWP is relative to the warming effect of a similar mass of carbon dioxide for a 100 year time-frame. Carbon dioxide is used as the reference gas because it has the greatest net impact on global warming. Halocarbon refrigerants typically have higher GWPs than carbon dioxide but are in much smaller quantities.

Heat Transfer Consideration

There is considerable marketing indicating that R-123 is the most efficient refrigerant. This is based on theoretical refrigerant models that do not take into account the heat transfer properties of the refrigerant. The models assume the energy will transfer at the design conditions specified. In fact, R-134a has better heat transfer properties than R-123.(see Table 1 - Refrigerant Properties*) This can lead to closer approaches in the heat exchangers and different refrigerant operating conditions (lower lift) for the same overall refrigeration system effect. The lower lift will reduce the power required and improve the system performance.*

ODP Consideration

R-22 is an HCFC with a 0.055 ODP. Its production in developed countries has already been capped and its use in new equipment will be stopped in 2010 in the United States. Currently, R-22 is the most popular refrigerant in use and there is no clear "drop in" replacement for it. The ODP for R-22 is causing the entire industry to redevelop a significant portion of their product lines.

GWP Consideration

R-134a is an HFC refrigerant. HFCs are one of six chemicals in a "basket" that are specifically signaled out by the Kyoto Protocol on global warming as a greenhouse gas. While this means countries attempting to meet the requirements of the Kyoto Protocol must be careful how they use HFCs, it does not mean there is a phaseout. There is no reason for HFCs not to be considered a viable solution as a refrigerant now or in the future. A better measure of the warming impact of refrigerants is TEWI *(See* TEWI, *Page 40).*

[6] Wuebbles, D.J. 1981. *The Relative efficiency of a number of halocarbons for destroying Stratospheric ozone*. Report UCID-18924, Livermore, Ca; Lawrence Livermore National Laboratory (LLNL)

The GWP of a refrigerant does not in itself exclude it from use but should be considered when evaluating it. Of greater importance is TEWI (total equivalent warming impact) which is covered in a later section.

Materials Compatibility

How a refrigerant reacts to other material used in a refrigeration circuit is critical to its real world application. Refrigerants will come into contact with copper, steel, brass, lubricants, gaskets, motor wind insulation, etc. All these must be checked carefully for compatibility. Foreign substances, such as moisture, must also be considered as part of a real world review.

One of the great benefits of CFCs was how stable and inert they were. This made materials compatibility straightforward. Unfortunately, it is the inherent stability of CFCs that led to their downfall since they have a very long atmospheric lifetime. As more environmentally friendly refrigerants are used, the materials challenge often increases.

Motor Windings

Many compressors use hermetic motors where the motor is exposed to the refrigerant for cooling it. Refrigerants and insulation can interact through the refrigerant extracting polymers from the insulation or the insulation absorbing the refrigerant. When polymers are extracted, the insulation can become brittle, delaminate and otherwise degrade. These can lead to a motor failure. The extracted polymers can deposit elsewhere in the refrigeration system and cause sticking and blockage.

Where refrigerants are absorbed by the insulation, the dielectric strength or physical integrity can be degraded. Rapid release of absorbed refrigerant when the windings heat up can cause blistering and premature failure of the windings.

The magnetic wire insulation is typically heat cured enamel. The enamel insulating performance is reduced when exposed to refrigerant at elevated temperatures as opposed to air.

Special care is taken when selecting motor insulation based on the refrigerant chosen. Of special interest is when the refrigerant specification is changed. It is critical that the materials used in the original design be compatible with the new refrigerant.

Elastomers and Plastics

Gaskets, O-rings, etc. can be made from elastomers. Refrigerants, lubricants or a combination of both can extract enough filler to adversely change the properties of elastomers. This can lead to shrinkage or swelling which will cause the gasket to fail. Some neoprenes tend to shrink in HFC refrigerants while nitriles tend to swell in R-123[7]. Plastics can also be affected by refrigerants. The effect of refrigerants on plastics usually decreases as the amount of fluorine in the refrigerant molecule increases.

Materials Compatibility Consideration

In most cases extreme care is taken during the design of a refrigeration system that material compatibility issues are resolved beforehand. In the case of a retrofit to a new refrigerant, the onus on compatibility shifts to the field technician. When the market place first started moving away from CFC refrigerants to HCFC-123 and HFC-134a, there was considerable emphasis placed on materials compatibility because HCFC-123 in particular was not compatible with insulation and gasket materials used in R-11 chillers. Once materials compatible with either R-11 or R-123 were identified, chillers were often supplied with the new materials regardless of the refrigerant used. This resolved a major cost in retrofitting these chillers in the field.

Today, almost half of the CFC based chillers are still in use. Many will be replaced at the end of their useful life. Those that are considered for retrofitting will need a full evaluation. Chillers that were not upgraded to materials compatible with HCFC-123 will cost significantly more to upgrade.

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[7] Haned, G.R. and R.H. Seiple. 1993. *Compatibility of refrigerants and lubricants with elastomers. Final Report No. DOE/CE 23810-14.* ARTI Database. Air-conditioning and refrigeration Technology Institute, Arlington, Va.

Refrigerants and Metals

Halocarbon refrigerants generally are very stable when exposed to metals. Under extreme conditions such as extreme heat, refrigerants can react with metals.[8] ANSI/ASHRAE Standard 97 provides a method for accelerated life materials compatibility testing by raising the temperature. In tests conducted by Imagination Resources Inc. R-12, R-500, R-123 and R-134a were exposed to copper, steel, aluminum and Sunisco 4GS oil following the Standard 97 procedure. Only R-123 showed signs of materials incompatibility.

Lubricants

Just like an automobile engine, the mechanical components of a refrigeration system must be lubricated. These include the compressor and various valves (including the TX valve) throughout the system. The goal of a good lubricant is to protect moving parts, improve sealing in the compressor (viscosity), be chemically compatible with the refrigerant and the other materials within the refrigeration system, have a low solubility in refrigerant and be safe.

In DX (Direct Expansion – See Glide in Evaporators, Page 18) refrigeration circuits, the lubricant often travels with the refrigerant throughout the circuit, lubricating components along the way. Care must be taken in the design of the piping to make sure the oil will return to the compressor and not be trapped somewhere in the circuit.

In flooded refrigeration systems, it is very easy for the lubricant to become trapped in the evaporator so it does not return to the compressor and also lowers the heat transfer effectiveness of the evaporator. In flooded systems, it is normal to have a lubricant return system that separates the lubricant from the refrigerant (an oil separator for instance) and return it to the compressor.

Since it is expected that the lubricant and the refrigerant will mix, they must be compatible. Materials used for lubricants include mineral oils, alkyl benzenes, polyol esters (POE), poly-alkene glycols, modified polyalkylene glycols and polyvinyl ethers. The two most familiar to commercial air conditioning are mineral oils and polyol esters or POE lubricants. Mineral oils are natural (derived from crude oil). POE oils are synthetic and manufactured from alcohols.

Refrigerants and Lubricants

How refrigerants interact with lubricants is critical to the proper operation of the refrigeration system and its longevity. CFC refrigerants often used mineral oils for lubricants. The Chlorine in the refrigerants provided good anti-wear characteristics, so little or no additives were required. Mineral and POE oils are not compatible. Although mixing these oils should not happen in normal circumstances, it may happen if the refrigerant is changed within the system.

HCFC refrigerants may use either mineral or synthetic lubricants. In some cases additives are used to improve lubricant performance. HFC refrigerants typically require a synthetic lubricant such as POE type.

Lubricant Consideration

Consider changing a negative pressure R-11 chiller to R-123. The original CFC refrigerant used a mineral oil. This oil has circulated throughout the refrigeration circuit and has come into contact with nearly every inner surface. Now the new HCFC-123 requires a synthetic lubricant such as a POE. While the POE lubricant and R-123 are compatible, the POE and mineral oil are not. The challenge now becomes, how do you remove all the previous mineral oil prior to adding the new POE lubricant? This challenge had to be overcome before R-123 could be considered a viable replacement for R-11. The problem was overcome by developing proper procedures for changeouts and adding additives to the POE lubricant to improve its compatibility with trace amounts of mineral oils.

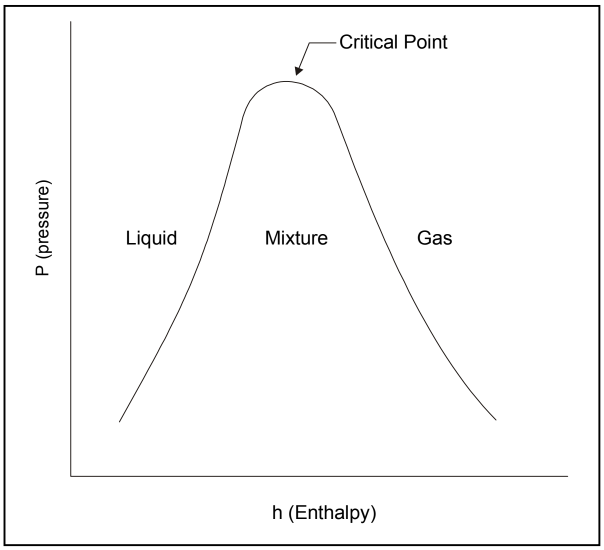
[8] Eiseman, B.J. 1963. *Reactions of chlorofluoro-hydrocarbons with metals* ASHRAE Journal 5(5):63

POE and Water

POE oils are more hygroscopic than mineral oils. That is, they absorb moisture very easily. Moisture within a refrigeration circuit is detrimental because the moisture can mix with carbon to form carbonic acid. Special care must be exercised by operators and technicians not to expose the POE lubricants to atmosphere where they will absorb moisture. This moisture can be introduced to the refrigeration circuit if the lubricant is then added.

Critical Point

Figure 6 - Critical Point



Critical point is the point on a Pressure-Enthalpy (P-H) diagram where the properties of liquid and vapor refrigerant meet and become indistinguishable. The temperature, density and composition of the substance are the same for a liquid or gas at this point. The properties at the critical point are referred to as the critical density, critical pressure, critical volume and critical temperature.

When operating at conditions above the critical point no separate liquid phase will be possible. Refrigeration cycles requiring condensation (most standard air conditioning cycles) will not be possible. It is possible to reject heat at super critical temperatures which is where current research into carbon dioxide is concentrating.

Operating below but near the critical point typically offers high volumetric capacity but low efficiency since the refrigeration effect is reduced[9].

Glide

Glide is a relatively new term to the market place that has surfaced with the advent of zeotropic refrigerant blends such as R-407C and R-410A. Zeotropic blends are comprised of refrigerant components that don't behave as one substance. Glide is the difference (in °F) between the beginning and end phase change process of a refrigerant in either the evaporator or the condenser. It does not include subcooling or superheating.

For example R-407C is made up of R-32 (-62°F boiling point), R-125 (-56°F boiling point) and R-134a (-15°F boiling point). When R-407C is boiled (the evaporation process) R-32 will boil first, the remaining substance will have a different composition and hence a different "average boiling point". This change in composition is known as *fractionation.* This changing of the "average boiling temperature" is the glide.

Critical Point Consideration

Consider R-410A, a front runner to replace R-22 in many applications. It has a critical point of 158.4°F as compared to R-22's critical temperature of 204.8°F. Where this is an issue is in air-cooled products in high ambient locations such as the U.S. south west. Here the design ambient condition is often 105°F or higher. Add to this a 25°F refrigerant approach and now R-410A is only 28°F from its critical point. R-410A is being pushed to the top of its "dome" leaving very little room for condensation. The result is reduced efficiency. It is not unusual for a 5 ton R-410A condensing unit at ARI conditions to be reduced to only a 3 ½ ton condensing unit in high ambient areas.

[9] McLinden, M.O., and D. A. Didion. 1987. *Quest for alternatives.* ASHRAE Journal 29, Atlanta Ga.

Figure 7 - Zeotropic Behavior (R-134a/32)

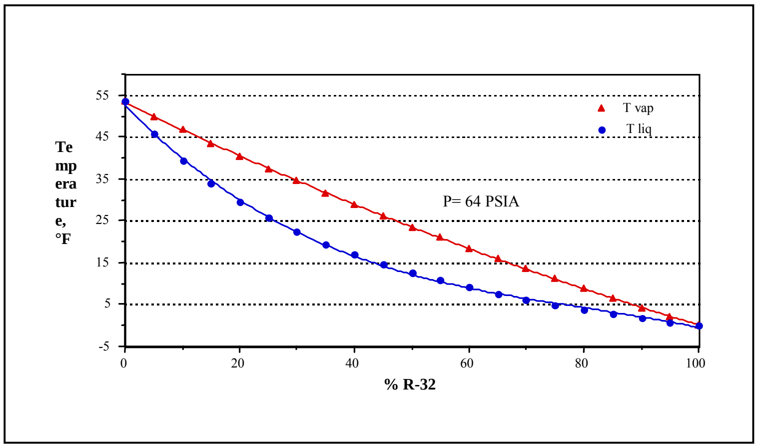
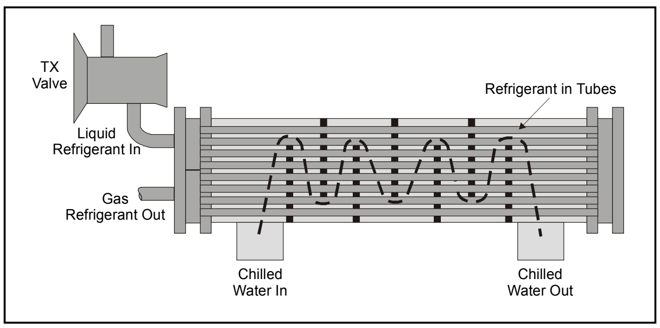


Figure 7 shows a zeotropic mixture of R-134a and R-32 where the ratio of R-32 is varied from 0 to 100%. By drawing a line vertically through the graph, the difference between the temperature as a liquid (lower line) and the temperature as a vapor (top line) can clearly be seen. The difference between the two lines is the glide.

Glide in Evaporators

There are two main types of evaporators used in the air conditioning industry, DX (Direct Expansion) and flooded. DX evaporators have the refrigerant in the tubes and either water (chillers) or air (DX coil) on the outside. Flooded evaporators are used in chillers and they have the water in the tubes and the refrigerant in the shell.

Figure 8 - DX Evaporator



DX evaporators are more forgiving to refrigerants with glide than flooded evaporators are but as a system component, they are less efficient. Figure 8 shows a DX evaporator. In this design, the refrigerant passes through the thermal expansion device (TX valve) and is atomized into very fine liquid droplets in the tubes of the evaporator. The fine droplets offer a large amount of surface area to absorb heat from either air or chilled water on the outside of the tubes.

Zeotropic refrigerants with glide will fractionate in the tubes. The compounds with lower boiling points will boil first followed by the other compounds. The high amount of superheat used in DX evaporators will make sure all the refrigerant subcomponents are boiled (converted to a gas) and the relative mass ratios will be maintained.

Figure 9 - Flooded Evaporator

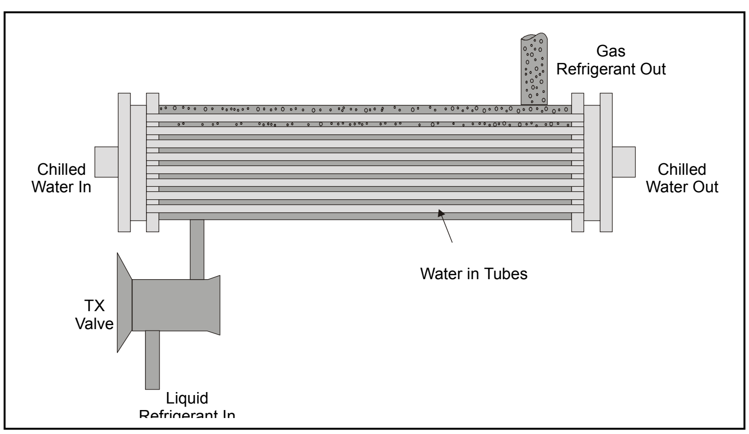


Figure 9 shows a flooded evaporator. The liquid refrigerant fills the shell and covers all the tubes. The heat from the chilled water in the tubes boils the refrigerant, which floats to the top of the shell. The inlet of the compressor draws in the gaseous refrigerant. The process is very similar to water boiling in a pot on a stove.

The issue with zeotropic refrigerants that have significant glides is that as the refrigerant fractionates, the compound with the lowest boiling point floats to the top first and enters the compressor. The relative mass ratios are not maintained.

Zeotropic Serviceability

Since zeotropic refrigerants fractionate, there is an issue when there is a leak. The problem for the technician is, which subcomponent leaked? It cannot be assumed that the subcomponents leaked in their design ratio. One solution would be to remove the entire charge and reload the refrigeration circuit with new refrigerant where the subcomponent ratio was known to be correct. This, however is not always practical.

For small leaks, adding new refrigerant has been shown to have minimal impact on the system performance. In an experimental study[10], a refrigeration system charged with R-407C had 12.5% of its charge removed (the ratio of subcomponents was not maintained) and then was recharged with brand new R-407C (proper subcomponent ratio). The process was repeated four times so half the initial charge was replaced. Table 2 shows the initial and final concentrations of the subcomponents before and after the leak/recharge process. Table 3 shows the performance loss with the leak/recharging. Dupont provides similar results (9% loss) based on theoretical models[11].

> **Glide Consideration**
>
> *Consider two of the frontrunners to replace R-22, R-407C and R-410A. Both are zeotropes. However, the glide for R-407C is 8°F while the glide for R-410A is only 1°F. The high glide for R-407C means it can be practically used only in DX systems, which limits the overall system efficiency that can be expected when using it. R-410A can be used in flooded systems, so even though it requires complete redesign of all components including the compressors (it operates at a significantly higher pressure), it is the common choice for redesigned refrigeration systems.*

Table 2 - Initial and Final Concentrations at Different Locations

Location	HFC-32/HFC-125/HFC-134a Weight %	
	Initial	After 4 leak/recharges
Reciever Inlet	23.2/25.5/51.3	20.1/22.6/57.3
Reciever Outlet	22.9/25.3/51.8	20.0/22.6/57.4
Evaporator Inlet	29.7/30.8/39.5	26.8/28.4/44.8
Evaporator Outlet	22.1/24.9/53.0	19.9/22.5/57.6
Condenser Inlet	25.0/26.6/48.4	21.6/23.6/54.9
Condenser Outlet	24.2/26.1/49.7	21.4/23.5/55.0

Table 3 - Reduction in Performance After Leak/Recharge

Parameter	Reduction, % calculated with R-407C Concentrations	Reduction, % calculated with Real Concentrations
Refrigeration Capacity	2.7	11.0
Electrical COP	1.0	3.9
Volumetric Capacity	3.0	8.0

Charging zeotropic blends is more involved because only liquid can be added. The "heal" or last bit of refrigerant in the tank cannot be used. Special tanks that allow only liquid to enter are required.

[10] Paulas-Lanckriet, M., O. Buyle .July, 1998. *Experimental Study on Fractionation of R-407C and Recharge Operations.* International refrigeration Conference at Purdue.
[11] *Retrofit Guidelines for Suva 407C, ART-34.* June 2000. Dupont. Wilmington, De.

Acoustic Velocity

Acoustic velocity is important to refrigeration system design because it sets the "speed limit" on refrigerant flow. Approaching supersonic speeds can lead to shock waves that will damage equipment. It is not unusual for the refrigerant gas velocity entering the inlet of a centrifugal compressor to be near supersonic (Mach=1.0). Acoustic velocity increases when temperature increases, and decreases when pressure increases. Table 1 shows the acoustic velocity for common refrigerants. The conditions are given in the footnotes.

Acoustic Velocity Consideration

In the mid-nineties, CFC refrigerants were phased out. Companies that had the technology to build R-12 based chillers quickly converted to R-134a. In a general sense, R-134a was considered a "drop in" replacement for R-12 or R-500. However the acoustic velocity in R-134a is about 8% higher than in R-12. To truly optimize the machinery for R-134a, refrigerant pathways had to be modified and in particular, the inlet geometry of the impeller reduced and improved.

Physical Properties

There are several key physical properties of refrigerant that are an indicator of their potential. In particular, atmospheric boiling point and freezing point. The boiling point is a direct indicator of the temperature level the refrigerant can be used at. The freezing point must be lower than any contemplated operating point.

Physical Properties Consideration

Boiling point can be used to show the difference between R-123 and R-134a, the two common refrigerants for centrifugal chillers. R-123 boils at 82.17°F at 14.7 psia. To lower the boiling point to approximately 40°F so that the refrigerant goes from a liquid to a gas (the evaporation process), the refrigerant must be placed in a vacuum. Hence the negative pressure chiller concept. R-134a boils at –15.08°F at 14.7 psia. To raise the boiling point to 40°F, the refrigerant must be placed under pressure.

Reviewing water (R-718) can show an example of the importance of freezing point. Water is used as the refrigerant in absorption chillers and it freezes at 32°F at 14.7 psia. It is not possible to use a water-lithium bromide absorption chiller to chiller brine to below freezing. Absorption chillers will not be used in ice storage systems!

Refrigerant Chemistry

General

It is really quite remarkable that with the nearly infinite number of substances in the universe, only a handful are suitable for refrigerants. Many efforts have been made to source other families of compounds that perform as well as the group (Fluorocarbons) Thomas Midgley Jr. found in 1928. None so far have proven to be comparable.

The following section provides a brief explanation of the chemical properties of the refrigerants in use today. It will provide the foundation for discussion of the challenges facing chemists in developing new refrigerants.

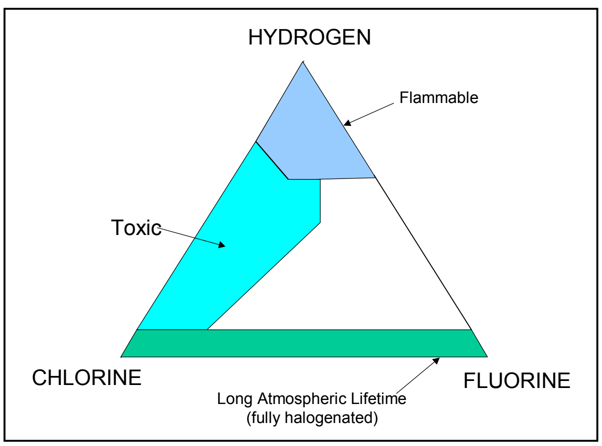
Inorganic Compounds

Water (R-718), carbon dioxide (CO_2) (R-744) and ammonia (NH_3) (R-717) are examples of natural refrigerants. Many were used in early development of refrigeration systems with water (absorption chillers) and ammonia being the only two in wide commercial use today.

Fluorocarbons

Most of the modern refrigerants (CFCs, HCFCs and HFCs) are derived from fluorocarbons. The results of varying the ratios of fluorine, carbon and hydrogen can be shown in Figure 10.

Figure 10 – Trade-offs in Varying F, Cl and H in Refrigerants[12]



Adding chlorine or bromine (moving to the lower left corner of the triangle) increases the ODP of the substance. Adding chlorine also tends to raise the boiling point[13].

Adding fluorine to the substance (moving to the lower right corner of the triangle) tends to increase the GWP of the substance. The GWP depends on infrared absorbence (carbon-fluorine bonds) and longevity. Increasing the fluorine also tends to reduce toxicity.[14]

Increasing the hydrogen content (moving up the triangle) tends to increase flammability. It also tends to decrease its atmospheric lifetime, which is a positive feature in light of global warming. CFCs, which have no hydrogen, have the longest lifetimes and are not flammable. Hydrocarbons (propane, isobutane) are highly flammable but have short atmospheric lifetimes.

[12] McLinden, M.O., and D. A. Didion. 1987. *Quest for alternatives.* ASHRAE Journal 29, Atlanta Ga.
[13] McLinden, M.O., and D. A. Didion. 1987. *Quest for alternatives.* ASHRAE Journal 29, Atlanta Ga.
[14] Clayton, Jr., J.W. 1967. *Fluorocarbon toxicity and the biological action.* Fluorine Chemistry Reviews.

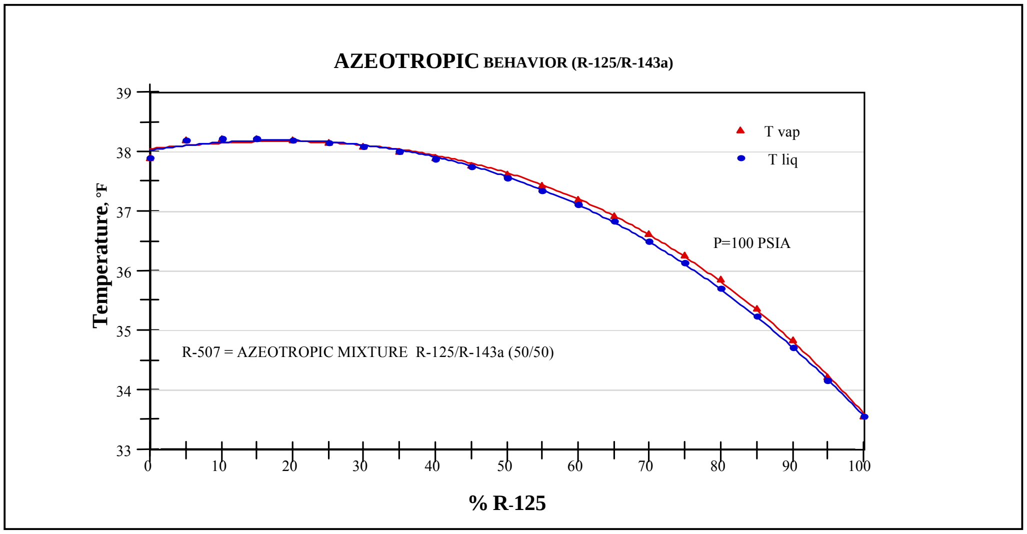
Blends

Blends are mixtures consisting of two or more compounds. With only a finite number of refrigerants available, new refrigerants made up of two or more other refrigerants increases the possibilities. By careful formulation it is possible to create a new refrigerant that will take advantage of existing technology (e.g. R-407C) or optimize new technology (e.g. scroll compressors and R-410A).

Azeotropes

Azeotropic refrigerants are blends made up of two or more refrigerants that have the same equilibrium vapor and liquid phase compositions at a given pressure. More simply stated, the refrigerant blend behaves as one refrigerant throughout the refrigeration cycle and does not fractionate. The slope of temperature vs. composition line is zero (no glide). Examples include R-500 and R-502. ASHRAE Std 34 designates Azeotropes with 500 series numbers.

Figure 11 - Azeotropic Refrigerants



Zeotropes

Zeotropic refrigerants are blends that change volumetric composition and saturation temperature (glide) as they boil. In short, they will fractionate. ASHRAE Standard 34 designates Zeotropes with 400 series numbers. Examples include R-407C and R-410A. Both are considered frontrunners to replace R-22. For more information on Glide, see page 17.

Hydrocarbons

Hydrocarbons are compounds containing only hydrogen and carbon. Hydrocarbon refrigerant examples include R-290 (propane) and R-600a (isobutane). The term hydrocarbon is often misapplied to cover any flammable refrigerant. Hydrocarbons used as refrigerants are highly flammable but can be good refrigerants. They can cause cardiac sensitization but generally breakdown quickly enough so that they offer lower overall toxicity risks. Hydrocarbons have also been connected to smog formation[15] because they are linked to ozone generation in the troposphere.

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[15] Corr, S., J.D. Morrison, F.T. Murphy and R.L. Powell, 1995. *Developing the hydrofluorocarbon range: Fluids for centrifugal chillers.* Proceedings of the 19th International Congress of Refrigeration, IIR. Paris, France

Chemical Trends

The following is a summary of trends[16] that occur with the use of various elements:

- Increasing carbon generally increases the molecular weight and the boiling point.
- Increasing nitrogen generally makes the compound more reactive. This can lead to toxicity and instability issues.
- Increasing oxygen generally reduces atmospheric stability, which is good for GWP and ODP but may lead to toxicity, flammability and reactivity issues.
- Increasing sulfur generally increases toxicity and decreases stability.
- Increasing hydrogen generally reduces atmospheric lifetime, which is good for GWP and ODP but increases flammability.
- Increasing fluorine attached to carbon increases GWP.
- Increasing chlorine improves lubricant miscibility but also ODP and toxicity.
- Increasing bromine increases ODP but lowers flammability.
- Using boron in lieu of carbon creates chemicals that are reactive and generally toxic.
- Using silicon in lieu of carbon creates substances that adversely react with water and have not performed well thermodynamically.

[16] Calm, J., David D. Didion, Oct 6-7, 1997. *Tradeoffs in Refrigerant Selections: Past, Present and Future.* Refrigerants for the 21st Century, ASHRAE/NIST Refrigeration Conference. ASHRAE, Atlanta, Ga.

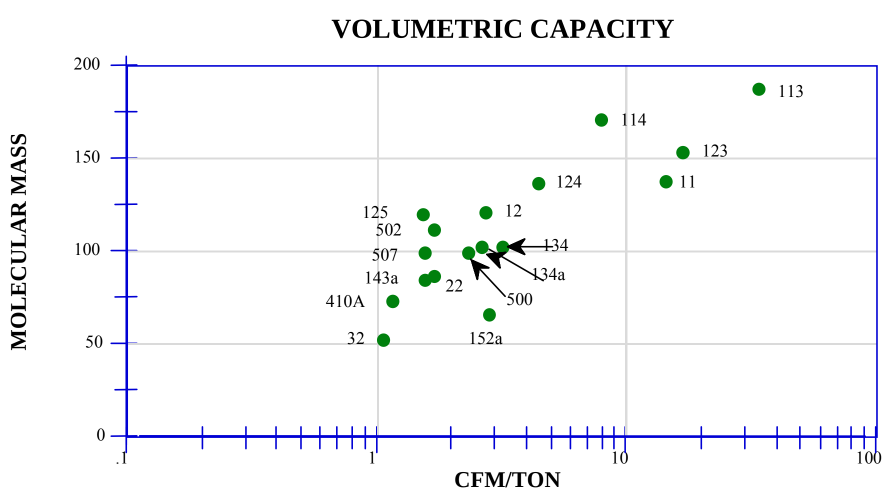
Refrigerants have many properties, which can affect their performance. These properties also affect which kind of refrigeration system they are used in and specifically what kind of compressor. Most commercial refrigeration systems are based on absorption or vapor compression technology. Absorption chillers use water as the refrigerant and lithium bromide as the absorbent. Other substances can be used as well, such as water and ammonia. Using water as the refrigerant limits the chilled water temperature (must stay above freezing) to conditions that are acceptable to commercial air conditioning.

Compressors

Vapor compression refrigeration systems utilize a compressor to raise the enthalpy (pressure and temperature) of the refrigerant which is often referred to as "lift". The operating conditions dictate the required lift (see Figure 3-Heat Exchanger Performance). Air-cooled equipment will need a higher lift than water-cooled because of the warmer condensing temperatures. Low temperature applications will also require a higher lift. The amount of refrigerant effect (the tons of refrigeration) is proportional to the refrigerant flow rate (lb/min or cfm per ton).

Positive displacement compressors tend to be high-lift, low-volume compressors. Examples include reciprocating, scroll and screw compressors. Centrifugal compressors tend to be low-lift, high flow rate compressors.

Figure 12 – Volumetric Capacity of Common Refrigerants

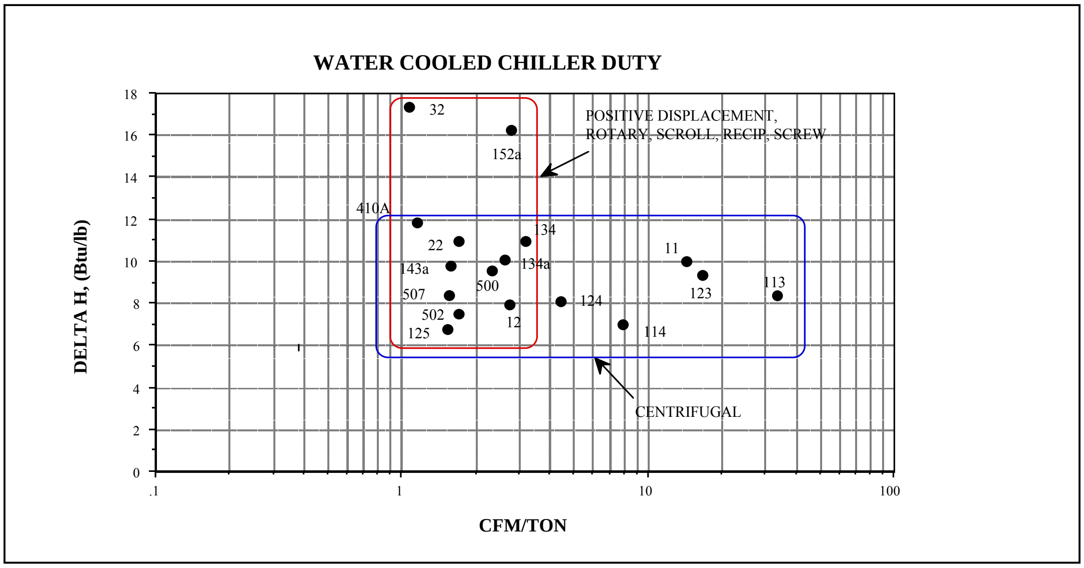


Refrigerants with small molecular mass tend to lend themselves to high enthalpy, low flow rate applications. In other words, they match up well with positive displacement compressors. Examples include R-22, R-410A and R-134a. Using R-410A as an example, Figure 12 shows its small molecular mass. Figure 13 shows R-410A provides high delta enthalpy capability. Both figures show how R-410A only requires about 1.5 cfm/ton capacity making it a good candidate for positive displacement compressors.

Refrigerants with large molecular size require high volume flow rates and tend to provide a smaller delta enthalpy. Examples include R-11 and R-123. Figure 13 shows these two refrigerants as strong candidates for centrifugal compressors. Both of these refrigerants require approximately 17 cfm/ton refrigerant flow.

R-134a is often used in both positive displacement and centrifugal compressors. Although it can be used with any kind of positive displacement compressor, it is often used with screw compressors because they have relatively high flow rates for a positive displacement type. R-134a requires a flowrate of approximately 3 cfm/ton.

Figure 13 - Delta H Vs. CFM/Ton



Heat Exchangers

Both the evaporator and the condenser are heat exchangers. A refrigerant's ability to transfer energy to and from a heat exchanger will affect the overall system performance. Heat transfer is proportional to surface area and temperature difference among other things. If a refrigerant has poor heat transfer properties, either the surface area must be increased (adding copper tubing adds a lot of cost) or the temperature difference must be increased. Increasing the temperature difference means increasing the compressor lift which will increase the compressor work. In commercial air conditioning, temperature differences for chillers can be down to 1 or 2 degrees F so small changes are very important.

As an example, R-123 has a thermal conductivity of 0.0476 Btu/h·ft·°F while R-134a has a thermal conductivity of 0.0521 Btu/h·ft·°F. The improved energy transfer provides the refrigeration system designer the choice of either reducing the copper tubing in the heat exchanger and thus lowering the cost or lowering the lift on the compressor and thus improving the performance.

Piping and Pressure Drops

All refrigerants, whether in vapor or liquid form, undergo a pressure drop as they flow through the refrigeration circuit. This can be in the piping connecting components or in a component (i.e. a compressor passageway). As the pressure changes, the temperature of the refrigerant changes as well. How much depends on the refrigerant. Changes in temperature generally adversely affect system performance. Consider pressure drops in the suction and discharge lines. So that there is the correct pressure (and temperature) at the evaporator and the condenser, the pressure drops (and hence temperature changes) will have to be added to the total lift the compressor provides. Which refrigerant is used affects the temperature change relative to the pressure change.

System Example

From an efficiency point of view, what is really important is to provide a system that meets the load (has enough refrigeration effect) for the least operating cost. In most cases, least operating cost means the least amount of energy input. Many refrigerant properties and the parameters discussed above all come together to affect the (energy) cost to operate the system. Following is an example of how all these properties interrelate. NIST Cycle_D, Version 2.0, a software program, was used to model the system performance.

Model Parameters

- ❑ Compare R-134a to R-123. Because these two refrigerants are used in large chillers, there has been a significant amount of marketing on this subject.
- ❑ Design conditions will be based on ARI 550/590-98 chiller design conditions. Namely:
    - ❑ 44°F supply chilled water temperature, 2.4 USgpm per ton
    - ❑ 85°F supply condenser water temperature, 3.0 USgpm per ton

Model 1 – Carnot

The first model is based on Carnot cycle. This is the best possible refrigerant effect and will set a benchmark. This is independent of refrigerant and is based solely on the temperatures. The efficiency is 0.323 kW/ton.

Table 4 - Refrigerant System Models

Model	Carnot	Ideal Cycle		Base Model		Base Model w/ Non condensables	
Property		**R-123**	**R-134a**	**R-123**	**R-134a**	**R-123**	**R-134a**
Chilled water Supply Temp (°F)	44	44	44	44	44	44	44
Cond. Water Supply Temp (°F)	85	85	85	85	85	85	85
Compressor Inlet Temp (°F)	44	44	44	41	42	41	42
Compressor Outlet Temp (°F)	95	95	95	97	96	99	96
Suction Line Press. Drop (°F)	N/a	0	0	1	1	1	1
Liq. Line Press. Drop (°F)	N/a	0	0	1	1	1	1
Evaporator Superheat (°F)	N/a	0	0	0	0	0	0
Condenser Subcooling (°F)	N/a	0	0	9.5	9.5	9.5	9.5
Isentropic Compressor Eff.	N/a	100%	100%	84%	85%	84%	85%
Compressor Motor Eff.	N/a	100%	100%	100%	100%	100%	100%
COP	10.88	8.949	8.472	6.444	6.506	6.201	6.506
KW/ton	0.323	0.393	0.415	0.546	0.541	0.567	0.541

Model 2 – Ideal Cycle

The definition of an ideal cycle is not formalized. In this example it means isentropic compression (100% efficient), perfect heat transfer and no pressure drops (temperature changes) as refrigerant flows through piping and components. Notice the refrigerant temperatures are the same as the water temperatures (no approaches) which cannot be obtained in practice. As well, there are no losses for transport (suction or liquid line pressure drops). R-123 has the better performance. This is the basis for claims that R-123 is the most efficient refrigerant available. However, it is impossible to build a refrigerant system based on an ideal cycle.

Model 2 – Base Model

The base model starts to allow for some real world performance. Notice there are approaches on the evaporator and the condenser (the refrigerant is a different temperature than the water). The approaches for R-123 are higher than for R-134a because R-134a has better heat transfer characteristics. The compressor efficiency is slightly lower (1%) for R-123 than for R-134a. The argument here is the transport properties for R-123 are worse than for R-134a adding losses to the compressor efficiency. Accounting for heat transfer and transport properties makes R-134a slightly more efficient.

Model 2 – Base Model Allowing For Non-condensables

Finally, non-condensables in the negative pressure system have been added which raised the condensing pressure 2 °F. This further worsened the performance of the negative pressure chiller and also showed the sensitivity efficiency has when non-condensables are added.

Summary

As soon as "real world" examples were modeled, choices had to be made about the system design. In fairness to R-123, the design favored R-134a. Subcooling significantly helps R-134a. Multistage compressors help R-123. If the Base Model conditions are repeated with R-123 and a multistage compressor the performance becomes 0.491 kW/ton (COP = 7.16). Accounting for non-condensables decreases the multi-stage performance to 0.508 kW/ton (COP = 6.92). By the same token, talking about ideal cycle efficiency and not accounting for heat transfer and transportation properties is not realistic either.

The customer should really stay focused on the overall equipment performance and consider whether full load or partload performance should be optimized.

Stratospheric Ozone Depletion

The Earth is surrounded by a layer of Ozone in the Stratosphere that protects life from the Sun's ultraviolet radiation (UV-B). Increased levels of UV-B at the Earth's surface may lead to skin cancer and other adverse health effects. Plants, aquatic and other terrestrial life can also be affected.

In 1970, Crutzen supposed that nitrogen oxides from fertilizers and supersonic aircraft might deplete the ozone layer. In 1974 Mario Molina and F. Sherwood Rowland identified CFC refrigerants as a source of chlorine in the stratosphere and the potential threat they proposed with increased use[17]. Both public and private research was started to investigate these theories. The ozone layer over the Antarctic was observed to be thinning in the austral spring for several seasons and the results were published in 1985[18]. This became known as the "ozone hole". The ozone hole has been observed every season since, varying in size and duration but generally increasing.

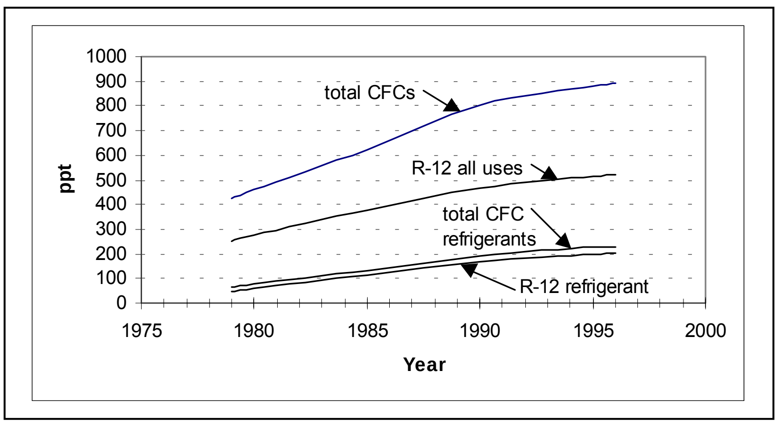
The Chemical Process

In the end, one of the key advantages of CFCs and HCFCs, their stability, became their Achilles' heel. CFCs and HCFCs are stable molecules, they do not react easily with other substances which gives them a long atmospheric life. The long life allows the CFCs and HCFCs to rise high up into the stratosphere where the ultraviolet light decomposes the CFCs and HCFCs and frees the chlorine.

Ozone on the other hand is very reactive. Once exposed to the free chlorine, it quickly breaks down in a catalytic process. The process releases the chlorine to react with another ozone molecule. A single chlorine atom can destroy thousands of ozone molecules. The effect is the thinning of the ozone layer.

Other chemicals also contribute to ozone depletion including Halons, carbon tetrachloride, methyl chloroform, hydrobromofluorocarbons (HBFCs) and methyl bromide.

Figure 14 - Atmospheric CFC Concentrations



The source for CFCs and HCFCs is not all refrigerant manufacture or emissions. Figure 14 shows concentrations of total CFCs, CFC-12 in all uses, total CFC refrigerants and R-12. Currently, about 27% of the CFCs in the atmosphere are from refrigerant emissions[19]. The balance of CFC emissions comes from solvents, foam blowing agents, aerosols, etc.

HCFC refrigerant emissions account for 83% of the total HCFCs found in the atmosphere. As of 1996, refrigerants were responsible for 28% of the anthropogenic (manmade) ozone depletion. Refrigerants over the next century will be responsible for 24% of the anthropogenic ozone depletion Refrigerants have been and will continue to be a major factor in ozone depletion.

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[17] Molina, M., F.S. Rowland. 1974. *Stratospheric sink for chlorofluoromethanes: Chlorine-atom catalyzed destruction of ozone.* Nature 249

[18] Farman, J., B. Gardiner, J. Shanklin. 1985. *Large losses of total ozone in Antarctica revealed seasonal C1O x NO x interaction.* Science 190

[19] AFEAS (Alternative Fluorocarbons Environmental Acceptability Study. 1997. *Production, sales and atmospheric release of fluorocarbons through 1995.* SPA-AFEAS Inc., Washington D.C.

Why Antarctica?

Actually some thinning of the ozone layer over the North Pole has been observed. The ozone occurrence has been linked over Antarctica to the presence of chlorine and bromine and unique Antarctic stratospheric weather, chemistry and physics. Antarctica has very cold polar stratospheric clouds (PSCs) which contain water and nitric acid crystals. When the sun hits (PSCs) in the austral spring the water and nitric acid crystals form reaction sites for the breakdown of ozone.

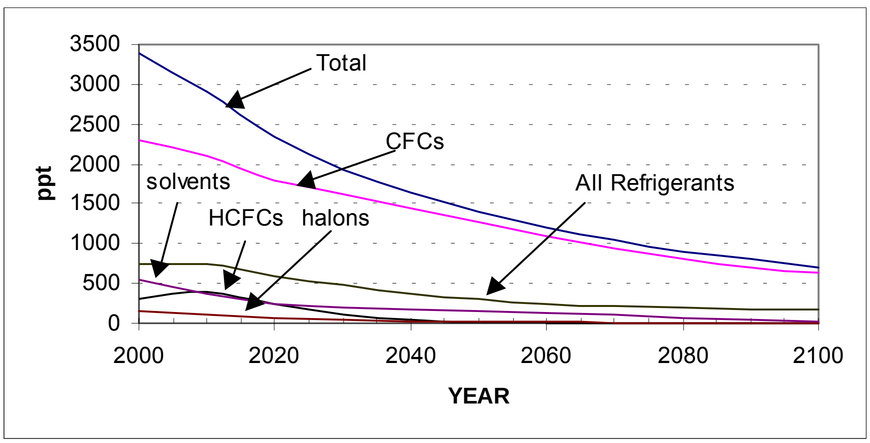
The Montreal Protocol

In 1987 the *Montreal Protocol on Substances That Deplete the Ozone Layer* (UNEP 1987) was ratified. It will be discussed in detail in the next section but the result was the phaseout of CFCs, HCFCs and several other ozone depleting substances.

Ozone Depletion in the Future

The concentrations of CFCs, HCFCs and other ozone depleting substances in the lower atmosphere peaked in 1994 and are now slowly declining. Recent evidence suggests that concentrations in the stratosphere may also have peaked.[20] The ozone layer is expected to return to pre-industrial levels by the middle of this century.

Figure 15 - Ozone Depletion Capacity (In equiv. Cl) Based On Global Adherence To The Montreal Protocol[21]



[20] Schrope, M. Dec. 7, 2000.*Successes in the fight to save ozone layer could close hole by 2050.* Nature V408.

[21] Frasier, P. 1998. *Refrigerants: contributions to climate change and ozone depletion.* AIRAH Journal, June 1998

Montreal Protocol and the EPA

Background

By the mid 1980s there was overwhelming evidence that the ozone layer needed to protect life on Earth was thinning and that this was due to manmade chemicals reacting with the ozone in the stratosphere. In 1985 the United Nations Environmental Program (UNEP) and the World Meteorological Organization (WMO) coordinated the Vienna convention which provided the framework for the Montreal Protocol. In 1987, the *Montreal Protocol on Substances That Deplete the Ozone Layer* (UNEP 1987) was ratified. This was a landmark event in that the majority of countries came together to identify a problem and agree on a solution.

Timeline

The original protocol has been amended several times over the years, adding substances, changing dates and so on. As well, the protocol differentiates between Annex 1 (developed countries) and Annex 2 (developing countries) providing different timelines for each group. The following is a summary on the original requirements and subsequent changes made over the years. The UNEP meets annually to discuss any further changes that the protocol may require so future changes are still possible.

Annex 1 (Developed) Countries[22]

DATE	DETAILS
1987	Montreal Protocol: Requires 50% reduction in CFC production by 2000. Other compounds were also controlled.
1990	London Amendment: Requires 100% phaseout of CFC production by 2000.
1992	Copenhagen Amendment: Advances CFC phaseout to 1996. Set HCFC consumption cap in 1996 with a ratcheted phaseout as follows ❑ 65% of Cap in 2004 ❑ 35% of Cap in 2010 ❑ 10% of Cap in 2015 ❑ And 0.5% of Cap in 2020 The cap was set as the ozone depletion potential weighted consumption for HCFC plus 3.1% of the CFC ODP weighted consumption wit ha base year of 1989.
1995	The CFC portion of the HCFC cap was reduced from 3.1% to 2.8%.
1997	Montreal Protocol Amendments: HCFC consumption from 2020 to 2030 only be used for service on existing equipment
1999	Beijing Amendments: HCFC production caps introduce to deal with export issues to developing countries.

[22] *Ozone Depleting Substances: Position Paper*. Approved by the Board Of Governors, Feb. 1, 2001. ASHRAE, Atlanta Ga.

Annex 2 (Developing) Countries

DATE	DETAILS
July 1999	Cap CFC consumption at the 1995-97 average levels and phase out consumption by 2010.
2016	Freeze HCFC consumption at 2015 levels phase out consumption by 2040.

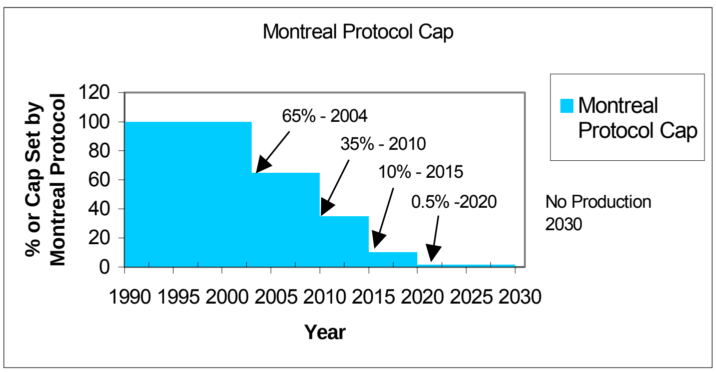
EPA and CFCs

Production of CFCs stopped December 31, 1995, in the United States as required by the Montreal Protocol for developed countries. The only source of CFCs (in particular R-11 and R-12) is reclamation from existing equipment.

Montreal Protocol and HCFCs

The Montreal Protocol does not differentiate between HCFCs although it does require the cap be based on an ODP-weighted average. The phase out schedule for HCFCs as required by the Montreal Protocol is shown in Figure 16.

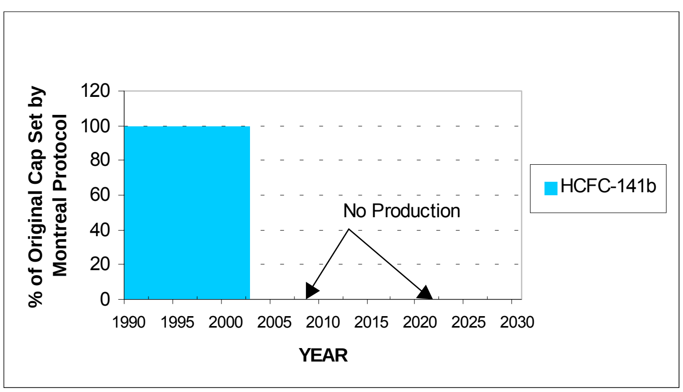
Figure 16 - HCFC Phaseout as Per Montreal Protocol



Many countries, including the United States, have modified versions of the Montreal Protocol phase out schedule, either choosing to accelerate the phase out of higher ODP substances or to exceed the minimum requirements set out in the protocol.

The multi-tiered approach has led to much confusion regarding which dates are actually correct. For a country to be in compliance with the Montreal Protocol, they must meet the minimum requirements shown in Figure 16. If a country chooses to exceed the requirements, then whatever schedule was approved by the governing body will be the minimum requirement.

EPA and HCFCs



The Environmental Protection Agency (EPA) is the governing body in the United States that ratified the Montreal Protocol into law. In July 1992, the EPA implemented section 604 of the Clean Air Act, which was in response to the Montreal Protocol. The cap for HCFCs went into effect in 1996 based on the 1989 baseline. For the United States, the HCFC cap is 15,240 ODP weighted metric tons. What is very important to understand is the phase out schedules required by the EPA and the Montreal Protocol are different. This has led to significant confusion in the market place, as several substances (R-22 for example) appear to have different phaseout schedules depending on which document is referenced.

Figure 17 - EPA Cap on R-141b

The EPA identified HCFCs that had higher ODPs and scheduled their phase-out sooner than other HCFCs with lower ODPs. In this manner the EPA intends to meet the ODP-weighted HCFC phase-out schedule required by the Montreal Protocol. So, although the EPA schedules are different from the Montreal Protocol's schedule, they meet the same goal.

The EPA has accelerated phase-out schedules for R-141b, R-142b and R-22. Figure 17 shows the phaseout schedule for R-141b, which is predominately used as a foam blowing agent. No production or importing is allowed beyond 2003. Phasing out R-141b will help the United States meet the 35% reduction in the HCFC cap required by the Montreal Protocol that goes into effect in 2004.

Figure 18 – EPA Cap on R-22 and R-142b

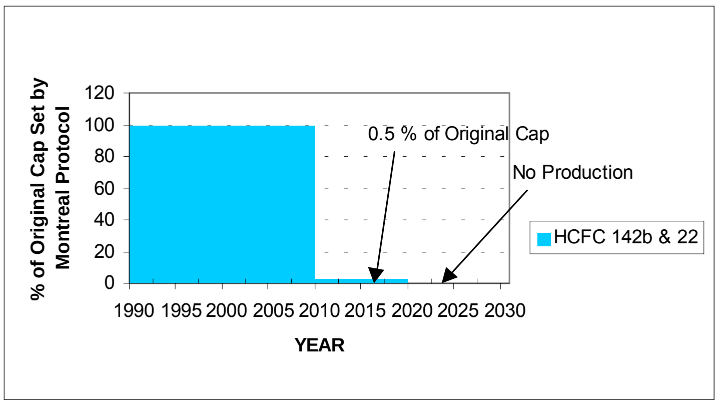


Figure 18 shows the phaseout schedule for R-22 and R-142b. Again, this is faster than required by the Montreal Protocol but will allow the United States to meet the second major reduction in HCFC consumption required in 2010.

Of significant interest to the HVAC market is the phase out of R-22 in 2010. Only 0.5% consumption for service will be allowed beyond that date and only for another 10 years. R-22 is the most popular refrigerant in the world. Phasing it out affects nearly every kind of refrigeration system including home air conditioning, rooftop units, and industrial refrigeration. See **Refrigerants in The Future** for possible replacements to R-22.

Figure 19 – EPA Cap On Remaining HCFC Refrigerants Including R-123

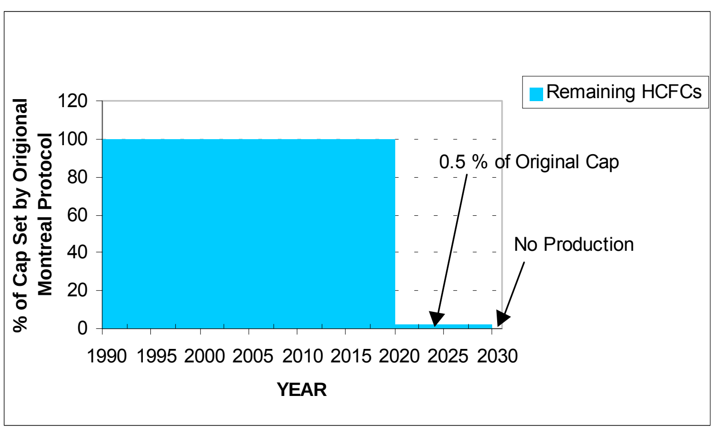


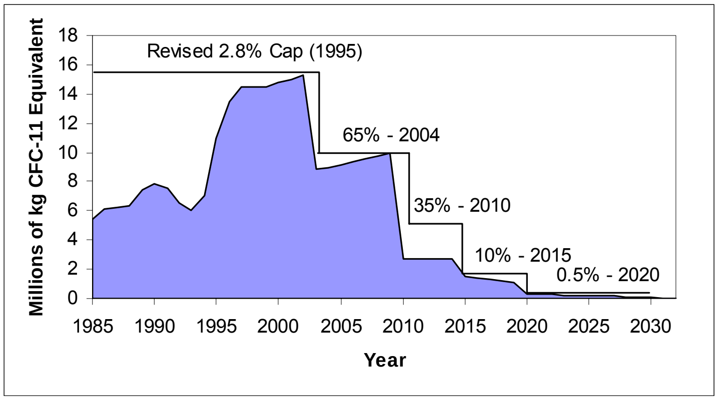
Figure 19 shows the phase-out schedule for remaining HCFC refrigerants in use in the United States. The United States phase-out for remaining HCFCs for non-refrigeration applications is 2015. Of key interest to the HVAC industry is R-123, the interim solution for negative pressure centrifugal chillers.

The EPA ruling requires no production or importing of any HCFCs except for use as refrigerants in new equipment produced before 1/1/2020. A small amount (0.5%) is allowed for service between 2020 and 2030.

What If the United States Reaches the Cap?

The overall goal by the EPA to phase out specific HCFCs as detailed above is to keep the United States within the requirements of the Montreal Protocol. Figure 20 shows the weighted U.S. HCFC anticipated usage and how it should fit within the cap required by the Montreal Protocol. In 1999, the United States reached 95.5% of the cap and has been hovering around that level since. In 1996, it was forecasted that HCFC consumption would approach the cap at the beginning of the millennium but not exceed it and then drop off. Another critical point will come in 2015 when the Montreal Protocol requires a reduction to 10%. The high consumption level prompted the EPA to issue plans for rationing refrigerants if the cap was actually meet. It is anticipated that cap will be reached and allocations will be required.

Figure 20 - U.S. HCFC Use and the Montreal Protocol Cap



EPA Proposed Allowance System for HCFCs

In July 2001 the EPA issued 40 CER Part 82, "Protection of Stratospheric Ozone; Allowance System for Controlling HCFC Production, Import and Export; Proposed Rule". The final rule has not been published at the time of this publication.

Allocation controls occur at the manufacturer, importer, and exporter levels. Parties involved in this business report their activities to the EPA, which then regulates the amounts. The market place is actually familiar with this process because it already does it for Class I (CFCs) substances. Here is a quick list of the requirements;

- Like the rules for Class I (CFCs) substances, Class II (HCFCs) will have both production and consumption (production + imports - exports) allowances.
- The allowances are chemical specific. That is, a company will have a production and consumption allowance for R-22 and R-141b etc., measured in kgs of a specific substance. Table 5 shows the allowances for production per company based on the substance.
- EPA will allocate 100% of the listed individual companies' production and consumption baselines. The EPA is reserving the difference in the sum of the all the companies' baseline allocations and the United States' total cap under the Montreal Protocol for narrow exceptions like a relatively late newcomer to the industry whose baseline is low.
- The baselines are based on each listed company's highest ODP weighted consumption and production level during the years of 1989, 1994, 1995, 1996 or 1997. The sum of these actually adds up to less than the United States total cap.
- Allowances can be shifted from one chemical to another by taking into account the ODP weighting. For example an allowance for 10,000 kg of R-142b can be transferred to a 5,909 kg allowance of R-141b. Permanent allowance transfers are also possible.
- The allocation baseline is set on a one time base year. The baseline is carried forward for each year. It will be reevaluated in 2010 to see if it will meet the requirements of the Montreal Protocol 2010 65% cap reduction.

- Permanent trades in baseline allocations are allowed. That is, a manufacturer can shift R-123 allocation to R-22.
- If a company chooses not to produce a substance even though it has an allocation, the EPA does not require the company to give up its allocation for redistribution to other companies. For example, if a company has an allocation for R-123 but chooses not to produce it, the EPA will not require the company to surrender the allocation so that another company can produce the refrigerant.
- When a phaseout for a specific substance is reached (e.g. R-141b in 2003) all allowances for that substance will cease.
- Between now and 2004, The EPA will allocate to each allowance holder 100% of their baseline allowance.
- In 2003, the EPA will subtract the R-141b allowance from all allowance holders.
- In 2004, if the levels will exceed the 35% Montreal Protocol reduction, the EPA will lower the allocations on each substance on a pro rata basis.
- In 2010, EPA will reevaluate the baseline levels to ensure the 65% Montreal Protocol reduction is met.
- In 2015, EPA will reevaluate the baseline levels to ensure the 90% Montreal Protocol reduction is met.

Table 5 - Proposed EPA Baseline Production Levels[23]

Company	Controlled Substance	Allowances (kg)
Allied (Honeywell)	HCFC-22	36,094,556
	HCFC-124	3,227,086
	HCFC-141b	27,719,366
	HCFC-142b	2,334,508
Ausimont	HCFC-142b	4,418,767
Dupont	HCFC-22	52,072,484
	HCFC-123	10,410
	HCFC-124	6,390
	HCFC-141b	10,464
	HCFC-142b	53,978
Elf Atochem (ATOFINA Chemicals)	HCFC-22	22,230,306
	HCFC-141b	23,801,431
	HCFC-142b	15,577,099
MDA	HCFC-22	2,301,966

Each year, the EPA will adjust the production levels as necessary so the United States meets the Montreal Protocol. Each refrigerant will have its production and consumption level adjusted. For instance, a 10% cap will lower the levels for all HCFC refrigerants 10% of their baseline levels. Table 5 lists the proposed production baselines for HCFCs. Table 6 lists the proposed consumption baselines for HCFCs.

[23] *EPA 40 CFR Part 82 Protection of Stratospheric Ozone; Allowance System for Controlling HCFC Production, Import and Export; Proposed Rule. July 20, 2001*

Table 6 - Proposed EPA Baseline Consumption Levels[24]

Company	Controlled Substance	Allowances (kg)
ABCO	HCFC-22	253,032
AGA	HCFC-225ca	109,653
Air systems	HCFC-225cb	134,024
Allied (Honeywell)	HCFC-22	32,056,219
	HCFC-124	2,958,382
	HCFC-141b	18,793,538
	HCFC-142b	1,191,783
Altair	HCFC-22	241,367
Ausimont	HCFC-142b	4,418,767
Automatic Equipment	HCFC-22	48,989
Condor	HCFC-22	603,374
Continental	HCFC-141b	18,400
Dupont	HCFC-22	46,599,488
	HCFC-123	71,063
	HCFC-124	6,302
	HCFC-141b	8,196
	HCFC-142b	47,820
Elf Atochem (ATOFINA Chemicals)	HCFC-22	26,741,356
	HCFC-141b	23,010,714
	HCFC-142b	15,101,025
HG Refrigeration	HCFC-22	36,291
ICC	HCFC-141b	73,568
ICI	HCFC-22	2,306,278
Kivlan	HCFC-22	1,837,718
Klomar	HCFC-22	7,776
MDA	HCFC-22	2,301,966
Mondy-Global	HCFC-22	255,258
National Refrigerants	HCFC-22	4,963,713
	HCFC-123	76,520
	HCFC-124	204,980
Refricenter	HCFC-22	345,350
Refricentro	HCFC-22	41,645
Rhone-Poulenc	HCFC-22	47,180
R-Lines	HCFC-22	57,217
Saez	HCFC-22	34,360
Solvay	HCFC-22	284,370
	HCFC-124	274,990
	HCFC-141b	3,568,700
Tesco	HCFC-22	43,520
Tulstar	HCFC-141b	78,720

Canada and CFCs

Like the United States, Canada stopped producing and using CFCs in new equipment at the end of 1995. Currently the only source of CFC refrigerants is from reclamation. However, Canada is now developing a strategy for accelerating the phase-out of equipment using CFCs by requiring replacements or conversions to acceptable refrigerants. The goal is to create an orderly transition from CFCs to other more environmentally friendly solutions. Table 7 provides a breakdown of how equipment using CFCs will be phased out.

[24] *EPA 40 CFR Part 82 Protection of Stratospheric Ozone; Allowance System for Controlling HCFC Production, Import and Export; Proposed Rule. July 20, 2001*

Table 7 - Existing CFC Phaseout Plan for Canada

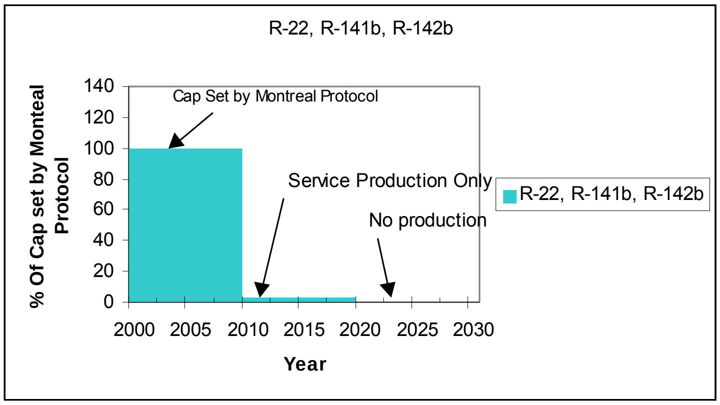
Sector	Approach
Mobile Air Conditioning	Prohibit refill with CFCs as soon as possible.
Mobile Refrigeration	Prohibit refill with CFCs effective 2003.
Household Appliances	Enhance implementation of existing recovery programs; If necessary, add a ban on converting equipment to use CFCs.
Commercial Refrigeration and A/C	Staged CFC refill ban effective by year: Equipment < 5 HP: 2004 Equipment <30 HP: 2005 Equipment >30 HP: 2006
Chillers	Limit releases from low pressure purges to less than 0.1 kg/kg air effective 2003; Require conversion or replacement of CFC-containing chillers at next overhaul effective 2005.
Halons	Prohibit refill of portable equipment effective 2003;For fixed systems, provide for one refill between 2005 and 2010. The refill would be allowed on the condition that the system is replaced by an alternative within a year of the refill. This would also be subject to critical use exemptions. Starting in 2010, refills will be prohibited.

Canada and HCFCs

Canada has adopted a slightly different plan from the United States in dealing with phasing out HCFCs. The approach is a combination of phasing out HCFC use in areas where other technology is available (the European approach) and phasing out HCFCs with higher ODPs first (The EPA approach). Here are some of the key points;

DATE	DETAILS
Now	HCFCs cannot be used in areas where it has never been used before. In other words, no new applications using HCFCs can be developed.
July 1999	Containers with 2 kg or less HCFCs cannot be imported or manufactured. Plastic foam where HCFCs were the blowing agent cannot be manufactured or imported (insulation applications are exempt). No cleaning agent using HCFC-141b can be imported or manufactured.
Jan. 2000	Containers with 2 kg or less HCFCs cannot be sold. (There are several exceptions). Polyurethane boardstock where HCFCs were the blowing agent cannot be manufactured or imported (insulation applications are exempt). No cleaning agent using HCFC-141b can be used or sold.
Jan 2010	HCFC-141b, HCFC-142b and HCFC-22 cannot be manufactured, sold or imported. No equipment that contains these refrigerants is allowed either (Refrigeration applications are exempt).
Jan. 2015	No other HCFC can be manufactured, imported or sold except HCFC-123.
Jan 2020	HCFC-123 for service only.
Jan 2030	All HCFCs phased out.

Figure 21 - Canadian Phaseout Schedule for R-22, 141b and 142b



HCFCs used as refrigerants have different phase out schedule. Figure 21 shows the phaseout for R-22, R-141b and R-142b. From an HVAC point of view, R-22 has the same phaseout as the United States.

Figure 22 - Canadian Phaseout Schedule For R-123

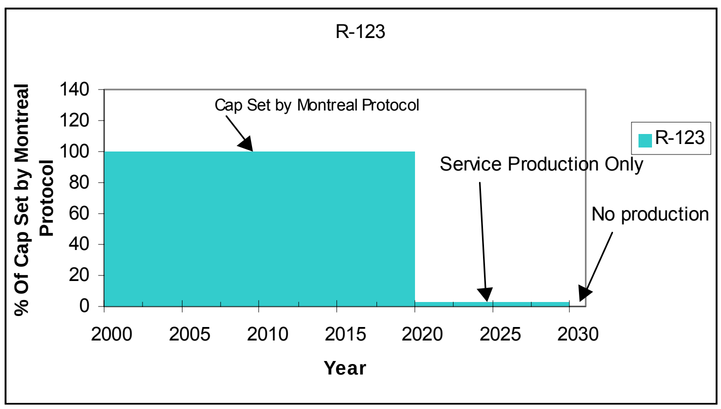


Figure 22 shows the Canadian phaseout schedule for R-123 used as a refrigerant. Again it is the same as the United States.

Figure 23 - Canadian Phaseout Schedule For Remaining HCFCs

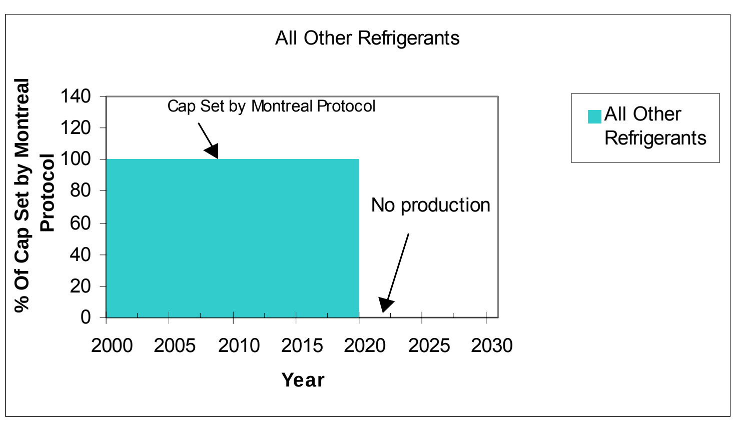
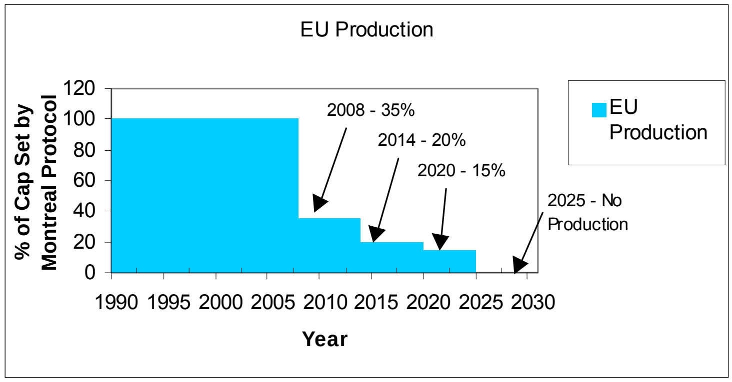


Figure 23 shows the phase out schedule for any other HCFCs used as refrigerants. This is slightly different than the United States but most HVAC products use one of the refrigerants listed above.

Europe

Figure 24 - EC HCFC Phaseout Schedule

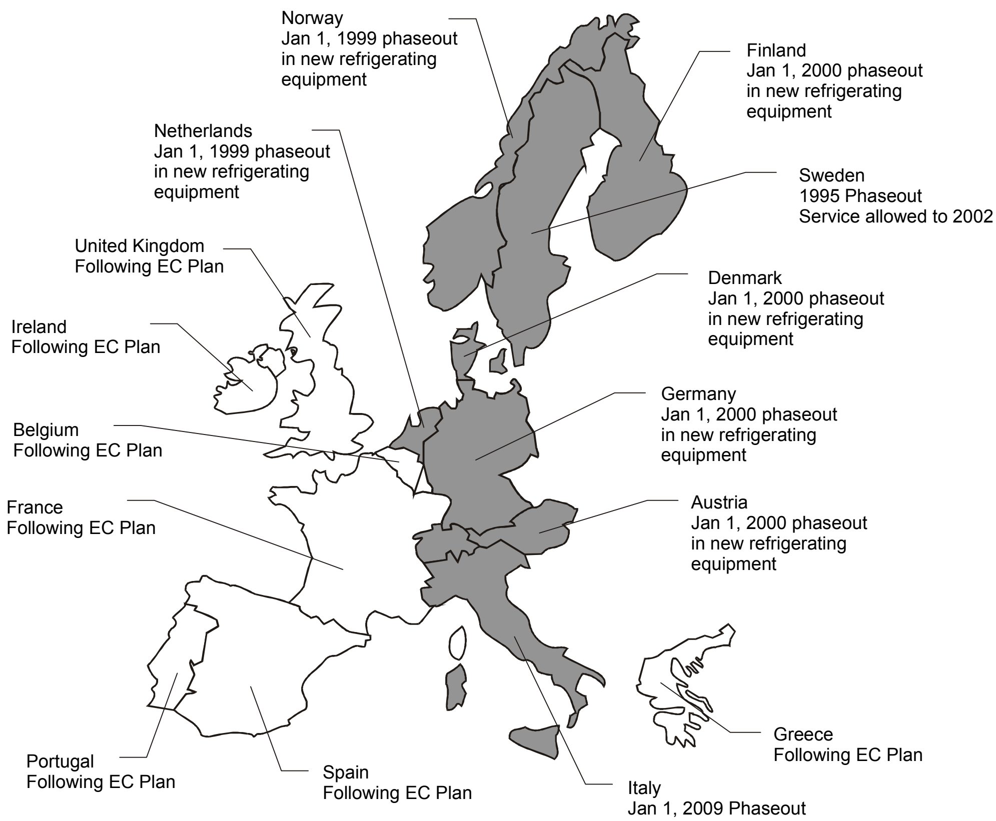


Europe also stopped using CFCs at the end of 1995. It is not as dependent on HCFC usage as North America and so has taken a more aggressive stance on phasing out HCFCs. The European Community (EC) has developed a phase out plan for HCFCs that exceeds the requirements of the Montreal Protocol. Many European phaseout policies are based on application as well as substance. For instance HCFC usage as a refrigerant can have one phaseout schedule while HCFC usage as a blowing agent another.

Figure 24 shows the phase-out scheduled in Council regulation 300R2037. The EC has committed to review HCFC production with an eye to a production cut in advance of 2008 and whether the levels for 2008, 2014 and 2020 should be lowered.

Many European countries have adopted legislation that exceeds the requirements of the EC. Figure 25 shows the accelerated phaseout schedules (beyond EC 300R2037) for several European countries.

Figure 25 - Accelerated HCFC Refrigerant Phaseout Schedule for European Countries



Several European countries are receptive to using hydrocarbons and other flammable refrigerants, particularly in domestic applications such as refrigerators. The trend is for countries to the north to use less HCFCs and more flammable substances. Some countries such as Denmark have legislation ready to phase out HFCs as well.

Montreal Protocol and EPA on HFCs

HFCs do not affect the ozone layer. They have an ODP = 0. Both the Montreal Protocol and the EPA have no restrictions on the use of HCFS nor do they have any phase requirements for HFCs. This is one of the main reasons that HFCs such as R-134a, have risen to such prominence as refrigerants in the last few years.

Climate Change and Refrigerants

Climate Change, sometimes referred to as global warming, is the second major environmental challenge to face the HVAC industry. The Earth is warmed by incoming solar radiation from the sun. The Earth and the gases in the atmosphere absorb about 2/3 of the incoming radiation. The remaining 1/3 is reflected back by cloud cover, airborne particles and the Earth's surface mostly as infrared radiation. Certain gases in the atmosphere can "trap" that energy and stop it from escaping. This raises the Earth's mean temperature. The process is often referred to as the "greenhouse" effect and the gases that can trap the energy are referred to as "greenhouse" gases (GHGs).

While some trapping of heat is desired, too much can cause the Earth to become too warm. Scenarios such as polar ice caps melting with wide spread flooding are an extension of this problem. The long time line for climate change events also makes it difficult to evaluate the problem. Climate change happens naturally over many thousands of years (ice ages for example). Modern science has been collecting data only for a very short time period making it very difficult to ascertain any trends.

While the greenhouse process is an accepted scientific model, there are many mechanisms connected with the process are that are not as clear and are seriously debated. For instance, a raising of the Earth's mean temperature should produce more evaporation of ocean water and hence more cloud cover. The cloud cover could reduce the incoming solar radiation offset the greenhouse effect. There is enough concern that the ASHRAE Position Paper on Climate Change[25] suggests global average surface temperatures could rise by 1.8 to 6.3°F by 2100 with a corresponding rise in sea levels of 6 to 37 inches by the end of the next century.

What is understood is that too much global warming is a serious problem and greenhouse gases play a key role in the process. Another way to look at it is that there are no plausible scientific models that dispel the greenhouse gas – global warming model. What is being debated is the severity of the change in climate. There is enough data that the Intergovernmental Panel on Climate Change (IPCC) under the United Nations Framework Convention on Climate Change (UNFCCC) reported in 1995 that "the balance of evidence suggests a discernable human influence on global climate". This led to the Kyoto Protocol.

[25] *Climate Change: Position Paper*. Approved by the Board Of Governors, June 24, 1999. ASHRAE, Atlanta Ga.

Greenhouse Gases Including Carbon Dioxide

Many substances are greenhouse gases, including methane, nitrous oxide, chlorofluorocarbons (CFCs) hydrochlorofluorocarbons (HCFCs), Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and carbon dioxide (CO_2). CFCs, HCFCs and HFCs represent most of the substances used for refrigerants in the world today. Much of the electrical power used to operate refrigeration systems comes from the burning of fossil fuels, which emit CO_2, which is also a greenhouse gas.

Figure 26 - Breakdown of Greenhouses Gases[26]

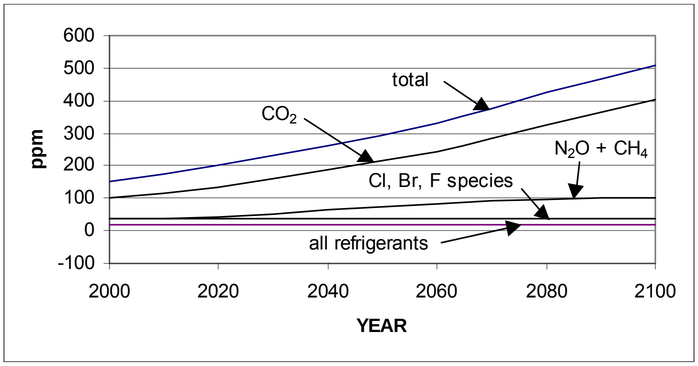


Figure 26 shows a breakdown of substances that contribute to climate change based on equivalent carbon dioxide concentrations. The common scale used to measure greenhouse gases is to equate greenhouse gases to carbon dioxide either as carbon dioxide equivalent concentration measured in parts per million (ppm) or as Global Warming Potential (GWP).

GWPs are based the relative warming effect a similar mass of carbon dioxide would have typically over a 100 year period. Table 1 lists the GWP for many common refrigerants. Carbon dioxide is used as reference because it has the single largest impact of any one greenhouse gas.

Carbon Dioxide Levels

Changes in carbon dioxide levels since the start of the industrial revolution are documented and alarming. Based on ice core samples the CO_2 concentration 150 years ago was 270 ppm. Today, the level has climbed to 370 ppm. Even if the Kyoto Protocol is adopted and there is steady energy efficiency improvements, there are predictions[27] that the CO_2 level will double by 2050, triple by 2100 and quadruple by 2150. The main source of CO_2 is the burning of fossil fuels for energy. It is estimated that in North America, 1/3 of the energy consumed is used in buildings. Energy efficient buildings will have a direct and major affect on CO_2 emissions.

Direct and Indirect Affects of Refrigerants

Refrigerants affect climate change in two ways. The first way is when released directly into the atmosphere. Most of the refrigerants in use today have some level of GWP. Some are very high. The good news is the actual amount of refrigerants released to the atmosphere is very small (especially when compared to CO_2 emissions) and so the overall direct effect is limited. Over the period 2000-2100, CFC, HCFC and HFC refrigerant manufacture and emissions will account for only 3% of the total climate forcing due to long-lived anthropogenic greenhouse gases.[28]

[26] Frasier, P. 1998. *Refrigerants: contributions to climate change and ozone depletion.* AIRAH Journal, June 1998

[27] Mahlman, J., Speaking at ASHRAE 2001 Winter Meeting. *Response to global warming will affect its severity.* ASHRAE Journal. March 2001.

[28] Frasier, P. 1998. *Refrigerants: contributions to climate change and ozone depletion.* AIRAH Journal, June 1998

The second way refrigerants affect climate change is indirect and deals with system efficiency. In many cases the energy used to operate a refrigeration system comes from the burning of fossil fuels. The carbon dioxide released in this process affects climate change. The more efficient the refrigeration system, the less carbon dioxide released.

TEWI

TEWI stands for Total Equivalent Warming Impact. It is the sum of the effect of a direct discharge of refrigerant plus the effect of carbon dioxide emissions due to energy use over the lifetime of the equipment. TEWIs are based on carbon dioxide which has a GWP =1.0. The refrigerant portion is converted to the amount of carbon dioxide that would have an equivalent affect and then added to the power station emissions also in carbon dioxide. The impact can exceed the life time of the equipment so it is necessary to choose a timeline to consider the effects. An Integrated Time Horizon (ITH) of 100 years is often used.

Because the two parts that make up TEWIs are based on the system, it is not possible to obtain a TEWI for a particular refrigerant. Leakage rates and refrigeration system efficiency are not properties of the refrigerant itself.

Figure 27 - TEWI For Chillers[29]

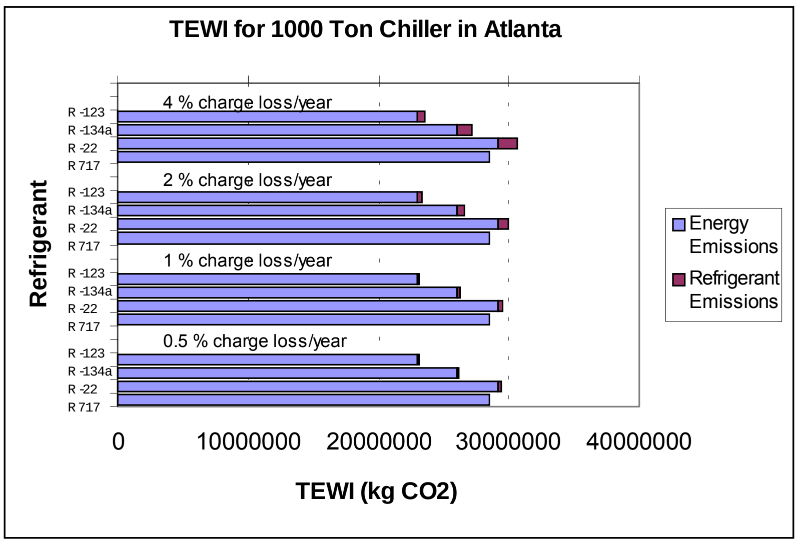


Figure 27 shows the TEWI for a 1000 ton chiller in Atlanta.[30] From these tables, it can be seen that refrigerant emissions is less than 5% of the total TEWI.

Recently, there has been a movement to take an even more holistic look at energy and environmental impact. The Term Life Cycle Warming Impact or LCWI has been used to discuss a cradle-to grave-approach that includes the energy cost to manufacture the system.

Refrigerant Emissions

To control the effect that refrigerants have on climate change, it is critical to control refrigerant emissions to the atmosphere. This goes beyond leaks to include servicing and reclamation at the end of the equipment life.

Energy Consumption

Based on Figure 27 it can be seen that energy efficiency is the most critical issue for refrigerants and climate change. It goes beyond just full load performance but must include the part load performance over the life of the equipment.

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[29] Baxter,V., S. Fischer, J Sand. September 1998. *Global Warming Implications of Replacing Ozone-Depleting Refrigerants*. ASHRAE Journal. Atlanta Ga.
[30] Baxter,V., S. Fischer, J Sand. September 1998. *Global Warming Implications of Replacing Ozone-Depleting Refrigerants*. ASHRAE Journal. Atlanta Ga.

Kyoto Protocol

Background

In 1990, the United Nations established a committee to form a framework on Climate Change. In May 1992, the countries at the Rio de Janeiro Earth Summit adopted the agreement. Since then, over 176 countries (including the United States) have ratified it.

The agreement established a process where countries could meet (known as a "Conference of parties" or COP) and discuss the formation of an international legal agreement or Protocol. The first COP-1 was held in Berlin. In 1997, the third COP meeting was held in Kyoto, Japan where the Kyoto Protocol was approved.

The Kyoto Protocol enters into force when at least 55% of the countries representing at least 55% of the annex 1 1990 carbon dioxide equivalent emissions have ratified it. To date, 13 countries have ratified the Protocol. The United States has not.

Kyoto Protocol Requirements

The Kyoto Protocol is intended to reduce the Annex 1 (developed countries) carbon dioxide emissions by 5.2% from the 1990 levels based on the emissions from 2008 to 2012. Each Annex 1 country has it's own target as shown in Table 8.

Table 8 - Carbon Dioxide Emissions Reductions by Country

Country	Percent Reduction	Country	Percent Reduction
Australia	+8	Liechtenstein	8
Austria	8	Lithuania	8
Belgium	8	Luxembourg	8
Bulgaria	8	Monaco	8
Canada	6	Netherlands	8
Croatia	5	New Zealand	0
Czech Republic	8	Norway	+1
Denmark	8	Poland	6
Estonia	8	Portugal	8
European Community	8	Romania	8
Finland	8	Russian Federation	0
France	8	Slovakia	8
Greece	8	Slovenia	8
Hungary	6	Spain	8
Iceland	+10	Sweden	8
Ireland	8	Switzerland	8
Italy	8	Ukraine	0
Japan	6	United Kingdom	8
Latvia	8	United States	7

The reductions required in Table 8 are real a challenge for most countries because their emission levels have increased since 1990. The United States for example, is expected to see a 34% growth in emissions during this period, requiring a 41% overall reduction. Only Germany and the United Kingdom are on track to meet their goals.

The Kyoto Protocol does not specify how a country should obtain the emissions level. This is left up to the individual country. The European community wanted stronger requirements.

Targeted Gases

There are 6 greenhouse gases covered by the Kyoto Protocol. These are carbon dioxide, methane (CH_4), nitrous oxide (N_2O), HFCs, perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6) (with a GWP of 23,900). Although CFCs and HCFCs are greenhouse gases, they are not included because they are being phased out by the Montreal Protocol. The baseline year each country is to use for carbon dioxide, methane and nitrogen oxide is 1990. Each country has the choice of setting the base level for HFCs, PFCs and SF_6 on either 1990 or 1995 levels.

The emissions for all these gases are added up for each country in what is referred to as a "basket". There are no requirements by the Kyoto Protocol to stop using any of these substances. The only requirement is to reduce their combined emissions to the target country's target. This is a very important difference between the Kyoto Protocol and the Montreal Protocol where specific substances were to be phased out of production and use.

Sinks

The Kyoto Protocol allows for "sinks". Forests, soil and land use can absorb carbon dioxide and thus lower the emissions from a particular country. Accounting for sinks is difficult, but was fundamental in getting the protocol passed.

Emissions Trading

The protocol allows for emissions trading among annex I parties. The actual mechanism has not been agreed upon but a country must have emission reduction projects within its borders and may not achieve all its reductions by emissions trading.

Clean Development Mechanism

The clean development mechanism (CDM-Article 12) allows annex I countries to fund emissions reductions projects in developing countries and get credit towards their own emissions reduction. The details of the mechanism have not been worked out.

Developing Countries

Developing or Annex II countries are not currently covered by the Kyoto Protocol. This is important for several reasons. The United States is not expected to ratify the Protocol until there are provisions for developing countries. The concern is the United States would be put into an economic disadvantage. Since the United States is the largest carbon dioxide emitter, it is unlikely that the Kyoto Protocol can be ratified without its support.

The second issue with developing countries is their significant increase as carbon dioxide emitters. Currently, the United States emits 4,881,000 metric tons equivalent carbon dioxide. China, an annex II country, produces 2,667,000 metric tons and is expected to surpass the United States in the next 15 years.

Montreal and Kyoto Protocols

The Montreal and Kyoto protocols are tied together in many ways. In some circumstances, they appear to be in conflict with each other. There is also data and scientific theories that indicate ozone depletion and global warming are physically tied together.

The Montreal Protocol's regulatory approach is to phase out consumption and use of ozone depleting substances such as CFCs and HCFCs. The Kyoto Protocol regulates reduced emissions of gases included in the "basket" (including HFCs).

Ozone depletion and climate change phenomena are also interrelated. Global warming tends to raise the troposphere (lower atmosphere) which cools the stratosphere (upper atmosphere). A colder stratosphere increases PSCs which leads to ozone depletion (see Why Antarctica?, page 29).

Refrigerants in The Future

In the mid-nineties, the HVAC and R industry went through a huge change as the requirements of the Montreal Protocol phased out CFCs. Many then unheard of refrigerants (R-134a and R-123) came to the forefront as replacements for old standbys like R-12 and R-11. The Industry is on the cusp of another change as the HCFCs start to be phased out (R-22 will be phased out by 2010 in the United States) and effects of Kyoto Protocol start being felt.

Despite the wide range of refrigerants available, only a few are under serious consideration. This section will look at the choices and offer some "speculation" on the outcome.

Water (R-718)

Water is the refrigerant in absorption chillers. It is non toxic, abundant, non-flammable and has no ODP or GWP. The main drawback is the efficiency on absorption chillers. The current commercial double effect, direct fired (operates on natural gas) chiller has a COP=1. Compare this with centrifugal chillers with COPs of 6.4 or better. A comparison of TEWIs for an absorption chiller and an electric centrifugal is the best way to decide which is the best with regards to climate change. The TEWI will depend on how the electrical power is generated.

In markets such as Japan, absorption chillers are the norm and centrifugal chillers are the exception. In North America, absorption chillers cost approximately twice as much as electric centrifugal chillers and often cost more to operate, making them difficult to justify.

Prediction
Absorption chillers will continue to see niche applications (Cogen and hybrid plants) in North America. If energy rates change enough (a possibility with deregulation) then absorption chillers may take on a larger role.

Ammonia (R-717)

Ammonia has excellent performance, no ODP and a small GWP. However, the health and flammability issues surrounding ammonia have limited it to industrial and controlled commercial applications.

Prediction
Ammonia will continue to see industrial and controlled commercial applications.

Carbon Dioxide (R-744)

Carbon dioxide is non-toxic, non-flammable and has no ODP and a low GWP. Its low critical point, however, makes it a poor performer at typical commercial operating conditions. As well, the operating pressures are very high (900 psig). Research is underway to study carbon dioxide at trans-critical conditions. As well, it has been used successfully in cascade refrigeration systems.

Prediction
Possible future applications in automotive air conditioning and cascade refrigeration plants.

Propane (R-290) and Isobutane (R-600a)

Propane and isobutane have low toxicity, good performance, no ODP and low GWP. However, they are flammable. Northern Europe has accepted them in refrigerators. Coca-Cola has announced it will move away from HFCs and has considered flammable refrigerants. In the United States, there are strong concerns about safety with respect to flammability.

Prediction
Flammable refrigerants will most likely continue to see use in the domestic and small system market.

There have been studies performed evaluating the efficiency of flammable refrigerants where brine is cooled and then pumped to where cooling is required (as opposed to direct DX cooling). These reports show propane and isobutane as less efficient than traditional direct cooling R-22 systems. However this should be understood in light of the use of brine. There are only a handful of large capacity installations in the world.

R-134a

R-134a is classified as an A1 (Lower toxicity – no flame propagation) refrigerant by ASHRAE, it has no ODP but the GWP is 1300. It has very good performance, heat transfer properties and is a good candidate for screw and centrifugal compressor applications. Its acceptance in the automotive industry makes it very abundant.

R-134a appears to be caught between the Montreal and Kyoto Protocols. The Montreal Protocol is systematically removing from service common refrigerant with ODP> 0. By default, the protocol is driving the market to refrigerants with ODP=0 such as R-134a. On the other hand, the Kyoto protocol has put HFCs in the basket of targeted gases.

R-134a is one of the best solutions available. It has 0 ODP and therefore has no phaseout date from the Montreal Protocol. Although HFCs are in the Kyoto Basket, only its emissions are regulated. There is no phase out date for HFCs. While CFCs and HCFCs are major contributors to ozone depletion (28% of anthropogenic ozone depletion), HFCs, CFCs and HCFCs direct effect is only a minor player in climate change (4% of anthropogenic global warming).

Prediction

R-134a will continue to be the main large capacity refrigerant in the HVAC industry for the foreseeable future.

All second generation centrifugal and screw chillers in the market place have been designed around R-134a.

Replacements for R-22

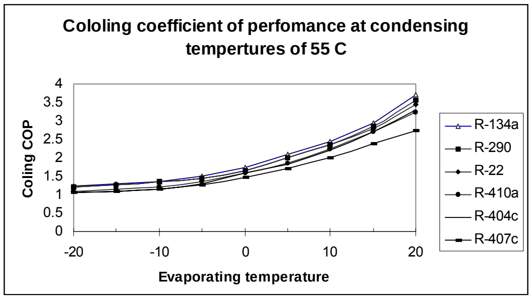
R-22 is classified as an A1 (Lower toxicity – no flame propagation) refrigerant by ASHRAE. It is the most popular refrigerant in the world. R-22 is also an HCFC and as such is being phased out. In the United States, R-22 is already capped and will be completely phased out in 2010 except small a amount for service. R-22 is extremely versatile. It is used in supermarket refrigeration, skating rinks, chillers with all types of compressors, packaged rooftop units and most residential air conditioning. There are no direct replacements for R-22. Different refrigerants will end up replacing various applications of R-22. Table 9 lists several replacements and their relative performance to R-22. Figure 28 shows the COP of the replacement refrigerants at a 130 °F condensing temperature[31].

Table 9 - Relative Performance of R-22 Replacements

	R-290	R-134a	R-404A	R-407C	R-410A	R507
Capacity	85%	67%	106%	95%	141%	109%
Efficiency	99%	100%	93%	98%	100%	94%
Suction Press, abs	94%	59%	121%	91%	159%	125%
Cond Press, abs	90%	68%	120%	115%	157%	122%
Glide	0	0	1F	8F	1F	0

[31] Meyer, J. 2000. *Experimental Evaluation of Five Refrigerants as Replacements For R-22.* ASHRAE MN-00-6-4

Figure 28 - COP of R-22 Replacements



The use of R-22's in centrifugal chillers has always been limited and for the most part that sector has moved to R-134a. R-22's use in screw chillers (water and air-cooled) is now moving to R-134a for the most part. All second-generation screw compressors have been developed to work with R-134a. R-404A and R-507 are being used in refrigeration applications previously performed by R-22.

This leaves all the small compressor applications including package rooftop units, small air and water cooled chillers (under 200 tons) and the entire residential air conditioning (multi-billion dollar) industry. The two main candidates are R-407C and R-410A. Propane (R-290) can be used in the residential market, but the concerns about flammability in North America have severely limited its application.

R-407C

R-407C is a zeotropic blend of HFC-32, HFC-125 and HFC-134a. Its properties have been "tuned" to be very close to R-22 but it has a glide of over 8°F. R-407C can be "dropped" into an existing R-22 refrigeration system and work although often with some performance loss. In many applications, the performance can be improved with minor changes to the refrigeration system sub-components (for example adding condenser surface area).

Prediction

R-407C will be used as a drop in replacement for R-22 in existing systems and as an interim solution for existing product lines until new lines are developed.

The high glide limits its applications to only to DX units such as rooftop units and some chillers where glide is less of an issue. R-407C is often considered a "replacement drop in" refrigerant to be used in upgrading existing systems to an HFC refrigerant. There is limited new generation product development based on R-407C.

R-410A

R-410A is a zeotropic blend of HFC-32 and HFC-125. It has a minimal glide (less that 1°F) and a very low volume flowrate (1.5 cfm/ton). It also operates at higher pressures than R-22 (450 psi). It cannot be dropped into an existing R-22 system but instead must be used in a new generation design.

There is a lot of interest in R-410A as the new generation replacement for R-22 with smaller systems. Compressor manufacturers have started to offer small (1/2 to 5 ton) compressors designed for R-410A, which has led to its introduction in the residential market (Carrier refers to residential R-410A systems as Pureon). As larger compressors become available, R-410A will spread into more commercial products. With the higher operating pressures associated with R-410A, all sub-components (valves, sight glasses, filter–driers etc) need to be redesigned, which has slowed R-410A's launch into the commercial market place.

Prediction

As more refrigeration sub components become available, next generation residential and light commercial products will utilize it. Some technology will be implemented to address the low critical point issue.

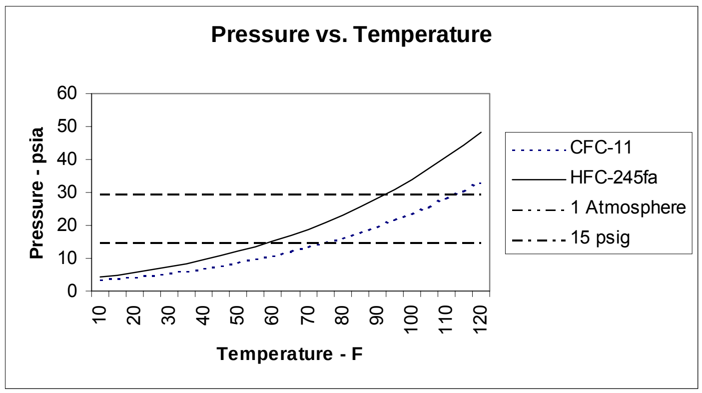
One issue with R-410A is the low critical point and applications in high ambient. This significantly reduces the performance of air cooled equipment in hot locations. Water-cooled equipment is generally unaffected because of the lower condensing temperatures.

Replacements for R-123

ASHRAE Standard 34 classifies R-123 as a B1 refrigerant (higher toxicity – no flame propagation). It is the HCFC replacement for CFC-11 and as such is being phased out. In the United States, R-123 is already capped and will be reduced to 0.5% production in 2020 for service only until 2030. R-123 is used almost exclusively in negative pressure centrifugal chillers.

There is no clear replacement for R-123. Possible use of R-601 (n-pentane) or R-601a (isopentane) is unlikely. These are both highly flammable. The required charge levels used in centrifugal chillers would make an explosion possible. As well, negative pressure chillers draw in air allowing an explosive mixture to be present in the chiller.

Figure 29 – Vapor Pressure of Low-pressure Refrigerants



The two closest HFCs are R-245ca and R-245fa (they are isomers – same atoms but different configuration). Most of the early work was centered around R-245ca until it was found that it was flammable. R-245fa is a B1 refrigerant (higher toxicity – no flame propagation). It also operates at higher pressures than R-123. Where R-123 does not require ASME rated shells (at normal conditions), R-245fa will require ASME rated condensers (See Figure 29[32]). R-245fa cannot be a replacement for existing R-123 chillers unless the chiller is ASME rated.

To refrigerant manufacturers, R-123 use in negative pressure centrifugal chillers is a small market. Fortunately, R-123 can be manufactured as a byproduct from manufacturing other more common refrigerants. R-245fa is a more expensive refrigerant to manufacture. Its realistic introduction into the market place would require other applications for the substance (e.g. foam blowing) to get the production quantities large enough to get the cost down.

Prediction

R-123 will be used in negative pressure chillers until it is phased out by the Montreal Protocol. There is some speculation that there may be an exemption for R-123 for refrigeration use, but that is unlikely. It would require a majority vote of the Montreal Protocol members. With its limited use outside the United States and other technologies available a change in the Protocol is extremely unlikely.

Possible retrofit kits for existing R-123 chillers with R-245fa may be available but only if the shells are ASME rated.

[32] Hughes, H.M. *Contemporary Fluorocarbons.* 1997. Refrigerants For the 21st Century. ASHRAE. Atlanta, Ga.

Conclusions

Because refrigerants are interwoven with major environmental concerns, they will be a major factor in the decision making process for air conditioning and refrigeration. This is true not only for equipment manufacturers, but also for HVAC engineers. At a minimum, when comparing systems and all other technical issues are balanced, refrigerant selection will tip the scales one way or the other. In many applications, refrigerants will have a much larger influence in the decision making process.

Although refrigerants only make up 3 to 4 % of the climate change problem directly, the energy consumed in by refrigeration systems will put the spot light on efficient refrigeration system design. Refrigerant selections that meet all other criteria but offer poor performance will not help the environment.

The imminent phase out of R-22 will again bring refrigerants to the forefront requiring the HVAC industry to provide guidance to decision makers everywhere. A similar discussion will occur as the phase out for R-123 approaches. A strong understanding of the material covered in this guide will certainly help. For more information please contact your McQuay Sales Representative or McQuay at www.mcquay.com.

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Trade-offs in Refrigerant Selections: Past, Present and Future – Calm, J., D. Didion. 1997. ASHRAE. Atlanta, Ga.

Websites

www.ARI.org	Air-conditioning and Refrigeration Institute
www.ASHRAE.org	American society of Heating Air-conditioning and Refrigeration Engineers.
www.ashraejournal.org	Direct Link to ASHRAE's monthly Journal Magazine
www.doe.gov	U.S. Department of Energy
www.dupont.com	Dupont, Manufacturer of refrigerant
www.ec.gc.ca	Environment Canada
www.epa.gov	U.S. Environmental Protection Agency
www.ARTI-21cr.org	ARTI is the research group for ARI
www.atofinaChemicals.com	Atofina, Manufacturer of refrigerants
www.iiar.org	International Institute of Ammonia Refrigeration
www.un.org	United Nations
www.ipcc.ch	Intergovernmental Panel on Climate Change. Joint group set up by United Nations and World Meteorological Organization.
www.europa.eu.int	European refrigerant policy
www.mcquay.com	McQuay International
www.iifiir.org	International Institute of Refrigeration
www.NIST.gov	National Institute of Standards and Technology

Appendix 1 R-134a MSDS Sheet

Information in this format is provided as a service to our customers and is intended only for their use. Others may use it at their own discretion and risk.

The MSDS format adheres to U.S. standards and regulatory requirements and may not meet regulatory requirements in other locations.

This information is based upon technical information believed to be reliable. It is subject to revision as additional knowledge and experience are gained. Please return to this website for the most current version.

"DYMEL" 134a

6001FR   Revised 17-AUG-2001

CHEMICAL PRODUCT/COMPANY IDENTIFICATION

Material Identification

"DYMEL" is a registered trademark of DuPont.

Corporate MSDS Number : DU000693
CAS Number : 811-97-2
Formula : CH2FCF3
CAS Name : 1,1,1,2-TETRAFLUOROETHANE

Tradenames and Synonyms

CC0050

Company Identification

MANUFACTURER/DISTRIBUTOR
DuPont Fluoroproducts
1007 Market Street
Wilmington, DE 19898

PHONE NUMBERS
Product Information : 1-800-441-7515 (outside the U.S. 302-774-1000)
Transport Emergency : CHEMTREC 1-800-424-9300(outside U.S. 703-527-3887)
Medical Emergency : 1-800-441-3637 (outside the U.S. 302-774-1000)

COMPOSITION/INFORMATION ON INGREDIENTS

Components

Material	CAS Number	%
ETHANE, 1,1,1,2-TETRAFLUORO- (HFC-134a)	811-97-2	100

HAZARDS IDENTIFICATION

Potential Health Effects

INHALATION

ETHANE, 1,1,1,2-TETRAFLUORO-
Gross overexposure may cause: Central nervous system depression with dizziness, confusion, incoordination, drowsiness or unconsciousness. Irregular heart beat with a strange sensation in the chest, "heart thumping", apprehension, lightheadedness, feeling of fainting, dizziness, weakness, sometimes progressing to loss of consciousness and death. Suffocation, if air is displaced by vapors.

SKIN CONTACT

ETHANE, 1,1,1,2-TETRAFLUORO-
Immediate effects of overexposure may include: Frostbite, if liquid or escaping vapor contacts the skin.

EYE CONTACT

ETHANE, 1,1,1,2-TETRAFLUORO-
"Frostbite-like" effects may occur if the liquid or escaping vapors contact the eyes.

ADDITIONAL HEALTH EFFECTS

ETHANE, 1,1,1,2-TETRAFLUORO-
Increased susceptibility to the effects of this material may be observed in persons with pre-existing disease of the: central nervous system, cardiovascular system.

Carcinogenicity Information

None of the components present in this material at concentrations equal to or greater than 0.1% are listed by IARC, NTP, OSHA or ACGIH as a carcinogen.

FIRST AID MEASURES

First Aid

INHALATION

If high concentrations are inhaled, immediately remove to fresh air. Keep person calm. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. Call a physician.

SKIN CONTACT

In case of contact, immediately flush skin with plenty of water for at least 15 minutes, while removing contaminated clothing and shoes. Call a physician. Wash contaminated clothing before reuse. Treat for frostbite if necessary by gently warming affected area.

EYE CONTACT

In case of contact, immediately flush eyes with plenty of water for at least 15 minutes. Call a physician.

INGESTION

Ingestion is not considered a potential route of exposure.

Notes to Physicians

Because of possible disturbances of cardiac rhythm, catecholamine drugs, such as epinephrine, should only be used with special caution in situations of emergency life support.

FIRE FIGHTING MEASURES

Flammable Properties

Flash Point : No flash point

Flammable Limits in Air, % by Volume:
LEL : None per ASTM E681
UEL : None per ASTM E681
Autoignition : >743 C(>1369 F)

Fire and Explosion Hazards:

Cylinders may rupture under fire conditions. Decomposition may occur.

Contact of welding or soldering torch flame with high concentrations of refrigerant can result in visible changes in the size and color of torch flames. This flame effect will only occur in concentrations of product well above the recommended exposure limit, therefore stop all work and ventilate to disperse refrigerant vapors from the work area before using any open flames.

HFC-134a is not flammable in air at temperatures up to 100 deg. C (212 deg. F) at atmospheric pressure. However, mixtures of HFC-134a with high concentrations of air at elevated pressure and/or temperature can become combustible in the presence of an ignition source. HFC-134a can also become combustible in an oxygen enriched environment (oxygen concentrations greater than that in air). Whether a mixture containing HFC-134a and air, or HFC-134a in an oxygen enriched atmosphere become combustible depends on the inter-relationship of 1) the temperature 2) the pressure, and 3) the proportion of oxygen in the mixture. In general, HFC-134a should not be allowed to exist with air above atmospheric pressure or at high temperatures; or in an oxygen enriched environment. For example HFC-134a should NOT be mixed with air under pressure for leak testing or other purposes.

Experimental data have also been reported which indicate combustibility of HFC-134a in the presence of certain concentrations of chlorine.

Extinguishing Media

Use media appropriate for surrounding material.

Fire Fighting Instructions

Cool tank/container with water spray. Self-contained breathing apparatus (SCBA) may be required if cylinders rupture or release under fire conditions.

Water runoff should be contained and neutralized prior to release.

ACCIDENTAL RELEASE MEASURES

Safeguards (Personnel)

NOTE: Review FIRE FIGHTING MEASURES and HANDLING (PERSONNEL) sections before proceeding with clean-up. Use appropriate PERSONAL PROTECTIVE EQUIPMENT during clean-up.

Ventilate area, especially low or enclosed places where heavy vapors might collect. Remove open flames. Use self-contained breathing apparatus (SCBA) if large spill or leak occurs.

HANDLING AND STORAGE

Handling (Personnel)

Use with sufficient ventilation to keep employee exposure below recommended limits.

Handling (Physical Aspects)

HFC-134a should not be mixed with air for leak testing or used for any other purpose above atmospheric pressure. See Flammable Properties section. Contact with chlorine or other strong oxidizing agents should also be avoided.

Storage

Store in a clean, dry place. Do not heat above 52 C (126 F).

EXPOSURE CONTROLS/PERSONAL PROTECTION

Engineering Controls

Normal ventilation for standard manufacturing procedures is generally adequate. Local exhaust should be used when large amounts are released. Mechanical ventilation should be used in low or enclosed places. Refrigerant concentration monitors may be necessary to determine vapor concentrations in work areas prior to use of torches or other open flames, or if employees are entering enclosed areas.

Personal Protective Equipment

Impervious gloves and chemical splash goggles should be used when handling liquid.

Under normal manufacturing conditions, no respiratory protection is required when using this product.

Self-contained breathing apparatus (SCBA) is required if a large release occurs.

Exposure Guidelines

Exposure Limits
"DYMEL" 134a

PEL (OSHA)	: None Established
TLV (ACGIH)	: None Established
AEL * (DuPont)	: 1000 ppm, 8 & 12 Hr. TWA
WEEL (AIHA)	: 1000 ppm, 8 Hr. TWA

* AEL is DuPont's Acceptable Exposure Limit. Where governmentally imposed occupational exposure limits which are lower than the AEL are in effect, such limits shall take precedence.

PHYSICAL AND CHEMICAL PROPERTIES

Physical Data

Boiling Point	: -26.5 C (-15.7 F) @ 736 mm Hg
Vapor Pressure	: 96 psia @ 25 C (77 F)
Vapor Density	: 3.6 (Air=1.0) @ 25 C (77 F)
% Volatiles	: 100 WT%
Solubility in Water	: 0.15 WT% @ 25 C (77 F) @ 14.7 psia
Odor	: Ether (slight).
Form	: Liquified Gas.
Color	: Colorless.
Liquid Density	: 1.21 g/cm3 @ 25 C (77 F)
Specific Gravity	: 1.208 @ 77 F (25 C)

Evaporation Rate : (CCL4 = 1); greater than 1

STABILITY AND REACTIVITY

Chemical Stability

Stable.

Conditions to Avoid

Avoid open flames and high temperatures.

Incompatibility with Other Materials

Incompatible with alkali or alkaline earth metals - powdered Al, Zn, Be, etc.

Decomposition

Decomposition products are hazardous. This material can be decomposed by high temperatures (open flames, glowing metal surfaces, etc.) forming hydrofluoric acid and possibly carbonyl fluoride.

These materials are toxic and irritating. Contact should be avoided.

Polymerization

Polymerization will not occur.

TOXICOLOGICAL INFORMATION

Animal Data

ETHANE, 1,1,1,2-TETRAFLUORO-

EYE:

A short duration spray of vapor produced very slight eye irritation.

SKIN:

Animal testing indicates this material is a slight skin irritant, but not a skin sensitizer.

INHALATION:

4 hour, ALC, rat: 567,000 ppm.

Single exposure caused: Cardiac sensitization, a potentially fatal disturbance of heart rhythm associated with a heightened sensitivity to the action of epinephrine. Lowest-Observed-Adverse-Effect-Level for cardiac sensitization: 75,000 ppm. Single exposure caused: Lethargy. Narcosis. Increased respiratory rates. These effects were temporary. Single exposure to near lethal doses caused: Pulmonary edema. Repeated exposure caused: Increased adrenals, liver, spleen weight. Decreased uterine, prostate weight. Repeated dosing of higher concentrations caused: the following temporary effects -

Tremors. Incoordination.

CARCINOGENIC, DEVELOPMENTAL, REPRODUCTIVE, MUTAGENIC EFFECTS:

In a two-year inhalation study, HFC-134a, at a concentration of 50,000 ppm, produced an increase in late-occurring benign testicular tumors, testicular hyperplasia and testicular weight. The no-effect-level for this study was 10,000 ppm. Animal data show slight fetotoxicity but only at exposure levels producing other toxic effects in the adult animal. Reproductive data on male mice show: No change in reproductive performance. Tests have shown that this material does not cause genetic damage in bacterial or mammalian cell cultures, or in animals. In animal testing, this material has not caused permanent genetic damage in reproductive cells of mammals (has not produced heritable genetic damage).

ECOLOGICAL INFORMATION

Ecotoxicological Information

AQUATIC TOXICITY:
48 hour EC50 - Daphnia magna: 980 mg/L.
96 hour LC50 - Rainbow trout: 450 mg/L

DISPOSAL CONSIDERATIONS

Waste Disposal

Contaminated HFC-134a can be recovered by distillation or removed to a permitted waste disposal facility. Comply with Federal, State, and local regulations.

TRANSPORTATION INFORMATION

Shipping Information

DOT/IMO

Proper Shipping Name	: 1,1,1,2-TETRAFLUOROETHANE
Hazard Class	: 2.2
UN No.	: 3159
DOT/IMO Label	: NONFLAMMABLE GAS

Shipping Containers

Tank Cars.
Tank Trucks.
Ton Tanks.
Cylinders.

REGULATORY INFORMATION

U.S. Federal Regulations

TSCA Inventory Status : Reported/Included.

TITLE III HAZARD CLASSIFICATIONS SECTIONS 311, 312

Acute : Yes
Chronic : Yes
Fire : No
Reactivity : No
Pressure : Yes

HAZARDOUS CHEMICAL LISTS

SARA Extremely Hazardous Substance: No
CERCLA Hazardous Substance : No
SARA Toxic Chemical : No

OTHER INFORMATION

NFPA, NPCA-HMIS

NPCA-HMIS Rating
Health : 1
Flammability : 0
Reactivity : 1

Personal Protection rating to be supplied by user depending on use conditions.

Additional Information

MEDICAL USE: CAUTION: Do not use in medical applications involving permanent implantation in the human body. For other medical applications see DuPont CAUTION Bulletin No. H-50102.

The data in this Material Safety Data Sheet relates only to the specific material designated herein and does not relate to use in combination with any other material or in any process.

Responsibility for MSDS : MSDS Coordinator
> : DuPont Fluoroproducts
Address : Wilmington, DE 19898
Telephone : (800) 441-7515

# Indicates updated section.

End of MSDS

Appendix 2 Refrigerant Properties[a]

Table 10 – Thermodynamic Properties of 22

Temp	Pressure	Density	Volume	Enthalpy		Entropy		Specific Heat		Sound Spd.		Viscosity		Therm. Cond.	
[F]	[psia]	[lb/ft^3]	[ft^3/lb]	[Btu/R-lb]		[Btu/R-lb]		[Btu/lb-°F]		[ft/s]		[lbm/ft-h]		[Btu/h-ft-R]	
		(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	V)	(L)	(V)
-150	0.2627	98.28	146.1	-28.12	87.57	-0.07757	0.296	0.2536	0.1185	3716	469.7	2.0916	0.017424	0.0831	0.00255
-145	0.34	97.82	114.6	-26.85	88.15	-0.07351	0.2919	0.2536	0.1194	3673	473	1.98	0.017712	0.08223	0.00261
-140	0.4359	97.36	90.76	-25.58	88.73	-0.06951	0.2881	0.2536	0.1204	3630	476.2	1.8756	0.018	0.08137	0.00267
-135	0.554	96.9	72.49	-24.31	89.31	-0.06557	0.2844	0.2536	0.1213	3587	479.3	1.7784	0.018288	0.08052	0.00274
-130	0.6981	96.44	58.38	-23.05	89.9	-0.0617	0.2809	0.2536	0.1223	3544	482.4	1.692	0.01854	0.07967	0.0028
-125	0.8725	95.98	47.39	-21.78	90.49	-0.05788	0.2776	0.2537	0.1233	3501	485.5	1.6128	0.018828	0.07883	0.00286
-120	1.082	95.52	38.75	-20.51	91.07	-0.05412	0.2744	0.2537	0.1244	3458	488.5	1.5372	0.019116	0.07799	0.00293
-115	1.332	95.06	31.9	-19.24	91.66	-0.05041	0.2714	0.2538	0.1254	3415	491.4	1.4688	0.019404	0.07717	0.003
-110	1.629	94.59	26.44	-17.97	92.25	-0.04675	0.2685	0.254	0.1265	3373	494.2	1.404	0.019692	0.07635	0.00306
-105	1.979	94.13	22.06	-16.7	92.84	-0.04315	0.2657	0.2541	0.1276	3330	497	1.3464	0.01998	0.07553	0.00313
-100	2.388	93.66	18.51	-15.43	93.43	-0.03959	0.2631	0.2543	0.1288	3287	499.7	1.2888	0.020268	0.07472	0.0032
-95	2.865	93.19	15.62	-14.15	94.02	-0.03608	0.2606	0.2546	0.13	3245	502.4	1.2384	0.020556	0.07392	0.00327
-90	3.417	92.71	13.26	-12.88	94.61	-0.03261	0.2582	0.2549	0.1312	3202	504.9	1.188	0.020844	0.07312	0.00334
-85	4.053	92.24	11.31	-11.6	95.19	-0.02918	0.2559	0.2552	0.1324	3160	507.4	1.1448	0.021132	0.07232	0.00341
-80	4.782	91.76	9.694	-10.33	95.78	-0.0258	0.2537	0.2556	0.1337	3118	509.8	1.1016	0.02142	0.07153	0.00348
-75	5.615	91.28	8.349	-9.046	96.36	-0.02245	0.2516	0.2561	0.135	3075	512.2	1.0584	0.021672	0.07075	0.00355
-70	6.561	90.79	7.222	-7.763	96.94	-0.01915	0.2495	0.2566	0.1363	3033	514.4	1.0224	0.02196	0.06997	0.00363
-65	7.631	90.31	6.274	-6.477	97.51	-0.01587	0.2476	0.2571	0.1377	2990	516.5	0.9864	0.022248	0.0692	0.0037
-60	8.836	89.82	5.473	-5.189	98.09	-0.01264	0.2458	0.2577	0.1392	2948	518.6	0.9504	0.022536	0.06843	0.00378
-55	10.19	89.33	4.792	-3.897	98.66	-0.00943	0.244	0.2583	0.1406	2906	520.5	0.918	0.022824	0.06766	0.00386
-50	11.7	88.83	4.212	-2.602	99.22	-0.00626	0.2423	0.2591	0.1422	2863	522.4	0.8856	0.023112	0.0669	0.00394
-45	13.39	88.33	3.715	-1.303	99.79	-0.00311	0.2407	0.2598	0.1438	2821	524.1	0.8568	0.0234	0.06614	0.00402
-41.46	14.67	98.97	3.4054	-0.381	100.343	0-.00091	0.2395	0.2604	0.1449	2791	525.3	0.837	0.0237	0.0656	0.00407
-40	15.26	87.82	3.287	0	100.3	0	0.2391	0.2606	0.1454	2778	525.8	0.828	0.023688	0.06539	0.0041
-35	17.34	87.32	2.918	1.308	100.9	0.00309	0.2376	0.2615	0.1471	2736	527.3	0.8028	0.02394	0.06464	0.00418
-30	19.62	86.8	2.598	2.62	101.4	0.00615	0.2361	0.2625	0.1488	2694	528.7	0.7776	0.024228	0.06389	0.00426
-25	22.14	86.29	2.32	3.937	102	0.00918	0.2348	0.2635	0.1506	2651	530	0.7524	0.024516	0.06315	0.00435
-20	24.91	85.76	2.078	5.26	102.5	0.0122	0.2334	0.2645	0.1525	2609	531.2	0.7272	0.024804	0.06241	0.00444
-15	27.93	85.24	1.866	6.588	103	0.01519	0.2321	0.2656	0.1544	2566	532.3	0.7056	0.025092	0.06167	0.00452
-10	31.23	84.71	1.679	7.923	103.6	0.01815	0.2309	0.2668	0.1564	2524	533.2	0.684	0.02538	0.06093	0.00461
-5	34.82	84.17	1.515	9.263	104.1	0.0211	0.2296	0.2681	0.1585	2481	534	0.6624	0.025668	0.0602	0.00471
0	38.73	83.63	1.37	10.61	104.6	0.02403	0.2285	0.2694	0.1607	2438	534.7	0.6408	0.025956	0.05947	0.0048
5	42.96	83.08	1.242	11.96	105.1	0.02694	0.2273	0.2708	0.1629	2396	535.3	0.6228	0.026244	0.05874	0.00489
10	47.54	82.52	1.128	13.33	105.6	0.02983	0.2263	0.2722	0.1652	2353	535.7	0.6048	0.026532	0.05802	0.00499
15	52.48	81.96	1.026	14.69	106.1	0.0327	0.2252	0.2737	0.1676	2310	536	0.5868	0.02682	0.05729	0.00509
20	57.79	81.39	0.9354	16.07	106.5	0.03556	0.2242	0.2753	0.1702	2268	536.1	0.5688	0.027108	0.05657	0.00519
25	63.51	80.82	0.8543	17.46	107	0.03841	0.2231	0.277	0.1728	2225	536.1	0.5508	0.027396	0.05585	0.0053
30	69.65	80.24	0.7815	18.85	107.4	0.04124	0.2222	0.2787	0.1755	2182	535.9	0.5328	0.02772	0.05513	0.0054
35	76.22	79.65	0.7161	20.25	107.9	0.04406	0.2212	0.2806	0.1783	2139	535.6	0.5184	0.028008	0.05441	0.00551
40	83.26	79.05	0.6572	21.66	108.3	0.04686	0.2203	0.2825	0.1813	2096	535.1	0.504	0.028296	0.05369	0.00562
45	90.76	78.44	0.604	23.08	108.7	0.04966	0.2194	0.2845	0.1844	2053	534.4	0.4896	0.02862	0.05297	0.00574
50	98.76	77.83	0.5558	24.51	109.1	0.05244	0.2185	0.2866	0.1877	2010	533.6	0.4716	0.028908	0.05225	0.00586
55	107.3	77.2	0.5122	25.96	109.5	0.05522	0.2176	0.2889	0.1911	1967	532.6	0.4608	0.029232	0.05153	0.00598
60	116.3	76.57	0.4725	27.41	109.9	0.05798	0.2167	0.2913	0.1947	1924	531.5	0.4464	0.029556	0.05081	0.00611
65	125.9	75.92	0.4364	28.87	110.3	0.06074	0.2159	0.2938	0.1985	1880	530.1	0.432	0.02988	0.05009	0.00625
70	136.1	75.27	0.4035	30.35	110.6	0.0635	0.215	0.2964	0.2025	1836	528.6	0.4176	0.030204	0.04937	0.00638
75	146.9	74.6	0.3734	31.84	110.9	0.06625	0.2142	0.2992	0.2067	1793	526.9	0.4068	0.030564	0.04865	0.00653
80	158.3	73.92	0.3459	33.34	111.2	0.06899	0.2133	0.3022	0.2112	1749	525	0.3924	0.030888	0.04793	0.00668
85	170.4	73.23	0.3207	34.86	111.5	0.07173	0.2125	0.3054	0.216	1705	522.9	0.3816	0.031248	0.04721	0.00684
90	183.1	72.52	0.2975	36.39	111.8	0.07447	0.2117	0.3089	0.2212	1660	520.6	0.3708	0.031608	0.04649	0.00701
95	196.5	71.8	0.2762	37.94	112	0.07721	0.2108	0.3126	0.2267	1615	518.1	0.3564	0.032004	0.04576	0.00718
100	210.6	71.06	0.2566	39.5	112.3	0.07996	0.21	0.3166	0.2327	1570	515.3	0.3456	0.032364	0.04503	0.00737
105	225.5	70.3	0.2385	41.08	112.5	0.0827	0.2091	0.3209	0.2391	1525	512.4	0.3348	0.032796	0.0443	0.00757
110	241.1	69.52	0.2217	42.69	112.7	0.08545	0.2083	0.3257	0.2461	1479	509.2	0.324	0.033192	0.04357	0.00778
115	257.5	68.72	0.2062	44.31	112.8	0.08821	0.2074	0.3309	0.2538	1433	505.8	0.3132	0.03366	0.04283	0.00801
120	274.7	67.9	0.1918	45.95	112.9	0.09098	0.2065	0.3367	0.2623	1387	502.1	0.3024	0.034092	0.04209	0.00825
125	292.7	67.05	0.1785	47.62	113	0.09376	0.2056	0.3431	0.2717	1340	498.1	0.2916	0.034596	0.04135	0.00851
130	311.6	66.18	0.166	49.32	113	0.09656	0.2046	0.3504	0.2822	1292	493.9	0.2808	0.0351	0.0406	0.0088
135	331.4	65.27	0.1544	51.04	113	0.09937	0.2036	0.3585	0.2941	1244	489.4	0.27	0.03564	0.03985	0.00911
140	352.1	64.32	0.1435	52.8	113	0.1022	0.2026	0.3679	0.3076	1195	484.6	0.2592	0.036216	0.0391	0.00946
145	373.7	63.34	0.1334	54.59	112.9	0.1051	0.2015	0.3787	0.3233	1146	479.5	0.2484	0.036864	0.03834	0.00984
150	396.4	62.31	0.1238	56.42	112.8	0.108	0.2004	0.3913	0.3416	1095	474.1	0.2412	0.037548	0.03759	0.01027
155	420	61.22	0.1149	58.31	112.5	0.111	0.1992	0.4063	0.3633	1044	468.4	0.2304	0.038268	0.03683	0.01076
160	444.7	60.07	0.1064	60.24	112.2	0.114	0.1979	0.4243	0.3897	992.3	462.3	0.2196	0.039096	0.03608	0.01131
165	470.6	58.84	0.09836	62.24	111.9	0.1171	0.1965	0.4467	0.4225	939	455.8	0.2088	0.039996	0.03535	0.01195
170	497.5	57.53	0.09072	64.31	111.4	0.1202	0.195	0.475	0.4643	884.3	449	0.198	0.04104	0.03464	0.0127
175	525.6	56.1	0.0834	66.47	110.8	0.1235	0.1933	0.5124	0.5198	827.8	441.6	0.1872	0.042192	0.034	0.0136
180	555	54.52	0.07635	68.76	110	0.1269	0.1914	0.5641	0.5972	768.8	433.9	0.1764	0.043596	0.03347	0.0147
185	585.6	52.74	0.06948	71.2	109	0.1306	0.1892	0.641	0.7132	706.5	425.6	0.1656	0.045252	0.03318	0.01609
190	617.6	50.67	0.06265	73.86	107.7	0.1345	0.1865	0.7681	0.9067	639.3	416.6	0.1512	0.04734	0.03338	0.01793
195	651.1	48.14	0.05565	76.88	105.8	0.1389	0.1832	1.02	1.295	565.2	406.9	0.1368	0.05022	0.03474	0.02061
200	686.2	44.68	0.0479	80.59	103	0.1444	0.1784	1.778	2.472	480.1	395.8	0.1224	0.05472	0.03946	0.02574
205.06	723.7	32.70	.0.0306	91.21	91.21	0.1601	0.1601	∞	∞∞	0.0	0.0	-	-	∞	∞

[a] NIST *Refprop*, NIST Standard Reference Database 23 – Version 6.01.

Table 11 – Thermodynamic Properties of 123

Temp	Pressure	Density	Volume	Enthalpy		Entropy		Specific Heat		Sound Spd.		Viscosity		Therm. Cond.	
[F]	[psia]	[lb/ft^3]	[ft^3/lb]	[Btu/R-lb]		[Btu/R-lb]		[Btu/lb-°F]		[ft/s]		[lbm/ft-h]		[Btu/h-ft-R]	
		(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	V)	(L)	(V)
-140	0.00302	108.9	7432	-22.24	71.78	-0.0605	0.2336	0.221	0.1181	3928	341.7	0	0.00000	0	0
-135	0.00427	108.5	5331	-21.14	72.38	-0.05707	0.231	0.2208	0.1192	3891	344.2	0	0.00000	0.06687	0.00425
-130	0.00598	108.1	3871	-20.03	72.97	-0.0537	0.2284	0.2207	0.1203	3854	346.6	0	0.00000	0.06642	0.00435
-125	0.00826	107.7	2843	-18.93	73.58	-0.05037	0.226	0.2207	0.1215	3816	349	0	0.00000	0.06317	0.00162
-120	0.01129	107.3	2112	-17.83	74.19	-0.0471	0.2238	0.2206	0.1226	3778	351.4	0	0.00000	0.06275	0.00171
-115	0.01526	107	1585	-16.72	74.8	-0.04388	0.2217	0.2207	0.1237	3740	353.8	0	0.00000	0.06233	0.00181
-110	0.02043	106.6	1201	-15.62	75.42	-0.0407	0.2197	0.2208	0.1248	3702	356.2	0	0.00000	0.06192	0.0019
-105	0.02707	106.2	918.9	-14.51	76.05	-0.03756	0.2178	0.2209	0.1259	3664	358.5	0	0.01690	0.0615	0.00199
-100	0.03556	105.8	709.5	-13.41	76.68	-0.03447	0.216	0.2211	0.127	3626	360.8	0	0.01714	0.06108	0.00208
-95	0.04629	105.4	552.5	-12.3	77.31	-0.03141	0.2143	0.2214	0.1281	3587	363.1	0	0.01739	0.06065	0.00217
-90	0.05975	105	433.8	-11.2	77.95	-0.0284	0.2128	0.2217	0.1291	3549	365.4	5.112	0.01763	0.06022	0.00226
-85	0.07651	104.6	343.3	-10.09	78.59	-0.02542	0.2113	0.222	0.1302	3510	367.6	4.68	0.01788	0.05978	0.00235
-80	0.09721	104.3	273.8	-8.975	79.24	-0.02247	0.2099	0.2224	0.1313	3472	369.9	4.284	0.01812	0.05934	0.00244
-75	0.1226	103.9	219.9	-7.862	79.9	-0.01956	0.2086	0.2228	0.1324	3433	372.1	3.96	0.01837	0.05888	0.00254
-70	0.1536	103.5	177.8	-6.746	80.56	-0.01668	0.2074	0.2233	0.1334	3394	374.3	3.672	0.01862	0.05842	0.00263
-65	0.191	103.1	144.7	-5.629	81.22	-0.01383	0.2062	0.2238	0.1345	3356	376.4	3.42	0.01886	0.05796	0.00272
-60	0.236	102.7	118.6	-4.509	81.89	-0.01101	0.2052	0.2243	0.1356	3317	378.5	3.204	0.01911	0.05749	0.00281
-55	0.2899	102.3	97.72	-3.386	82.56	-0.00821	0.2042	0.2248	0.1366	3279	380.7	2.988	0.01935	0.05701	0.0029
-50	0.3539	101.9	81	-2.26	83.23	-0.00545	0.2032	0.2254	0.1377	3240	382.7	2.808	0.01960	0.05653	0.00299
-45	0.4296	101.5	67.52	-1.132	83.91	-0.00271	0.2024	0.226	0.1388	3202	384.8	2.664	0.01984	0.05604	0.00308
-40	0.5185	101.1	56.58	0	84.59	0	0.2016	0.2266	0.1398	3164	386.8	2.52	0.02009	0.05555	0.00317
-35	0.6226	100.7	47.65	1.135	85.28	0.00269	0.2008	0.2272	0.1409	3126	388.8	2.376	0.02033	0.05505	0.00326
-30	0.7438	100.3	40.33	2.272	85.97	0.00535	0.2001	0.2279	0.142	3087	390.7	2.268	0.02058	0.05455	0.00335
-25	0.8843	99.94	34.3	3.414	86.66	0.00799	0.1995	0.2285	0.143	3049	392.7	2.088	0.02089	0.05405	0.00344
-20	1.046	99.54	29.3	4.558	87.35	0.01061	0.1989	0.2292	0.1441	3012	394.5	2.016	0.02115	0.05355	0.00353
-15	1.232	99.14	25.14	5.706	88.05	0.0132	0.1984	0.2299	0.1452	2974	396.4	1.944	0.02141	0.05305	0.00362
-10	1.445	98.73	21.66	6.857	88.75	0.01578	0.1979	0.2306	0.1463	2936	398.2	1.872	0.02167	0.05255	0.00371
-5	1.688	98.33	18.73	8.012	89.46	0.01833	0.1975	0.2313	0.1473	2899	399.9	1.8	0.02193	0.05205	0.00381
0	1.963	97.92	16.26	9.17	90.16	0.02086	0.1971	0.232	0.1484	2862	401.7	1.728	0.02218	0.05155	0.0039
5	2.274	97.51	14.17	10.33	90.87	0.02337	0.1967	0.2327	0.1495	2825	403.3	1.656	0.02244	0.05105	0.00399
10	2.625	97.1	12.4	11.5	91.58	0.02587	0.1964	0.2334	0.1506	2788	405	1.584	0.02269	0.05055	0.00408
15	3.019	96.69	10.88	12.67	92.29	0.02834	0.1961	0.2341	0.1517	2751	406.6	1.548	0.02295	0.05005	0.00417
20	3.46	96.28	9.578	13.84	93.01	0.0308	0.1958	0.2349	0.1528	2714	408.1	1.476	0.02320	0.04956	0.00426
25	3.952	95.86	8.459	15.02	93.72	0.03324	0.1956	0.2356	0.154	2678	409.6	1.44	0.02345	0.04907	0.00435
30	4.499	95.44	7.494	16.2	94.44	0.03566	0.1954	0.2364	0.1551	2641	411	1.368	0.02370	0.04858	0.00444
35	5.107	95.02	6.659	17.38	95.16	0.03806	0.1953	0.2371	0.1562	2605	412.4	1.332	0.02395	0.04809	0.00453
40	5.778	94.6	5.933	18.57	95.88	0.04045	0.1952	0.2379	0.1574	2569	413.7	1.296	0.02420	0.04761	0.00462
45	6.519	94.17	5.3	19.76	96.6	0.04282	0.1951	0.2387	0.1585	2533	414.9	1.26	0.02444	0.04714	0.00471
50	7.334	93.74	4.747	20.96	97.32	0.04518	0.195	0.2394	0.1597	2498	416.1	1.224	0.02469	0.04666	0.00481
55	8.229	93.31	4.263	22.16	98.04	0.04752	0.195	0.2402	0.1609	2462	417.3	1.152	0.02493	0.04619	0.0049
60	9.208	92.88	3.837	23.36	98.76	0.04984	0.1949	0.241	0.1621	2427	418.3	1.116	0.02517	0.04573	0.00499
65	10.28	92.44	3.462	24.57	99.48	0.05215	0.1949	0.2418	0.1633	2392	419.4	1.08	0.02541	0.04527	0.00508
70	11.44	92.01	3.13	25.78	100.2	0.05444	0.1949	0.2426	0.1645	2357	420.3	1.044	0.02565	0.04481	0.00518
75	12.71	91.56	2.836	27	100.9	0.05673	0.195	0.2434	0.1657	2322	421.2	1.008	0.02588	0.04436	0.00527
80	14.09	91.12	2.575	28.22	101.6	0.05899	0.195	0.2442	0.1669	2287	422	1.008	0.02612	0.04391	0.00537
82.08	14.7	90.94	2.475	28.73	101.9	0.05993	0.195	0.2445	0.1951	2273	422.3	0.978	0.0262	0.0437	0.00540
85	15.58	90.67	2.343	29.44	102.4	0.06124	0.1951	0.245	0.1682	2252	422.7	0.972	0.02636	0.04347	0.00546
90	17.19	90.22	2.136	30.67	103.1	0.06348	0.1952	0.2458	0.1695	2218	423.3	0.936	0.02659	0.04304	0.00556
95	18.93	89.77	1.95	31.9	103.8	0.06571	0.1953	0.2467	0.1707	2184	423.9	0.9	0.02682	0.0426	0.00565
100	20.8	89.31	1.784	33.14	104.5	0.06792	0.1955	0.2475	0.172	2149	424.4	0.864	0.02705	0.04217	0.00575
105	22.82	88.85	1.635	34.38	105.2	0.07012	0.1956	0.2484	0.1734	2115	424.8	0.864	0.02728	0.04175	0.00585
110	24.98	88.39	1.501	35.63	106	0.07231	0.1958	0.2492	0.1747	2081	425.2	0.828	0.02751	0.04133	0.00595
115	27.3	87.92	1.379	36.88	106.7	0.07449	0.1959	0.2501	0.1761	2047	425.4	0.792	0.02775	0.04092	0.00604
120	29.78	87.45	1.27	38.13	107.4	0.07665	0.1961	0.251	0.1775	2014	425.6	0.756	0.02797	0.04051	0.00614
125	32.43	86.98	1.171	39.39	108.1	0.07881	0.1963	0.252	0.1789	1980	425.6	0.756	0.02820	0.04011	0.00625
130	35.25	86.5	1.081	40.66	108.8	0.08095	0.1965	0.2529	0.1803	1946	425.6	0.72	0.02843	0.03971	0.00635
135	38.26	86.01	0.9996	41.93	109.5	0.08308	0.1967	0.2539	0.1818	1913	425.5	0.72	0.02866	0.03931	0.00645
140	41.46	85.52	0.9253	43.2	110.2	0.0852	0.1969	0.2548	0.1833	1879	425.3	0.684	0.02888	0.03892	0.00656
145	44.87	85.03	0.8577	44.48	110.9	0.08732	0.1972	0.2559	0.1848	1846	425	0.684	0.02911	0.03853	0.00666
150	48.48	84.53	0.7959	45.76	111.6	0.08942	0.1974	0.2569	0.1863	1813	424.6	0.648	0.02934	0.03815	0.00677
160	56.36	83.52	0.6876	48.35	113	0.09359	0.1979	0.2591	0.1896	1746	423.5	0.612	0.02980	0.03739	0.00699
170	65.17	82.49	0.5965	50.95	114.3	0.09773	0.1984	0.2614	0.1929	1680	422	0.576	0.03026	0.03665	0.00722
180	74.99	81.43	0.5195	53.58	115.7	0.1018	0.1989	0.2638	0.1965	1614	420.1	0.54	0.03073	0.03592	0.00745
190	85.87	80.34	0.4539	56.24	117	0.1059	0.1995	0.2665	0.2004	1548	417.7	0.504	0.03122	0.0352	0.00769
200	97.89	79.23	0.3979	58.92	118.3	0.11	0.2	0.2694	0.2045	1482	414.7	0.504	0.03171	0.03449	0.00795
210	111.1	78.08	0.3497	61.63	119.6	0.114	0.2005	0.2726	0.2089	1416	411.3	0.468	0.03223	0.03378	0.00821
220	125.7	76.89	0.308	64.37	120.8	0.118	0.2011	0.2761	0.2138	1349	407.3	0.432	0.03279	0.03309	0.00849
230	141.6	75.66	0.2719	67.14	122	0.122	0.2016	0.28	0.2191	1283	402.8	0.396	0.03338	0.0324	0.00877
240	158.9	74.38	0.2404	69.95	123.2	0.126	0.2021	0.2845	0.2251	1216	397.6	0.396	0.03401	0.03171	0.00908
250	177.8	73.04	0.2128	72.8	124.3	0.13	0.2025	0.2896	0.2319	1148	391.7	0.36	0.03471	0.03102	0.0094
260	198.3	71.64	0.1885	75.7	125.4	0.134	0.203	0.2956	0.2398	1080	385.1	0.36	0.03549	0.03032	0.00974
270	220.5	70.16	0.167	78.65	126.4	0.1379	0.2033	0.3026	0.249	1012	377.7	0.324	0.03638	0.02963	0.0101
280	244.6	68.6	0.1479	81.67	127.3	0.142	0.2036	0.311	0.2603	942	369.4	0.324	0.03740	0.02892	0.0105
290	270.5	66.92	0.1309	84.75	128.1	0.146	0.2039	0.3215	0.2742	871.5	360.2	0.288	0.03859	0.0282	0.01092
300	298.5	65.11	0.1155	87.92	128.9	0.1501	0.204	0.3349	0.2922	799.6	349.9	0.288	0.04002	0.02746	0.01139
310	328.7	63.12	0.1016	91.19	129.4	0.1543	0.2039	0.3529	0.3166	726.1	338.5	0.252	0.04179	0.02671	0.01191
320	361.2	60.91	0.08887	94.59	129.8	0.1585	0.2037	0.3785	0.352	650.3	325.7	0.252	0.04401	0.02593	0.01251
330	396.1	58.37	0.07704	98.19	130	0.163	0.2032	0.4186	0.4084	571.4	311.5	0.216	0.04694	0.02511	0.01321
340	433.8	55.33	0.06578	102.1	129.7	0.1677	0.2022	0.4925	0.5138	487.9	295.4	0.18	0.05104	0.02427	0.01411
350	474.4	51.32	0.05444	106.5	128.6	0.173	0.2004	0.683	0.7861	396.8	277	0.18	0.05754	0.02343	0.01539
360	518.7	43.97	0.04031	112.7	125.1	0.1804	0.1955	2.507	3.263	289.8	255.2	0.144	0.07301	0.02269	0.01819
362.63	531.10	34.34	0.0291	118.8	118.8	0.1877	0.1877	∞	∞	0.0	0.0	-	-	∞	∞

Table 12 – Thermodynamic Properties of 134a

Temp	Pressure	Density	Volume	Enthalpy		Entropy		Specific Heat		Sound Spd.		Viscosity		Therm. Cond.	
[F]	[psia]	[lb/ft^3]	[ft^3/lb]	[Btu/R-lb]		[Btu/R-lb]		[Btu/lb-°F]		[ft/s]		[lbm/ft-h]		[Btu/h-ft-R]	
		(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	V)	(L)	(V)
-153.5	0.057	99.34	564.85	-32.99	80.36	-0.09154	.2793	0.283	0.1399	3723	416	5.262	0.0156	0.084	0.00178
-150	0.072	98.97	452.1	-31.88	80.91	-0.08791	0.2763	0.283	0.1411	3638	418.3	4.7916	0.01584	0.0832	0.00188
-145	0.0968	98.51	341.4	-30.46	81.6	-0.08338	0.2728	0.2832	0.1427	3592	421.3	4.2912	0.016128	0.08223	0.00201
-140	0.1288	98.05	260.6	-29.05	82.3	-0.07891	0.2694	0.2834	0.1443	3545	424.2	3.8808	0.016452	0.08126	0.00214
-135	0.1696	97.59	201	-27.63	83.01	-0.07451	0.2663	0.2838	0.1459	3499	427.1	3.5352	0.01674	0.08031	0.00227
-130	0.221	97.13	156.5	-26.21	83.73	-0.07017	0.2633	0.2842	0.1475	3452	429.9	3.24	0.017028	0.07936	0.0024
-125	0.2854	96.66	123	-24.79	84.44	-0.06589	0.2605	0.2847	0.1491	3406	432.7	2.9844	0.017316	0.07843	0.00253
-120	0.3653	96.2	97.48	-23.36	85.17	-0.06166	0.2578	0.2853	0.1508	3360	435.4	2.7612	0.017604	0.07751	0.00265
-115	0.4635	95.73	77.91	-21.93	85.9	-0.05749	0.2554	0.2859	0.1524	3314	438.2	2.5668	0.017892	0.0766	0.00278
-110	0.5833	95.27	62.76	-20.5	86.63	-0.05337	0.253	0.2866	0.154	3269	440.8	2.394	0.01818	0.0757	0.00291
-105	0.7284	94.8	50.94	-19.07	87.37	-0.04929	0.2508	0.2874	0.1557	3223	443.4	2.2428	0.018468	0.0748	0.00304
-100	0.903	94.33	41.64	-17.63	88.11	-0.04527	0.2487	0.2881	0.1573	3178	446	2.106	0.01872	0.07392	0.00317
-95	1.111	93.85	34.27	-16.18	88.85	-0.04128	0.2467	0.2889	0.159	3132	448.5	1.98	0.019008	0.07304	0.0033
-90	1.359	93.38	28.38	-14.74	89.6	-0.03734	0.2449	0.2898	0.1607	3087	450.9	1.8684	0.019296	0.07217	0.00343
-85	1.651	92.9	23.65	-13.28	90.35	-0.03344	0.2432	0.2907	0.1624	3043	453.3	1.7676	0.019584	0.07132	0.00356
-80	1.993	92.42	19.83	-11.83	91.1	-0.02959	0.2415	0.2916	0.1641	2998	455.6	1.674	0.019872	0.07047	0.00369
-75	2.392	91.94	16.71	-10.37	91.86	-0.02577	0.24	0.2925	0.1658	2954	457.8	1.5876	0.02016	0.06962	0.00382
-70	2.854	91.46	14.16	-8.903	92.61	-0.02198	0.2385	0.2935	0.1676	2909	460	1.5084	0.020412	0.06879	0.00395
-65	3.389	90.97	12.06	-7.432	93.37	-0.01824	0.2372	0.2945	0.1694	2866	462.1	1.4364	0.0207	0.06796	0.00408
-60	4.002	90.49	10.32	-5.957	94.13	-0.01452	0.2359	0.2955	0.1713	2822	464.1	1.368	0.020988	0.06714	0.0042
-55	4.703	90	8.873	-4.476	94.89	-0.01085	0.2347	0.2965	0.1731	2778	466	1.3068	0.02124	0.06633	0.00433
-50	5.501	89.5	7.662	-2.989	95.65	-0.0072	0.2336	0.2976	0.1751	2735	467.8	1.2492	0.021528	0.06553	0.00446
-45	6.406	89	6.644	-1.498	96.41	-0.00358	0.2325	0.2987	0.177	2691	469.6	1.1916	0.02178	0.06473	0.0046
-40	7.427	88.5	5.784	0	97.17	0	0.2315	0.2999	0.179	2648	471.2	1.1412	0.022068	0.06394	0.00473
-35	8.576	88	5.054	1.503	97.92	0.00356	0.2306	0.301	0.1811	2605	472.8	1.0944	0.022356	0.06316	0.00486
-30	9.862	87.49	4.433	3.013	98.68	0.00708	0.2297	0.3022	0.1832	2563	474.2	1.0512	0.022608	0.06238	0.00499
-25	11.3	86.98	3.901	4.529	99.43	0.01058	0.2289	0.3035	0.1853	2520	475.6	1.008	0.022896	0.06161	0.00512
-20	12.9	86.47	3.445	6.051	100.2	0.01406	0.2282	0.3047	0.1875	2477	476.8	0.9684	0.023148	0.06084	0.00525
-15	14.67	85.95	3.051	7.58	100.9	0.01751	0.2274	0.306	0.1898	2435	477.9	0.9288	0.023436	0.06009	0.00538
-14.9	14.69	85.94	3.047	7.600	101.0	0.01755	0.2273	0.3061	0.1898	2434	477.9	0.928	0.0234	0.06010	0.00486
-10	16.63	85.43	2.711	9.115	101.7	0.02093	0.2268	0.3074	0.1921	2393	478.9	0.8928	0.023688	0.05933	0.00552
-5	18.79	84.9	2.415	10.66	102.4	0.02433	0.2262	0.3088	0.1945	2350	479.8	0.8604	0.02394	0.05858	0.00565
0	21.17	84.37	2.158	12.21	103.2	0.02771	0.2256	0.3102	0.1969	2308	480.5	0.828	0.024228	0.05784	0.00578
5	23.78	83.83	1.933	13.76	103.9	0.03107	0.225	0.3117	0.1995	2266	481.1	0.7992	0.02448	0.0571	0.00592
10	26.63	83.29	1.736	15.33	104.6	0.0344	0.2245	0.3132	0.2021	2224	481.6	0.7704	0.024768	0.05637	0.00605
15	29.74	82.74	1.562	16.9	105.3	0.03772	0.224	0.3147	0.2047	2182	482	0.7416	0.02502	0.05564	0.00619
20	33.12	82.19	1.409	18.48	106.1	0.04101	0.2236	0.3164	0.2075	2140	482.2	0.7164	0.025308	0.05492	0.00632
25	36.8	81.63	1.274	20.07	106.8	0.04429	0.2232	0.3181	0.2103	2098	482.2	0.6876	0.02556	0.0542	0.00646
30	40.78	81.06	1.154	21.67	107.5	0.04755	0.2228	0.3198	0.2132	2056	482.2	0.666	0.025848	0.05348	0.0066
35	45.09	80.49	1.048	23.27	108.2	0.05079	0.2224	0.3216	0.2163	2014	481.9	0.6408	0.026136	0.05277	0.00674
40	49.74	79.9	0.9528	24.89	108.9	0.05402	0.2221	0.3235	0.2194	1973	481.5	0.6192	0.026388	0.05206	0.00688
45	54.75	79.32	0.868	26.51	109.5	0.05724	0.2217	0.3255	0.2226	1931	481	0.5976	0.026676	0.05136	0.00703
50	60.13	78.72	0.792	28.15	110.2	0.06044	0.2214	0.3275	0.226	1889	480.3	0.576	0.026964	0.05066	0.00717
55	65.91	78.11	0.7238	29.8	110.9	0.06362	0.2212	0.3297	0.2294	1847	479.4	0.558	0.027252	0.04996	0.00732
60	72.11	77.5	0.6625	31.45	111.5	0.0668	0.2209	0.3319	0.2331	1805	478.3	0.54	0.02754	0.04926	0.00747
65	78.73	76.87	0.6072	33.12	112.2	0.06996	0.2206	0.3343	0.2368	1763	477	0.522	0.027828	0.04857	0.00762
70	85.8	76.24	0.5572	34.8	112.8	0.07311	0.2204	0.3368	0.2408	1721	475.6	0.504	0.028116	0.04787	0.00777
75	93.35	75.59	0.512	36.49	113.4	0.07626	0.2201	0.3394	0.2449	1679	474	0.486	0.02844	0.04718	0.00793
80	101.4	74.94	0.471	38.2	114	0.07939	0.2199	0.3422	0.2492	1636	472.2	0.468	0.028764	0.04649	0.00809
85	109.9	74.27	0.4338	39.91	114.6	0.08252	0.2197	0.3451	0.2537	1594	470.1	0.4536	0.029052	0.04581	0.00825
90	119	73.58	0.3999	41.65	115.2	0.08565	0.2194	0.3482	0.2585	1551	467.9	0.4356	0.029376	0.04512	0.00842
95	128.6	72.88	0.369	43.39	115.7	0.08877	0.2192	0.3515	0.2636	1509	465.4	0.4212	0.029736	0.04443	0.0086
100	138.9	72.17	0.3407	45.15	116.3	0.09188	0.219	0.3551	0.269	1466	462.7	0.4068	0.03006	0.04374	0.00878
105	149.7	71.44	0.3148	46.93	116.8	0.095	0.2187	0.3589	0.2747	1423	459.8	0.3924	0.03042	0.04306	0.00897
110	161.1	70.69	0.2911	48.73	117.3	0.09811	0.2185	0.363	0.2809	1380	456.7	0.378	0.03078	0.04237	0.00916
115	173.1	69.93	0.2693	50.55	117.8	0.1012	0.2183	0.3675	0.2875	1337	453.2	0.3636	0.031176	0.04168	0.00936
120	185.9	69.14	0.2493	52.38	118.3	0.1044	0.218	0.3723	0.2948	1294	449.6	0.3528	0.031572	0.04099	0.00958
125	199.3	68.32	0.2308	54.24	118.7	0.1075	0.2177	0.3775	0.3026	1250	445.6	0.3384	0.031968	0.0403	0.00981
130	213.4	67.49	0.2137	56.12	119.1	0.1106	0.2174	0.3833	0.3112	1206	441.3	0.324	0.032436	0.03961	0.01005
135	228.3	66.62	0.198	58.02	119.5	0.1138	0.2171	0.3897	0.3208	1162	436.8	0.3132	0.032868	0.03891	0.01031
140	243.9	65.73	0.1833	59.95	119.8	0.1169	0.2167	0.3968	0.3315	1117	432	0.2988	0.033372	0.03821	0.01058
145	260.4	64.8	0.1697	61.92	120.1	0.1201	0.2163	0.4048	0.3435	1072	426.8	0.288	0.033876	0.03751	0.01089
150	277.6	63.83	0.1571	63.91	120.4	0.1233	0.2159	0.4138	0.3571	1027	421.2	0.2772	0.034452	0.0368	0.01122
155	295.7	62.82	0.1453	65.94	120.6	0.1265	0.2154	0.4242	0.3729	980.4	415.3	0.2628	0.035064	0.03609	0.01158
160	314.7	61.76	0.1343	68	120.7	0.1298	0.2149	0.4362	0.3914	933.5	409.1	0.252	0.035712	0.03537	0.01199
165	334.7	60.65	0.1239	70.12	120.8	0.1331	0.2143	0.4504	0.4134	885.7	402.4	0.2412	0.036432	0.03465	0.01245
170	355.5	59.47	0.1142	72.28	120.8	0.1364	0.2136	0.4675	0.44	836.8	395.3	0.2304	0.037224	0.03392	0.01297
175	377.4	58.21	0.1051	74.51	120.8	0.1399	0.2127	0.4887	0.4733	786.5	387.7	0.216	0.038124	0.0332	0.01358
180	400.3	56.86	0.09637	76.81	120.6	0.1433	0.2118	0.5156	0.5159	734.5	379.6	0.2052	0.039132	0.03247	0.0143
185	424.4	55.38	0.08808	79.19	120.3	0.1469	0.2107	0.5512	0.5729	680.5	371	0.1944	0.04032	0.03175	0.01516
190	449.5	53.76	0.08011	81.69	119.8	0.1507	0.2094	0.6012	0.6532	624.1	361.8	0.18	0.041724	0.03106	0.01623
195	475.9	51.91	0.07236	84.34	119.1	0.1546	0.2077	0.6768	0.7751	564.9	352	0.1692	0.043452	0.03044	0.0176
200	503.6	49.76	0.06466	87.21	118.1	0.1588	0.2056	0.8062	0.9835	502.5	341.3	0.1548	0.04572	0.02997	0.01949
205	532.7	47.08	0.05673	90.45	116.5	0.1635	0.2028	1.083	1.425	436	329.4	0.1404	0.048852	0.02996	0.0224
210	563.4	43.2	0.04769	94.53	113.7	0.1694	0.1981	2.113	3.008	363.4	315.5	0.120	0.0543	0.0316	0.02848
213.9	588.7	31.96	0.0313	103.89	103.89	0.1832	0.1832	∞	∞	0	0	∞	∞	∞	∞

Table 13 – Thermodynamic Properties of 407a

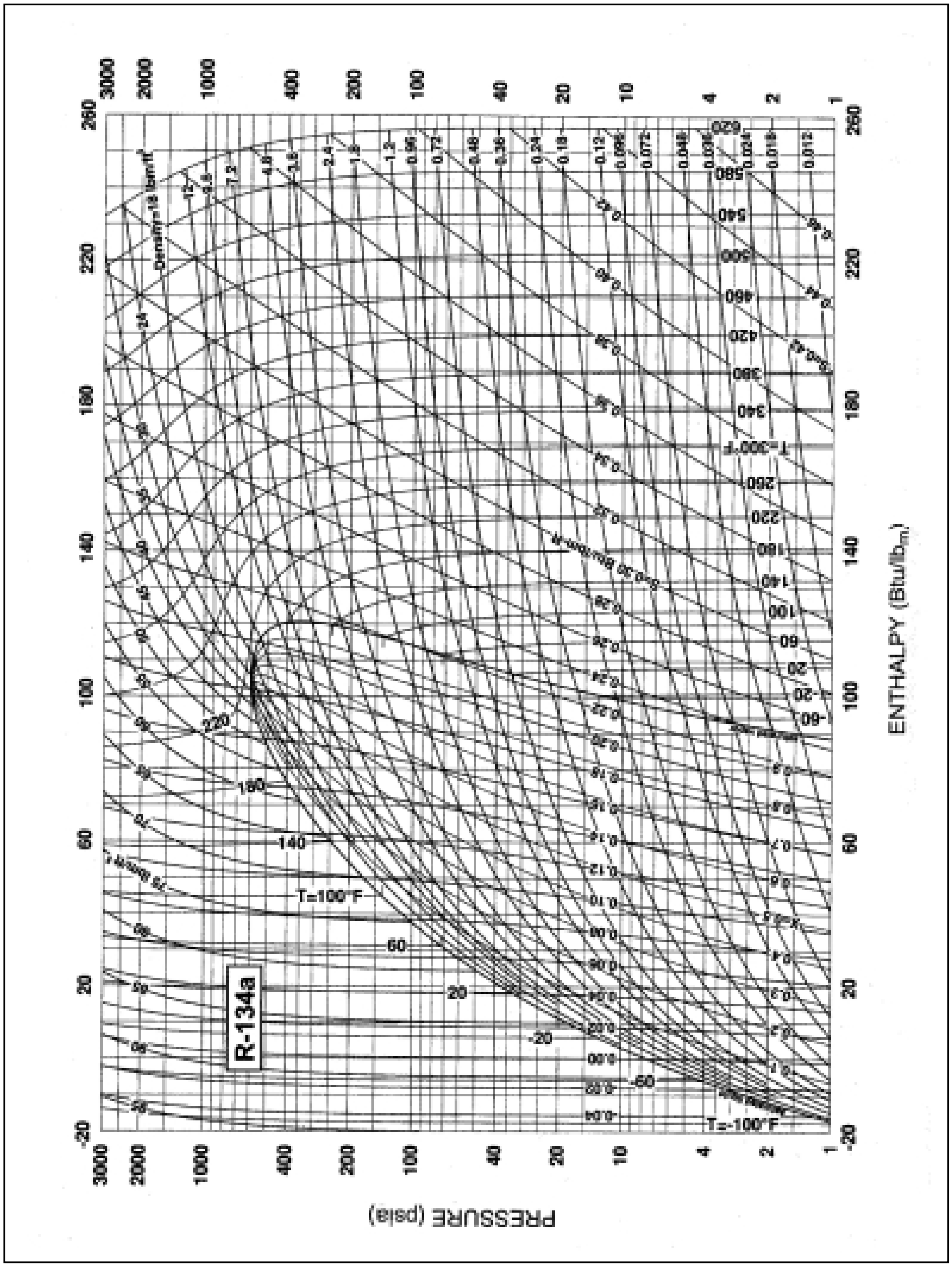
Press.	Temp.		Density	Volume	Enthalpy		Entropy		Specific Heat		Sound Spd.		Viscosity		Therm. Cond.	
[psia]	°F		[lb/ft^3]	[ft^3/lb]	[Btu/R-lb]		[Btu/R-lb]		[ft/s]		[Btu/lb-°F]		[lbm/ft-h]		[Btu/h-ft-R]	
	(b)	(d)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)
1	-125.9	-111.6	94.25	43.06	-26.02	93.37	-0.06921	0.2813	0.2948	0.1567	3380	484.1	1.944	0.019368	0.0866	0.0034
2	-109	-95	92.61	22.47	-21.01	95.79	-0.05456	0.2722	0.2978	0.1621	3214	493.2	1.584	0.020304	0.08329	0.00372
3	-98.15	-84.37	91.54	15.36	-17.76	97.35	-0.04546	0.2672	0.2996	0.1659	3111	498.5	1.404	0.020916	0.08122	0.00393
4	-89.97	-76.35	90.72	11.73	-15.31	98.52	-0.03874	0.2638	0.3011	0.1688	3035	502.3	1.296	0.021348	0.07968	0.00409
5	-83.32	-69.83	90.06	9.519	-13.3	99.47	-0.03337	0.2612	0.3023	0.1714	2973	505.2	1.224	0.021708	0.07844	0.00422
6	-77.68	-64.3	89.48	8.023	-11.59	100.3	-0.02887	0.2591	0.3033	0.1736	2922	507.5	1.152	0.022032	0.07739	0.00433
7	-72.75	-59.47	88.98	6.944	-10.09	101	-0.02498	0.2574	0.3043	0.1756	2877	509.4	1.116	0.022284	0.07649	0.00443
8	-68.37	-55.18	88.53	6.126	-8.755	101.6	-0.02155	0.2559	0.3052	0.1774	2838	511	1.08	0.022536	0.07569	0.00452
10	-60.78	-47.74	87.74	4.968	-6.431	102.6	-0.01567	0.2535	0.3068	0.1807	2770	513.7	1.008	0.022968	0.07432	0.00467
12	-54.32	-41.41	87.07	4.186	-4.443	103.5	-0.01074	0.2516	0.3082	0.1836	2712	515.7	0.936	0.023328	0.07316	0.0048
14	-48.67	-35.88	86.47	3.621	-2.696	104.3	-0.00647	0.25	0.3092	0.1862	2662	517.3	0.9	0.023616	0.07215	0.00492
14.7	-46.82	-34.08	86.28	3.459	-2.12	104.5	-0.00508	0.2516	0.3095	0.1875	2635	517.8	0.898	0.0237	0.0718	0.00496
16	-43.63	-30.94	85.93	3.193	-1.131	105	-0.0027	0.2487	0.3107	0.1886	2617	518.6	0.864	0.023904	0.07126	0.00503
18	-39.06	-26.47	85.44	2.857	0.292	105.6	0.00069	0.2475	0.3118	0.1909	2577	519.7	0.828	0.024156	0.07046	0.00512
20	-34.88	-22.37	84.99	2.586	1.6	106.2	0.00378	0.2465	0.3129	0.193	2540	520.6	0.828	0.024372	0.06972	0.00521
22	-31.02	-18.59	84.57	2.363	2.814	106.7	0.00661	0.2456	0.314	0.195	2505	521.3	0.792	0.024588	0.06905	0.00529
24	-27.42	-15.06	84.18	2.176	3.947	107.2	0.00923	0.2448	0.3149	0.1969	2474	521.9	0.756	0.024768	0.06842	0.00537
26	-24.05	-11.76	83.81	2.017	5.012	107.6	0.01168	0.244	0.3159	0.1987	2444	522.4	0.756	0.024984	0.06784	0.00544
28	-20.87	-8.654	83.45	1.88	6.018	108	0.01397	0.2434	0.3168	0.2004	2416	522.9	0.72	0.025164	0.06729	0.00551
30	-17.87	-5.715	83.12	1.76	6.973	108.4	0.01613	0.2427	0.3177	0.2021	2389	523.2	0.72	0.025344	0.06677	0.00558
32	-15.02	-2.925	82.8	1.655	7.882	108.8	0.01817	0.2421	0.3186	0.2037	2364	523.5	0.72	0.025524	0.06628	0.00565
34	-12.3	-0.267	82.49	1.562	8.75	109.1	0.0201	0.2416	0.3194	0.2053	2340	523.7	0.684	0.025668	0.06581	0.00571
36	-9.708	2.271	82.2	1.479	9.582	109.5	0.02195	0.2411	0.3203	0.2068	2317	523.9	0.684	0.025812	0.06537	0.00577
38	-7.222	4.703	81.91	1.405	10.38	109.8	0.02371	0.2406	0.3211	0.2083	2295	524	0.648	0.025956	0.06494	0.00582
40	-4.835	7.037	81.64	1.337	11.15	110.1	0.02539	0.2402	0.3219	0.2098	2274	524.1	0.648	0.0261	0.06453	0.00588
42	-2.539	9.283	81.37	1.276	11.89	110.4	0.02701	0.2398	0.3227	0.2112	2254	524.1	0.648	0.026244	0.06414	0.00593
44	-0.325	11.45	81.12	1.22	12.61	110.6	0.02856	0.2394	0.3234	0.2125	2235	524.2	0.648	0.026388	0.06377	0.00599
46	1.813	13.54	80.87	1.169	13.3	110.9	0.03006	0.239	0.3242	0.2139	2216	524.1	0.612	0.026496	0.0634	0.00604
48	3.881	15.56	80.63	1.122	13.97	111.2	0.03151	0.2386	0.3249	0.2152	2197	524.1	0.612	0.026604	0.06305	0.00609
50	5.884	17.52	80.39	1.079	14.63	111.4	0.0329	0.2383	0.3257	0.2165	2180	524	0.612	0.026748	0.06271	0.00613
55	10.63	22.16	79.83	0.9835	16.18	112	0.0362	0.2375	0.3275	0.2197	2138	523.8	0.576	0.027036	0.06191	0.00625
60	15.07	26.48	79.3	0.9038	17.64	112.5	0.03926	0.2367	0.3292	0.2227	2099	523.4	0.576	0.027288	0.06116	0.00636
65	19.23	30.54	78.79	0.8359	19.02	113	0.04212	0.2361	0.331	0.2257	2062	522.9	0.54	0.02754	0.06046	0.00647
70	23.15	34.37	78.31	0.7773	20.32	113.4	0.04481	0.2354	0.3326	0.2285	2027	522.3	0.54	0.027792	0.0598	0.00657
75	26.86	38	77.85	0.7264	21.56	113.8	0.04735	0.2349	0.3343	0.2313	1994	521.6	0.54	0.028008	0.05917	0.00666
80	30.39	41.44	77.41	0.6815	22.75	114.2	0.04975	0.2344	0.336	0.2341	1962	520.9	0.504	0.028224	0.05858	0.00676
85	33.76	44.72	76.98	0.6418	23.88	114.6	0.05204	0.2339	0.3376	0.2368	1932	520.2	0.504	0.02844	0.05802	0.00685
90	36.98	47.86	76.57	0.6063	24.98	114.9	0.05422	0.2334	0.3392	0.2394	1904	519.4	0.504	0.028656	0.05748	0.00694
95	40.07	50.87	76.17	0.5745	26.03	115.2	0.05631	0.2329	0.3408	0.242	1876	518.5	0.468	0.028836	0.05696	0.00703
100	43.04	53.76	75.78	0.5457	27.04	115.5	0.05831	0.2325	0.3424	0.2446	1850	517.6	0.468	0.029052	0.05646	0.00711
110	48.66	59.23	75.03	0.4957	28.98	116.1	0.06209	0.2317	0.3455	0.2497	1799	515.7	0.468	0.029412	0.05552	0.00728
120	53.91	64.33	74.33	0.4538	30.8	116.6	0.06561	0.231	0.3487	0.2547	1752	513.8	0.432	0.029772	0.05464	0.00744
130	58.84	69.12	73.65	0.4181	32.53	117	0.0689	0.2303	0.3518	0.2597	1707	511.7	0.432	0.030096	0.05382	0.0076
140	63.49	73.64	72.99	0.3873	34.17	117.5	0.07201	0.2297	0.355	0.2647	1665	509.5	0.396	0.030456	0.05303	0.00776
150	67.91	77.91	72.36	0.3605	35.74	117.8	0.07495	0.2291	0.3582	0.2697	1625	507.3	0.396	0.03078	0.05229	0.00792
160	72.1	81.98	71.75	0.337	37.25	118.2	0.07775	0.2285	0.3614	0.2747	1587	505	0.396	0.031068	0.05159	0.00807
170	76.11	85.86	71.16	0.316	38.7	118.5	0.08042	0.228	0.3646	0.2797	1550	502.7	0.36	0.031392	0.05091	0.00823
180	79.94	89.57	70.58	0.2974	40.1	118.7	0.08297	0.2274	0.368	0.2848	1515	500.3	0.36	0.03168	0.05026	0.00839
190	83.62	93.12	70.01	0.2806	41.45	119	0.08542	0.2269	0.3713	0.29	1481	497.9	0.36	0.032004	0.04964	0.00854
200	87.16	96.54	69.46	0.2654	42.76	119.2	0.08778	0.2264	0.3748	0.2953	1448	495.5	0.36	0.032292	0.04903	0.0087
220	93.86	103	68.38	0.239	45.28	119.6	0.09225	0.2254	0.3819	0.3062	1385	490.5	0.324	0.032868	0.04789	0.00903
240	100.1	109	67.33	0.2169	47.66	119.9	0.09644	0.2245	0.3894	0.3177	1327	485.4	0.324	0.033444	0.04681	0.00936
260	106	114.7	66.31	0.198	49.95	120.2	0.1004	0.2236	0.3974	0.3299	1271	480.3	0.288	0.03402	0.04579	0.00971
280	111.6	120	65.3	0.1817	52.14	120.3	0.1041	0.2226	0.4058	0.3429	1217	475	0.288	0.034596	0.04482	0.01008
300	116.8	125	64.32	0.1674	54.25	120.4	0.1077	0.2217	0.415	0.357	1166	469.7	0.288	0.035172	0.04389	0.01046
320	121.9	129.8	63.34	0.1548	56.3	120.5	0.1112	0.2208	0.4249	0.3722	1117	464.3	0.252	0.035784	0.043	0.01088
340	126.6	134.4	62.36	0.1436	58.29	120.5	0.1145	0.2199	0.4357	0.3889	1069	458.8	0.252	0.03636	0.04214	0.01132
360	131.2	138.7	61.39	0.1336	60.23	120.4	0.1177	0.2189	0.4476	0.4074	1023	453.3	0.252	0.037008	0.04131	0.01179
380	135.6	142.9	60.41	0.1245	62.13	120.3	0.1208	0.2179	0.4608	0.4281	977.9	447.8	0.216	0.037656	0.04051	0.0123
400	139.9	146.8	59.43	0.1162	64	120.1	0.1238	0.2169	0.4757	0.4513	933.7	442.1	0.216	0.03834	0.03973	0.01286
450	149.8	156.1	56.9	0.09841	68.56	119.4	0.1311	0.2141	0.5228	0.5252	826.5	427.8	0.216	0.040176	0.03789	0.01448
500	158.9	164.6	54.21	0.08359	73.07	118.3	0.1382	0.211	0.5937	0.6365	722.1	413.1	0.18	0.042372	0.0362	0.01657
550	167.4	172.3	51.22	0.07075	77.66	116.7	0.1452	0.2072	0.7154	0.8259	619.1	397.9	0.144	0.04518	0.03474	0.01945
600	175.3	179.2	47.62	0.05896	82.58	114.1	0.1527	0.2023	0.981	1.226	516	381.7	0.144	0.04914	0.03385	0.02397
650	182.8	185.4	42.52	0.04651	88.57	109.5	0.1618	0.1943	1.988	2.655	412.5	362.9	0.108	0.056448	0.03557	0.03352
672.20	186.9	186.9	31.6	0.0317	98.5	98.5	0.1771	0.1771	-	-	-	-	-	-	-	-

Table 14 – Thermodynamic Properties of 410A

Press.	Temp.		Density	Volume	Enthalpy		Entropy		Specific Heat		Sound Spd.		Viscosity		Therm. Cond.	
[psia]	°F		[lb/ft^3]	[ft^3/lb]	[Btu/R-lb]		[Btu/R-lb]		[ft/s]		[Btu/lb-°F]		[lbm/ft-h]		[Btu/h-ft-R]	
	(b)	(d)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)
1	-135.8	-135.7	92.04	47.55	-30.47	99.84	-0.08217	0.3201	0.309	0.1567	3496	518	1.4832	0.019296	0.09941	0.00354
2	-119.7	-119.6	90.46	24.84	-25.48	102.1	-0.06715	0.3081	0.3122	0.1623	3327	528.2	1.2528	0.020268	0.09598	0.00377
3	-109.4	-109.4	89.43	17	-22.26	103.5	-0.05782	0.3013	0.3139	0.1663	3225	534.2	1.134	0.020844	0.09384	0.00392
4	-101.7	-101.6	88.64	12.99	-19.82	104.6	-0.05093	0.2966	0.3152	0.1696	3151	538.4	1.0584	0.021312	0.09224	0.00404
5	-95.37	-95.3	87.99	10.54	-17.83	105.5	-0.04543	0.293	0.3162	0.1725	3091	541.7	1.0008	0.021672	0.09095	0.00413
6	-90.03	-89.95	87.44	8.889	-16.14	106.2	-0.04082	0.2901	0.3171	0.175	3041	544.3	0.9576	0.021996	0.08987	0.00422
7	-85.37	-85.29	86.95	7.695	-14.66	106.8	-0.03685	0.2876	0.3179	0.1773	2998	546.5	0.9216	0.022248	0.08893	0.00429
8	-81.21	-81.14	86.52	6.79	-13.33	107.4	-0.03334	0.2856	0.3187	0.1795	2959	548.3	0.8892	0.0225	0.0881	0.00435
10	-74.03	-73.96	85.76	5.509	-11.04	108.3	-0.02734	0.2821	0.3201	0.1833	2893	551.3	0.8424	0.022932	0.08666	0.00447
12	-67.93	-67.85	85.1	4.643	-9.079	109.1	-0.02231	0.2793	0.3213	0.1867	2837	553.6	0.8028	0.023292	0.08546	0.00457
14	-62.59	-62.5	84.52	4.017	-7.358	109.8	-0.01796	0.277	0.3225	0.1898	2788	555.5	0.7704	0.02358	0.08442	0.00466
14.70	-60.93	-60.74	84.33	3.838	-6.77	110.0	-0.0165	0.276	0.3221	0.1926	2749	556.0	0.7602	0.0239	0.0843	0.00492
16	-57.82	-57.74	84	3.543	-5.817	110.4	-0.01411	0.275	0.3236	0.1926	2745	557	0.7416	0.023868	0.08348	0.00474
18	-53.51	-53.42	83.53	3.171	-4.417	110.9	-0.01066	0.2733	0.3246	0.1952	2705	558.3	0.72	0.02412	0.08264	0.00481
20	-49.56	-49.47	83.09	2.871	-3.131	111.4	-0.00752	0.2717	0.3256	0.1977	2669	559.4	0.6984	0.024336	0.08187	0.00488
22	-45.91	-45.82	82.69	2.623	-1.939	111.8	-0.00463	0.2703	0.3266	0.2	2636	560.3	0.6804	0.024552	0.08115	0.00494
24	-42.52	-42.42	82.3	2.416	-0.8265	112.3	-0.00197	0.2691	0.3275	0.2023	2605	561	0.666	0.024768	0.08049	0.00501
26	-39.33	-39.23	81.95	2.24	0.2188	112.6	0.00052	0.2679	0.3284	0.2044	2575	561.7	0.6516	0.024948	0.07987	0.00506
28	-36.34	-36.24	81.61	2.088	1.206	113	0.00285	0.2669	0.3293	0.2064	2548	562.2	0.6372	0.025092	0.07929	0.00512
30	-33.51	-33.4	81.28	1.955	2.141	113.3	0.00504	0.2659	0.3301	0.2083	2522	562.7	0.6228	0.025272	0.07874	0.00517
32	-30.82	-30.71	80.97	1.839	3.032	113.6	0.00711	0.265	0.331	0.2102	2497	563.1	0.612	0.025416	0.07822	0.00522
34	-28.26	-28.15	80.68	1.736	3.882	113.9	0.00908	0.2641	0.3318	0.212	2473	563.4	0.6012	0.02556	0.07772	0.00527
36	-25.81	-25.7	80.39	1.643	4.697	114.2	0.01095	0.2633	0.3326	0.2138	2451	563.7	0.5904	0.025668	0.07724	0.00531
38	-23.47	-23.35	80.12	1.561	5.479	114.5	0.01274	0.2625	0.3334	0.2155	2429	563.9	0.5832	0.025884	0.07679	0.00536
40	-21.22	-21.1	79.85	1.486	6.231	114.7	0.01445	0.2618	0.3342	0.2171	2408	564.1	0.5724	0.026028	0.07635	0.00541
42	-19.06	-18.94	79.6	1.418	6.956	114.9	0.01609	0.2611	0.335	0.2188	2388	564.2	0.5652	0.026172	0.07593	0.00546
44	-16.97	-16.85	79.35	1.356	7.657	115.2	0.01766	0.2605	0.3357	0.2203	2369	564.3	0.558	0.02628	0.07552	0.00551
46	-14.96	-14.83	79.11	1.299	8.335	115.4	0.01918	0.2599	0.3365	0.2219	2350	564.4	0.5508	0.026424	0.07513	0.00555
48	-13.01	-12.89	78.88	1.247	8.993	115.6	0.02065	0.2593	0.3372	0.2234	2332	564.4	0.5436	0.026568	0.07475	0.0056
50	-11.13	-11	78.65	1.199	9.631	115.8	0.02206	0.2587	0.338	0.2249	2315	564.4	0.5364	0.026712	0.07439	0.00564
55	-6.654	-6.523	78.11	1.094	11.15	116.3	0.0254	0.2574	0.3398	0.2285	2273	564.4	0.5184	0.027	0.07351	0.00574
60	-2.485	-2.35	77.6	1.005	12.57	116.7	0.0285	0.2562	0.3416	0.2319	2234	564.1	0.504	0.027288	0.0727	0.00584
65	1.426	1.564	77.11	0.9298	13.91	117.1	0.0314	0.2551	0.3433	0.2352	2197	563.8	0.4932	0.027576	0.07194	0.00593
70	5.113	5.255	76.65	0.8648	15.19	117.4	0.03412	0.2541	0.345	0.2385	2162	563.4	0.4788	0.027828	0.07121	0.00602
75	8.603	8.749	76.21	0.8083	16.4	117.8	0.03669	0.2531	0.3467	0.2416	2129	562.9	0.468	0.02808	0.07053	0.00611
80	11.92	12.07	75.78	0.7585	17.55	118.1	0.03912	0.2522	0.3484	0.2447	2098	562.3	0.4572	0.028296	0.06988	0.0062
85	15.08	15.24	75.37	0.7144	18.66	118.3	0.04143	0.2514	0.3501	0.2477	2068	561.7	0.45	0.028548	0.06926	0.00628
90	18.11	18.26	74.98	0.6751	19.72	118.6	0.04364	0.2506	0.3517	0.2507	2039	561	0.4392	0.028764	0.06866	0.00637
95	21.01	21.17	74.59	0.6397	20.75	118.9	0.04575	0.2498	0.3534	0.2536	2011	560.3	0.432	0.02898	0.06809	0.00645
100	23.79	23.95	74.22	0.6078	21.73	119.1	0.04778	0.2491	0.355	0.2565	1984	559.6	0.4248	0.02916	0.06753	0.00653
110	29.06	29.23	73.51	0.5523	23.61	119.5	0.05159	0.2478	0.3583	0.2622	1933	557.9	0.4104	0.029556	0.06649	0.00669
120	33.98	34.15	72.83	0.5057	25.39	119.9	0.05515	0.2465	0.3616	0.2678	1886	556.2	0.396	0.029952	0.06551	0.00685
130	38.6	38.77	72.19	0.4661	27.06	120.2	0.05848	0.2454	0.3648	0.2734	1841	554.3	0.3852	0.030312	0.06458	0.00701
140	42.95	43.13	71.56	0.432	28.66	120.5	0.06161	0.2443	0.3682	0.2789	1798	552.4	0.3708	0.030672	0.0637	0.00717
150	47.08	47.26	70.96	0.4022	30.18	120.7	0.06458	0.2433	0.3715	0.2845	1757	550.4	0.3636	0.030996	0.06287	0.00733
160	51	51.19	70.38	0.376	31.64	121	0.0674	0.2423	0.3749	0.2901	1718	548.3	0.3528	0.03132	0.06207	0.0075
170	54.74	54.93	69.82	0.3528	33.05	121.2	0.07009	0.2414	0.3783	0.2957	1680	546.2	0.342	0.031644	0.0613	0.00766
180	58.32	58.52	69.27	0.3321	34.4	121.3	0.07267	0.2405	0.3818	0.3015	1644	544.1	0.3348	0.031968	0.06056	0.00784
190	61.76	61.95	68.74	0.3134	35.71	121.5	0.07514	0.2396	0.3853	0.3073	1610	541.9	0.3276	0.032256	0.05985	0.00801
200	65.06	65.26	68.21	0.2966	36.98	121.6	0.07751	0.2388	0.3889	0.3132	1576	539.6	0.3204	0.032544	0.05917	0.00819
220	71.3	71.5	67.2	0.2673	39.41	121.8	0.08201	0.2372	0.3964	0.3254	1512	535.1	0.306	0.033156	0.05785	0.00857
240	77.13	77.34	66.21	0.2428	41.72	122	0.08623	0.2357	0.4042	0.3381	1451	530.4	0.2916	0.033696	0.05662	0.00897
260	82.6	82.81	65.25	0.2218	43.92	122	0.09021	0.2342	0.4126	0.3517	1393	525.7	0.2808	0.034272	0.05544	0.0094
280	87.77	87.97	64.32	0.2037	46.04	122	0.09398	0.2328	0.4214	0.3661	1338	520.9	0.27	0.034812	0.05432	0.00986
300	92.66	92.87	63.4	0.1879	48.07	122	0.09758	0.2314	0.4309	0.3816	1285	516	0.2592	0.035388	0.05324	0.01036
320	97.31	97.51	62.49	0.174	50.05	121.9	0.101	0.23	0.4411	0.3984	1234	511.1	0.2484	0.035964	0.0522	0.0109
340	101.7	101.9	61.59	0.1616	51.96	121.8	0.1043	0.2287	0.4523	0.4167	1185	506.1	0.2412	0.036504	0.0512	0.01149
360	106	106.2	60.69	0.1505	53.83	121.6	0.1075	0.2273	0.4644	0.4368	1137	501	0.234	0.03708	0.05022	0.01212
380	110	110.2	59.8	0.1405	55.65	121.4	0.1107	0.226	0.4778	0.4591	1090	495.9	0.2232	0.037692	0.04928	0.01282
400	113.9	114.1	58.9	0.1314	57.44	121.1	0.1137	0.2246	0.4927	0.4839	1045	490.8	0.216	0.038304	0.04835	0.01358
450	123.1	123.3	56.63	0.1119	61.79	120.1	0.1209	0.221	0.5386	0.5614	935.2	477.6	0.198	0.039924	0.04613	0.01581
500	131.4	131.6	54.25	0.09571	66.06	118.9	0.1279	0.2172	0.6042	0.6738	830.2	464.1	0.18	0.04176	0.04401	0.01865
550	139.1	139.3	51.69	0.08191	70.33	117.1	0.1348	0.213	0.7078	0.854	727.9	450.1	0.1656	0.043992	0.04198	0.02242
600	146.3	146.4	48.79	0.06958	74.77	114.8	0.1419	0.2079	0.9018	1.196	626	435.1	0.1476	0.046836	0.04005	0.0278
650	152.9	153	45.17	0.05773	79.71	111.3	0.1496	0.2012	1.427	2.119	519.7	418.2	0.1472	0.0468	0.03987	0.03689
694.87	158.4	158.4	34.2	0.0293	90.2	90.2	0.1663	0.1663	-	-	-	-	-	-	-	-

Appendix 3 Sample Pressure-Enthalpy Diagram

Pressure-Enthalpy Diagram for Refrigerant 134a[33]



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