Related Commercial Resources

CHAPTER 29

REFRIGERANTS

REFRIGERANTS are the working fluids in refrigeration, air-conditioning, and heat-pumping systems. They absorb heat from one area, such as an air-conditioned space, and reject it into another, such as outdoors, usually through evaporation and condensation, respectively. These phase changes occur both in absorption and mechanical vapor compression systems, but not in systems operating on a gas cycle using a fluid such as air. (See Chapter 2 for more information on refrigeration cycles.) The design of the refrigeration equipment depends strongly on the selected refrigerant's properties. Tables 1 and 2 list standard refrigerant designations, some properties, and safety classifications from ASHRAE *Standard* 34.

Refrigerant selection involves compromises between conflicting desirable thermophysical properties. A refrigerant must satisfy many requirements, some of which do not directly relate to its ability to transfer heat. Chemical stability under conditions of use is an essential characteristic. Safety codes may require a nonflammable refrigerant of low toxicity for some applications. Environmental consequences of refrigerant leaks must also be considered. Cost, availability, efficiency, and compatibility with compressor lubricants and equipment materials are other concerns.

Latent heat of vaporization is another important property. On a molar basis, fluids with similar boiling points have almost the same latent heat. Because compressor displacement is defined on a volumetric basis, refrigerants with similar boiling points produce similar refrigeration effect with a given compressor. On a mass basis, latent heat varies widely among fluids. Efficiency of a theoretical vapor compression cycle is maximized by fluids with low vapor heat capacity. This property is associated with fluids having a simple molecular structure and low molecular mass.

Transport properties (e.g., thermal conductivity and viscosity) affect performance of heat exchangers and piping. High thermal conductivity and low viscosity are desirable.

No single fluid satisfies all the attributes desired of a refrigerant; consequently, various refrigerants are used. This chapter describes the basic characteristics of various refrigerants, and Chapter 30 lists thermophysical properties.

REFRIGERANT PROPERTIES

Global Environmental Properties

Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) can affect both stratospheric ozone and climate change, whereas hydrofluorocarbons (HFCs) can affect climate change. Minimizing all refrigerant releases from systems is important not only because of environmental impacts, but also because charge losses lead to insufficient system charge levels, which in turn results in suboptimal operation and lowered efficiency.

Stratospheric Ozone Depletion. The stratospheric ozone layer filters out the UV-B portion of the sun's ultraviolet (UV) radiation. Overexposure to this radiation increases the risk of skin cancer, cataracts, and impaired immune systems. It also can damage sensitive crops, reduce crop yields, and stress marine phytoplankton (and thus human food supplies from the oceans). In addition, exposure to UV radiation degrades plastics and wood.

Stratospheric ozone depletion has been linked to the presence of chlorine and bromine in the stratosphere. Chemicals with long atmospheric lifetimes can migrate to the stratosphere, where the molecules break down from interaction with ultraviolet light or through chemical reaction. Chemicals such as CFCs and HCFCs release chlorine, which reacts with stratospheric ozone.

Ozone-depleting substances, including CFCs and HCFCs, are to be phased out of production under the Montreal Protocol (UNEP 2003, 2006). U.S. regulations for CFC and HCFC refrigerants, including phaseout schedules, may be found at http://www.epa.gov/ozone/strathome.html. The Alliance for Responsible Atmospheric Policy (http://www.arap.org/regs/) also briefly summarizes regulations for several countries. Reclaimed CFC and HCFC refrigerants that meet the requirements of ARI *Standard* 700 can continue to be used for servicing existing systems.

Global Climate Change. The average global temperature is determined by the balance of energy from the sun heating the earth and its atmosphere and of energy radiated from the earth and the atmosphere to space. **Greenhouse gases (GHGs)**, such as carbon dioxide (CO_2) and water vapor, as well as small particles trap heat at and near the surface, maintaining the average temperature of the Earth's surface about 34 K warmer than would be the case if these gases and particles were not present (the **greenhouse effect**).

Global warming (also called **global climate change**) is a concern because of an increase in the greenhouse effect from increasing concentrations of GHGs attributed to human activities. The major GHG of concern is CO_2 released to the atmosphere when fossil fuels (coal, oil, and natural gas) are burned for energy. Methane (CH_4), nitrous oxide (N_2O), CFCs, HCFCs, HFCs, perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also GHGs.

In 1988, the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) established the Intergovernmental Panel on Climate Change (IPCC) to provide an objective source of information about the causes of climate change, its potential environmental and socioeconomic consequences, and the adaptation and mitigation options to respond to it. According to IPCC (2007a), atmospheric concentration of carbon dioxide has increased by more than 35% over the past 250 years, primarily from burning fossil fuels, with some contribution from deforestation. Concentration of methane has increased by over 145%, and nitrous oxide by about 18%. IPCC (2007a) deems atmospheric concentrations of fluorochemicals, including fluorocarbon gases (CFCs, HCFCs, and HFCs) and sulfur hexafluoride, to be a smaller contributor to global climate change. On whether observed warming is attributable to human influence, IPCC (2007b) concludes that "Most of the observed increase in global averaged temperatures since the mid-twentieth century [about 0.65 K] is very likely [90% confident] due to the observed increase in anthropogenic greenhouse gas concentrations."

The preparation of this chapter is assigned to TC 3.1, Refrigerants and Secondary Coolants.

Table 1 Refrigerant Data and Safety Classifications

Refrigerant Number	Chemical Name[a,b]	Chemical Formula[a]	Molecular Mass[a]	Normal Boiling Point,[a] °C	Safety Group
Methane Series					
11	Trichlorofluoromethane	CCl_3F	137.4	24	A1
12	Dichlorodifluoromethane	CCl_2F_2	120.9	–30	A1
12B1	Bromochlorodifluoromethane	$CBrClF_2$	165.4	–4	
13	Chlorotrifluoromethane	$CClF_3$	104.5	–81	A1
14	Tetrafluoromethane (carbon tetrafluoride)	CF_4	88.0	–128	A1
21	Dichlorofluoromethane	$CHCl_2F$	102.9	9	B1
22	Chlorodifluoromethane	$CHClF_2$	86.5		A1
23	Trifluoromethane	CHF_3	70.0	–82	A1
30	Dichloromethane (methylene chloride)	CH_2Cl_2	84.9	40	B2
31	Chlorofluoromethane	CH_2ClF	68.5	–9	
32	Difluoromethane (methylene fluoride)	CH_2F_2	52.0	–52	A2
40	Chloromethane (methyl chloride)	CH_3Cl	50.4	–24	B2
41	Fluoromethane (methyl fluoride)	CH_3F	34.0	–78	
50	Methane	CH_4	16.0	–161	A3
Ethane Series					
113	1,1,2-trichloro-1,2,2-trifluoroethane	CCl_2FCClF_2	187.4	48	A1
114	1,2-dichloro-1,1,2,2-tetrafluoroethane	$CClF_2CClF_2$	170.9	4	A1
115	Chloropentafluoroethane	$CClF_2CF_3$	154.5	–39	A1
116	Hexafluoroethane	CF_3CF_3	138.0	–78	A1
123	2,2-dichloro-1,1,1-trifluoroethane	$CHCl_2CF_3$	153.0	27	B1
124	2-chloro-1,1,1,2-tetrafluoroethane	$CHClFCF_3$	136.5	–12	A1
125	Pentafluoroethane	CHF_2CF_3	120.0	–79	A1
134a	1,1,1,2-tetrafluoroethane	CH_2FCF_3	102.0	–26	A1
141b	1,1-dichloro-1-fluoroethane	CH_3CCl_2F	117.0	32	
142b	1-chloro-1,1-difluoroethane	CH_3CClF_2	100.5	–10	A2
143a	1,1,1-trifluoroethane	CH_3CF_3	84.0	–47	A2
152a	1,1-difluoroethane	CH_3CHF_2	66.0	–25	A2
170	Ethane	CH_3CH_3	30.0	–89	A3
Ethers					
E170	Dimethyl ether	CH_3OCH_3	46.0	–25	A3
Propane Series					
218	Octafluoropropane	$CF_3CF_2CF_3$	188.0	–37	A1
236fa	1,1,1,3,3,3-hexafluoropropane	$CF_3CH_2CF_3$	152.0	–1	A1
245fa	1,1,1,3,3-pentafluoropropane	$CF_3CH_2CHF_2$	134.0	15	B1
290	Propane	$CH_3CH_2CH_3$	44.0	–42	A3
Cyclic Organic Compounds (see Table 2 for blends)					
C318	Octafluorocyclobutane	$–(CF_2)_4–$	200.0	–6	A1
Miscellaneous Organic Compounds					
Hydrocarbons					
600	Butane	$CH_3CH_2CH_2CH_3$	58.1	0	A3
600a	Isobutane	$CH(CH_3)_2CH_3$	58.1	–12	A3
601	Pentane	$CH_3(CH_2)_3CH_3$	72.15	36.1	A3
601a	Isopentane	$(CH_3)_2CHCH_2CH_3$	72.15	27.8	A3
Oxygen Compounds					
610	Ethyl ether	$CH_3CH_2OCH_2CH_3$	74.1	35	
611	Methyl formate	$HCOOCH_3$	60.0	32	B2
Sulfur Compounds					
620	(Reserved for future assignment)				
Nitrogen Compounds					
630	Methyl amine	CH_3NH_2	31.1	–7	
631	Ethyl amine	$CH_3CH_2(NH_2)$	45.1	17	
Inorganic Compounds					
702	Hydrogen	H_2	2.0	–253	A3
704	Helium	He	4.0	–269	A1
717	Ammonia	NH_3	17.0	–33	B2
718	Water	H_2O	18.0	100	A1
720	Neon	Ne	20.2	–246	A1
728	Nitrogen	N_2	28.1	–196	A1
732	Oxygen	O_2	32.0	–183	
740	Argon	Ar	39.9	–186	A1
744	Carbon dioxide	CO_2	44.0	–78[c]	A1
744A	Nitrous oxide	N_2O	44.0	–90	
764	Sulfur dioxide	SO_2	64.1	–10	B1
Unsaturated Organic Compounds					
1150	Ethene (ethylene)	$CH_2{=}CH_2$	28.1	–104	A3
1270	Propene (propylene)	$CH_3CH{=}CH_2$	42.1	–48	A3

Source: ANSI/ASHRAE *Standard* 34-2007.

[a]Chemical name, chemical formula, molecular mass, and normal boiling point are not part of this standard.

[b]Preferred chemical name is followed by the popular name in parentheses.

[c]Sublimes.

Table 2 Data and Safety Classifications for Refrigerant Blends

Refrigerant Number	Composition (Mass %)	Composition Tolerances	Azeotropic Temperature, °C	Molecular Mass[a]	Normal Boiling Point, °C	Safety Group
Zeotropes						
400	R-12/114 (must be specified)		none			A1
401A	R-22/152a/124 (53.0/13.0/34.0)	(±2/+0.5,–1.5/±1)				A1
401B	R-22/152a/124 (61.0/11.0/28.0)	(±2/+0.5,–1.5/±1)				A1
401C	R-22/152a/124 (33.0/15.0/52.0)	(±2/+0.5,–1.5/±1)				A1
402A	R-125/290/22 (60.0/2.0/38.0)	(±2/±0.1,–1/±2)				A1
402B	R-125/290/22 (38.0/2.0/60.0)	(±2/±0.1,–1/±2)				A1
403A	R-290/22/218 (5.0/75.0/20.0)	(+0.2,–2/±2/±2)				A1
403B	R-290/22/218 (5.0/56.0/39.0)	(+0.2,–2/±2/±2)				A1
404A	R-125/143a/134a (44.0/52.0/4.0)	(±2/±1/±2)				A1
405A	R-22/152a/142b/C318 (45.0/7.0/5.5/42.5)	(±2/±1/±1/±2)				
406A	R-22/600a/142b (55.0/4.0/41.0)	(±2/±1/±1)				A2
407A	R-32/125/134a (20.0/40.0/40.0)	(±2/±2/±2)				A1
407B	R-32/125/134a (10.0/70.0/20.0)	(±2/±2/±2)				A1
407C	R-32/125/134a (23.0/25.0/52.0)	(±2/±2/±2)				A1
407D	R-32/125/134a (15.0/15.0/70.0)	(±2/±2/±2)				A1
407E	R-32/125/134a (25.0/15.0/60.0)	(±2,±2,±2)				A1
408A	R-125-143a-22 (7.0/46.0/47.0)	(±2/±1/±2)				A1
409A	R-22/124/142b (60.0/25.0/15.0)	(±2/±2/±1)				A1
409B	R-22/124/142b (65.0/25.0/10.0)	(±2/±2/±1)				A1
410A	R-32/125 (50.0/50.0)	(+0.5,–1.5/+1.5,–0.5)				A1
410B	R-32/125 (45.0/55.0)	(±1/±1)				A1
411A	R-1270/22/152a (1.5/87.5/11.0)	(+0,–1/+2,–0/+0,–1)				A2
411B	R-1270/22/152a (3.0/94.0/3.0)	(+0,–1/+2,–0/+0,–1)				A2
412A	R-22/218/142b (70.0/5.0/25.0)	(±2/±1/±1)				A2
413A	R-218/134a/600a (9.0/88.0/3.0)	(±1/±2/±0,–1)				A2
414A	R-22/124/600a/142b (51.0/28.5/4.0/16.5)	(±2/±2/±0.5/±0.5,–1)				A1
414B	R-22/124/600a/142b (50.0/39.0/1.5/9.5)	(±2/±2/±0.5/±0.5,–1)				A1
415A	R-22/152a (82.0/18.0)	(±1/±1)				A2
415B	R-22/152a (25.0/75.0)	(±1/±1)				A2
416A	R-134a/124/600 (59.0/39.5/1.5)	(+0.5,–1/+1,–0.5/+1,–0.2)				A1
417A	R-125/134a/600 (46.6/50.0/3.4)	(±1/±1/±0.1,–0.4)				A1
418A	R-290/22/152a (1.5/96.0/2.5)	(±0.5/±1/±0.5				A2
419A	R-125/134a/E170 (77.0/19.0/4.0)	(±1/±1/±1)				A2
420A	R-134a/142b (88.0/12.0)	(±1,–0,+0,–1)				A1
421A	R-125/134a (58.0/42.0)	(±1/ ±1)				A1
421B	R125/134a (85.0/15.0)	(±1/±1)				A1
422A	R-125/134a/600a (85.1/11.5/3.4)	(±1/ ±1/+0.1,–0.4)				A1
422B	R-125/134a/600a (55.0/42.0/3.0)	(±1/ ±1/+0.1,–0.5)				A1
422C	R-125/134a/600a (82.0/15.0/3.0)	(±1/ ±1/+0.1,–0.5)				A1
423A	R-134a/227ea (52.5/47.5)	(±1/±1)				A1
424A	R-125/134a/600a/600/601a (50.5/47.0/0.9/1.0/0.6)	(±1/ ±1/+0.1,–0.2/+0.1, –0.2/+0.1,–0.2)				A1
425A	R-32/134a/227ea (18.5/69.5/12.0)	(±0.5/±0.5/±0.5)				A1
426A	R-125/134a/600a/601a (5.1/93.0/1.3/0.6)	(±1/ ±1/+0.1,–0.2/+0.1,–0.2)				A1
427A	R-32/125/143a/134a (15.0/25.0/10.0/50.0)	(±2/ ±2/±2/ ±2)				A1
428A	R-125/143a/290/600a (77.5/20.0/0.6/1.9)	(±1/ ±1/+0.1, –0.2/+0.1,–0.2)				A1
Azeotropes[b]						
500	R-12/152a (73.8/26.2)		0	99.3	–33	A1
501	R-22/12 (75.0/25.0)[c]		–41	93.1	–41	A1
502	R-22/115 (48.8/51.2)		19	112.0	–45	A1
503	R-23/13 (40.1/59.9)		88	87.5	–88	
504	R-32/115 (48.2/51.8)		17	79.2	–57	
505	R-12/31 (78.0/22.0)[c]		115	103.5	–30	
506	R-31/114 (55.1/44.9)		18	93.7	–12	
507A[d]	R-125/143a (50.0/50.0)		–40	98.9	–46.7	A1
508A[d]	R-23/116 (39.0/61.0)		–86	100.1	–86	A1
508B	R-23/116 (46.0/54.0)		–45.6	95.4	–88.3	A1
509A[d]	R-22/218 (44.0/56.0)		0	124.0	–47	A1

Source: ANSI/ASHRAE *Standard* 34-2007.

[a]Molecular mass and normal boiling point are not part of this standard.

[b]Azeotropic refrigerants exhibit some segregation of components at conditions of temperature and pressure other than those at which they were formulated. Extent of segregation depends on the particular azeotrope and hardware system configuration.

[c]Exact composition of this azeotrope is in question, and additional experimental studies are needed.

[d]R-507, R-508, and R-509 are allowed designations for R-507A, R-508A, and R-509A because of a change in designations after assignment of R-500 through R-509. Corresponding changes were not made for R-500 through R-506.

Global Environmental Characteristics of Refrigerants. Atmospheric release of CFC and HCFC refrigerants such as R-11, R-12, R-22, and R-502 contributes to depletion of the ozone layer. The measure of a material's ability to deplete stratospheric ozone is its **ozone depletion potential (ODP)**, a value relative to that of R-11 which is 1.0.

Halocarbons (CFCs, HCFCs, and HFCs) and many nonhalocarbons (e.g., hydrocarbons, carbon dioxide) are also greenhouse gases. The **global warming potential (GWP)** of a GHG is an index describing its relative ability to trap radiant energy compared to CO_2 (R-744), which has a very long atmospheric lifetime. GWP may be calculated for any particular **integration time horizon (ITH)**. Typically, a 100 year ITH is used for regulatory purposes, and may be designated as GWP_{100}.

The energy refrigeration appliances consume is often produced from fossil fuels, which results in emission of CO_2, a contributor to global warming. This indirect effect associated with energy consumption is frequently much larger than the direct effect of refrigerant emissions. The **total equivalent warming impact (TEWI)** of an HVAC&R system is the sum of direct refrigerant emissions expressed in terms of CO_2 equivalents, and indirect emissions of CO_2 from the system's energy use over its service life. Another measure is **life-cycle climate performance (LCCP)**, which includes TEWI and adds direct and indirect emissions effects associated with manufacturing the refrigerant.

Ammonia (R-717), hydrocarbons, HCFCs, and most HFCs have shorter atmospheric lifetimes than CFCs because they are largely destroyed in the lower atmosphere by reactions with OH radicals. A shorter atmospheric lifetime generally results in lower ODP and GWP_{100} values. Environmentally preferred refrigerants (1) have low or zero ODP, (2) have relatively short atmospheric lifetimes, (3) have low GWP_{100}, (4) provide good system efficiency, (5) have appropriate safety properties, and (6) yield a low TEWI or LCCP in system applications (i.e., leaks are minimized or prevented, and performance is optimized).

Table 3 shows atmospheric lifetime, ODP, and GWP_{100} of refrigerants being phased out under the Montreal Protocol and of refrigerants being used to replace them, alone or as components of blends. Because HFCs do not contain chlorine or bromine, their ODP values are negligible (Ravishankara et al. 1994) and thus are shown as 0 in Table 3. Nonhalocarbon refrigerants listed have zero ODP and very low GWP_{100}.

There are some differences between the values stipulated for reporting under the Montreal and Kyoto protocols and the latest scientific values. These are not of sufficient magnitude to significantly alter design decisions based on the numbers in the table. All these values have rather wide error bands and may change with each assessment of the science. Changes in GWP assessments are largely dominated by changes in understanding of CO_2, which is the reference chemical.

Table 4 shows the calculated ODPs and GWP_{100}s for refrigerant blends, using the latest scientific assessment values as reported in Calm and Hourahan (2007).

Table 3 Refrigerant Environmental Properties

Refrigerant	Atmospheric Lifetime, years[a]	ODP[b]	GWP_{100}[c]
R-11	45	1	4750
R-12	100	1	10 900
R-13	640	1	14 400
R-22	12	0.055	1810
R-23	270	0	14 800
R-32	4.9	0	675
R-113	85	0.8	6130
R-114	300	1	10 000
R-115	1700	0.6	7370
R-116	10 000	0	12 200
R-123	1.3	0.02	77
R-124	5.8	0.022	609
R-125	29	0	3500
R-134a	14	0	1430
R-141b	9.3	0.11	725
R-142b	17.9	0.065	2310
R-143a	52	0	4470
R-152a	1.4	0	124
R-218	2600	0	8830
R-227ea	34.2	0	3220
R-236fa	240	0	9810
R-245ca	6.2[d]	0	693[d]
R-245fa	7.6	0	1030
R-C318	3200	0	10 300
R-744	Variable	0	1
R-290	0.41[d]	0	~20[d]
R-600	0.018[d]	0	~20[d]
R-600a	0.019[d]	0	~20[d]
R-601a	0.01[d]	0	~20[d]
R-717	0.01[d]	0	<1[d]
R-1270	0.001[d]	0	~20[d]

[a]Atmospheric lifetimes from Table 2.14 of IPCC (2007b) except where indicated.
[b]ODP from UNEP (2006), Section 1.1, Annexes A, B, and C, pp. 23-25.
[c]GWP_{100} from Table 2.14 of IPCC (2007b) except where indicated.
[d]Calm and Hourahan (2007).

Physical Properties

Table 5 lists some physical properties of commonly used refrigerants, a few very-low-boiling-point cryogenic fluids, some newer refrigerants, and some older refrigerants of historical interest. These refrigerants are arranged in increasing order of atmospheric boiling point.

Table 5 also includes the freezing point, critical properties, and refractive index. Of these properties, normal boiling point is most important because it is a direct indicator of the temperature at which a refrigerant can be used. The freezing point must be lower than any contemplated usage. The critical properties describe a material at the

Table 4 Environmental Properties of Refrigerant Blends

Refrigerant Number	ODP*	GWP_{100}*	Refrigerant Number	ODP*	GWP_{100}*
401A	0.033	1200	415B	0.013	550
401B	0.036	1300	416A	0.008	1100
401C	0.027	930	417A	0.000	2300
402A	0.019	2800	418A	0.048	1700
402B	0.030	2400	419A	0	3000
403A	0.038	3100	420A	0.008	1500
403B	0.028	4500	421A	0	2600
404A	0	3900	421B	0	3200
405A	0.026	5300	422A	0	3100
406A	0.056	1900	422B	0	2500
407A	0	2100	422C	0	3100
407B	0	2800	422D	0	2700
407C	0	1800	423A	0	2300
407D	0	1600	424A	0	2400
407E	0	1600	425A	0	1500
408A	0.024	3200	426A	0	1500
409A	0.046	1600	427A	0	2100
409B	0.045	1600	428A	0	3600
410A	0	2100	500	0.738	8100
411A	0.044	1600	502	0.250	4700
411B	0.047	1700	503	0.599	15 000
412A	0.053	2300	507A	0	4000
413A	0	2100	508A	0	13 000
414A	0.043	1500	508B	0	13 000
414B	0.039	1400	509A	0.022	5700
415A	0.028	1500			

*ODPs and GWP_{100}s from Calm and Hourahan (2007), computed based on mass-weighted averages of values for individual components.

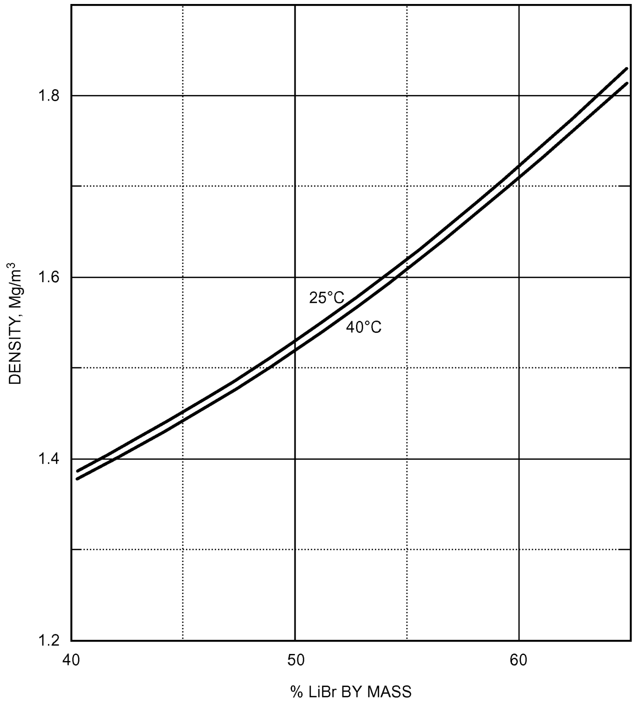

Fig. 1 Specific Density of Aqueous Solutions of Lithium Bromide

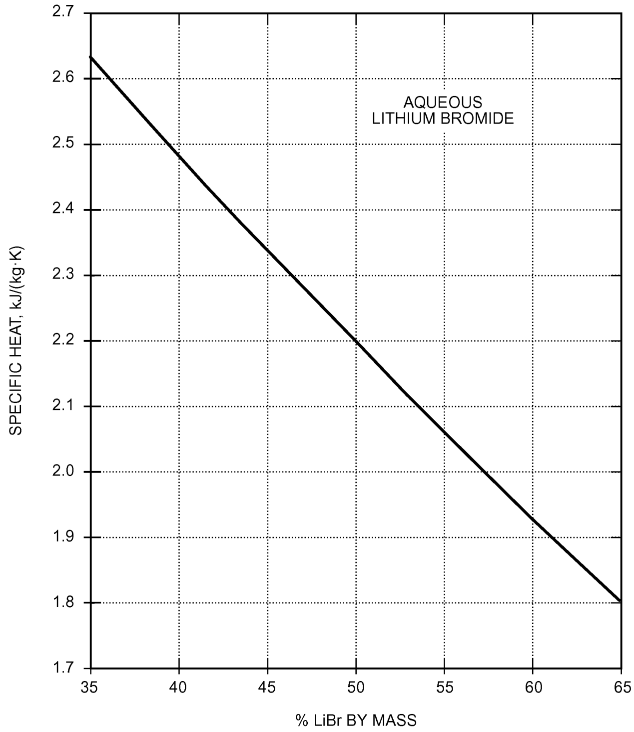

Fig. 2 Specific Heat of Aqueous Lithium Bromide Solutions

point where the distinction between liquid and gas is lost. At higher temperatures, no separate liquid phase is possible for pure fluids. In refrigeration cycles involving condensation, a refrigerant must be chosen that allows this change of state to occur at a temperature somewhat below the critical. Cycles that reject heat at supercritical temperatures (such as cycles using carbon dioxide) are also possible.

Lithium Bromide/Water and Ammonia/Water Solutions. These are the most commonly used working fluids in absorption refrigeration systems. Figure 1 shows density, Figure 2 shows specific heat, and Figure 3 shows viscosity of lithium bromide/water solutions. Chapter 30 has an enthalpy-concentration diagram and a vapor pressure diagram for lithium bromide/water solutions. Chapter 30 also has equilibrium properties of water/ammonia solutions.

Electrical Properties

Tables 6 and 7 list the electrical characteristics of refrigerants that are especially important in hermetic systems.

Sound Velocity

The practical velocity of a gas in piping or through openings is limited by the velocity of sound in the gas.

Table 8 gives examples of the velocity of sound in the vapor phase of various refrigerants. Chapter 30 has sound velocity data for many refrigerants. The velocity increases when temperature is increased and decreases when pressure is increased. The velocity of sound can be calculated from the equation

$$V_a = \sqrt{(dp/d\rho)_S} = \sqrt{\gamma(dp/d\rho)_T} \quad (1)$$

where

V_a = sound velocity, m/s
p = pressure, Pa
ρ = density, kg/m³
γ = c_p/c_v = ratio of specific heats
S = entropy, kJ/(kg·K)
T = temperature, K

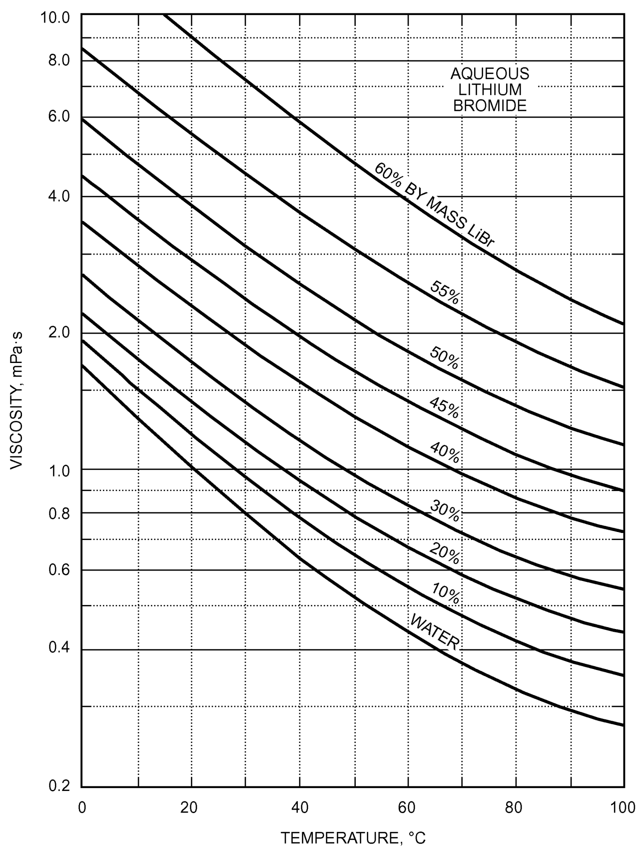

Fig. 3 Viscosity of Aqueous Solutions of Lithium Bromide

Table 5 Physical Properties of Selected Refrigerants[a]

Refrigerant									
No.	Chemical Name or Composition (% by Mass)	Chemical Formula	Molecular Mass	Boiling Pt. (NBP) at 101.325 kPa, °C	Freezing Point, °C	Critical Temperature, °C	Critical Pressure, kPa	Critical Density, kg/m^3	Refractive Index of Liquid[b,c]
728	Nitrogen	N_2	28.013	–195.8	–210.0	–146.96	3395.8	313.3	1.205 (83 K) 589.3 nm
729	Air	—	28.959	–194.25	—	–140.59	3789.6	335.94	—
740	Argon	Ar	39.948	–185.85	–189.34	–122.46	4863.0	535.6	1.233 (84 K) 589.3 nm
732	Oxygen	O_2	31.999	–182.96	–218.79	–118.57	5043.0	436.14	1.221 (92 K) 589.3 nm
50	Methane	CH_4	16.043	–161.48	–182.46	–82.586	4599.2	162.66	—
14	Tetrafluoromethane	CF_4	88.005	–128.05	–183.61	–45.64	3750.0	625.66	—
170	Ethane	C_2H_6	30.07	–88.581	–182.8	32.72	4872.2	206.18	—
503	R-23/13 (40.1/59.9)	—	87.247	–87.76	—	18.417	4280.5	565.68	—
508A[4]	R-23/116 (39/61)	—	100.1	–87.233	—	10.192	3650.8	567.58	—
508B[4]	R-23/116 (46/54)	—	95.394	–87.206	—	11.205	3771.6	568.45	—
23	Trifluoromethane	CHF_3	70.014	–82.018	–155.13	26.143	4832	526.5	—
13	Chlorotrifluoromethane	$CClF_3$	104.46	–81.48	–181.15	28.85	3879	582.88	1.146 (25)[2]
744	Carbon dioxide	CO_2	44.01	–78.4[d]	–56.558[e]	30.978	7377.3	467.6	1.195 (15)
504	R-32/115 (48.2/51.8)	—	79.249	–57.906	—	62.138	4428.8	504.68	—
32	Difluoromethane	CH_2F_2	52.024	–51.651	–136.81	78.105	5782.0	424	—
410A	R-32/125 (50/50)	—	72.585	–51.446	—	71.358	4902.6	459.53	—
125	Pentafluoroethane	C_2HF_5	120.02	–48.09	–100.63	66.023	3617.7	573.58	—
1270	Propylene	C_3H_6	42.08	–47.62	–185.2	91.061	4554.8	230.03	1.3640 (–50)[1]
143a	Trifluoroethane	CH_3CF_3	84.041	–47.241	–111.81	72.707	3761.0	431.0	—
507A	R-125/143a (50/50)	—	98.859	–46.741	—	70.617	3705	490.77	—
404A	R-125/143a/134a (44/52/4)	—	97.604	–46.222	—	72.046	3728.9	486.53	—
502	R-22/115 (48.8/51.2)	—	111.63	–45.174	—	80.507	4016.8	568.70	—
407C	R-32/125/134a (23/25/52)	—	86.204	–43.627	—	86.034	4629.8	484.23	—
290	Propane	C_3H_8	44.096	–42.11	–187.62	96.74	4251.2	220.4	1.3397 (–42)
22	Chlorodifluoromethane	$CHClF_2$	86.468	–40.81	–157.42	96.145	4990.0	523.84	1.234 (25)[2]
115	Chloropentafluoroethane	$CClF_2CF_3$	154.47	–39.25	–99.39	79.95	3129.0	614.8	1.221 (25)[2]
500	R-12/152a (73.8/26.2)	—	99.303	–33.603	—	102.09	4168.6	495.1	—
717	Ammonia	NH_3	17.03	–33.327	–77.655	132.25	11 333.0	225.0[d]	1.325 (16.5)
12	Dichlorodifluoromethane	CCl_2F_2	120.91	–29.752	–157.05	111.97	4136.1	565.0	1.288 (25)[2]
134a	Tetrafluoroethane	CF_3CH_2F	102.03	–26.074	–103.3	101.06	4059.3	511.9	—
152a	Difluoroethane	CHF_2CH_3	66.051	–24.023	–118.59	113.26	4516.8	368	—
124	Chlorotetrafluoroethane	$CHClFCF_3$	136.48	–11.963	–199.15	122.28	3624.3	560.0	—
600a	Isobutane	C_4H_{10}	58.122	–11.75	–159.42	134.66	3629.0	225.5	1.3514 (–25)[1]
142b	Chlorodifluoroethane	$CClF_2CH_3$	100.5	–9.15	–130.43	137.11	4055.0	466.0	—
C318	Octafluorocyclobutane	C_4F_8	200.03	–5.975	–39.8	115.23	2777.5	619.97	
600	Butane	C_4H_{10}	58.122	–0.49	–102.7	151.98	3796.0	227.94	1.3562 (–15)[1]
114	Dichlorotetrafluoroethane	$CClF_2CClF_2$	170.92	3.586	–94.15	145.68	3257.0	579.97	1.294 (25)
11	Trichlorofluoromethane	CCl_3F	137.37	23.708	–110.47	197.96	4407.6	554.0	1.362 (25)[2]
123	Dichlorotrifluoroethane	$CHCl_2CF_3$	152.93	27.823	–107.15	183.68	3661.8	550.0	—
141b	Dichlorofluoroethane	CCl_2FCH_3	116.95	32.05	–103.5	204.4	4212.0	458.6	—
113	Trichlorotrifluoroethane	CCl_2FCClF_2	187.38	47.585	–36.22	214.06	3392.2	560.0	1.357 (25)[2]
718[3]	Water	H_2O	18.015	99.974	0.01	373.95	22 064.0	322.0	—

Notes:
[a]Data from NIST (2007) REFPROP v. 8.0.
[b]Temperature of measurement (°C, unless kelvin is noted) shown in parentheses. Data from CRC (1987), unless otherwise noted.
[c]For the sodium D line.
[d]Sublimes.
[e]At 527 kPa.

References:
[1]Kirk and Othmer (1956).
[2]*Bulletin* B-32A (DuPont).
[3]*Handbook of Chemistry* (1967).
[4]*NIST Standard Reference Database 23*, v. 7 (Lemmon et al. 2002).

Sound velocity can be estimated from tables of thermodynamic properties. Change in pressure with a change in density ($dp/d\rho$) can be estimated at either constant entropy or constant temperature. It is simpler to estimate at constant temperature, but the ratio of specific heats must also be known.

REFRIGERANT PERFORMANCE

Chapter 2 describes several methods of calculating refrigerant performance, and Chapter 30 includes tables of thermodynamic properties of refrigerants.

Table 9 shows the theoretical calculated performance of a number of refrigerants for a standard cycle of 258 K evaporation and 303 K condensation. In most cases, suction vapor is assumed to be saturated, and compression is assumed adiabatic or at constant entropy. For R-113 and R-114, for example, these assumptions cause some liquid in the discharge vapor. In these cases, it is assumed that discharge vapor is saturated and that suction vapor is slightly superheated. Note that actual operating conditions and performance differ somewhat from numbers in the table because of additional factors such as compressor efficiency and transport properties.

Table 6 Electrical Properties of Liquid Refrigerants

Refrigerant No.	Chemical Name or Composition (% By Mass)	Temp., °C	Dielectric Constant	Volume Resistivity, MΩ·m	Ref.
11	Trichlorofluoromethane	28.9	2.28		1
		a	1.92	63 680	2
		25	2.5	90	3
		25	2.32		10
12	Dichlorodifluoromethane	28.9	2.13		1
		a	1.74	53 900	2
		25	2.1	>120	3
		25	2.100		4
		25	2.14		10
13	Chlorotrifluoromethane	–30	2.3	120	4
		20	1.64		
22	Chlorodifluoromethane	23.9	6.11		1
		a	6.12	0.83	2
		25	6.6	75	3
		25	6.42		10
23	Trifluoromethane	–30	6.3		3
		20	5.51		4
32	Difluoromethane	a	14.27		6
		25	14.67		10
113	Trichlorotrifluoroethane	30	2.44		1
		a	1.68	45 490	2
		25	2.6	>120	3
114	Dichlorotetrafluoroethane	31.1	2.17		1
		a	1.83	66 470	2
		25	2.2	>70	3
123	2,2-dichloro-1,1,1-trifluoroethane	a	4.50	14 700	7
124	2-chloro-1,1,1,2-tetrafluoroethane	25	4.89		10
124a	Chlorotetrafluoroethane	25	4.0	50	3
125	Pentafluoroethane	20	4.94		8
		25	5.10		10
134a	1,1,1,2-tetrafluoroethane	a	9.51	17 700	7
		25	9.87		10
143a	1,1,1-trifluoroethane	25	9.78		10
236fa	1,1,1,3,3,3-hexafluoropropane	25	7.89		10
245fa	1,1,1,3,3-pentafluoropropane	25	6.82		10
290	Propane	a	1.27	73 840	2
404A	R-125/143a/134a (44/52/4)	a	7.58	8450	9
		25	8.06		10
407C	R-32/125/134a (23/25/52)	a	8.74	7420	9
		25	10.21		10
410A	R-32/125 (50/50)	a	7.78	3920	9
		25	5.37		10
500	R-12/152a (73.8/26.2)	a	1.80	55 750	2
507A	R-125/143a (50/50)	a	6.97	5570	9
		25	7.94		10
508A	R-23/116 (39/61)	–30	6.60		1
		0	5.02		1
508B	R-23/116 (46/54)	–30	7.24		1
		0	5.48		1
717	Ammonia	20.6	15.5		5
744	Carbon dioxide	0	1.59		5

a = ambient temperature

References:
1 Data from E.I. DuPont de Nemours & Co., Inc.
2 Beacham and Divers (1955)
3 Eiseman (1955)
4 Fellows et al. (1991)
5 CRC (1987)
6 Bararo et al. (1997)
7 Fellows et al. (1991)
8 Pereira et al. (1999)
9 Meurer et al. (2001)
10 Gbur (2005)

Table 7 Electrical Properties of Refrigerant Vapors

Refrigerant No.	Chemical Name or Composition (% by mass)	Pressure, kPa	Temp., °C	Dielectric Constant	Relative Dielectric Strength, Nitrogen = 1	Volume Resistivity, GΩ·m	Ref.
11	Trichlorofluoromethane	50.7	26.1	1.0019			3
		a	b	1.009		74.35	2
		101.3	22.8		3.1		4
12	Dichlorodifluoromethane	50.7	28.9	1.0016			3
		a	b	1.012	452[c]	72.77	2
		101.3	22.8		2.4		4
		101.3	25	1.0064			6
13	Chlorotrifluoromethane	50.7	28.9	1.0013			3
		101.3	22.8		1.4		4
14	Tetrafluoromethane	50.7	24.4	1.0006			3
		101.3	22.8		1.0		4
22	Chlorodifluoromethane	50.7		1.0035			3
		a	b	1.004	460[c]	2113	2
		101.3	22.8		1.3		4
		101.3	25	1.0068			6
32	Difluoromethane	101.3	25	1.0102			6
113	Trichlorotrifluoroethane	a	b	1.010	440[c]	94.18	2
		40.5	22.8		2.6		4
114	Dichlorotetrafluoroethane	50.7	26.7	1.0021			3
		a	b	1.002	295[c]	148.3	2
		101.3	22.8		2.8		4
116	Hexafluoroethane	95.2	22.8	1.002			3
124	2-chloro-1,1,1,2-tetrafluoroethane	101.3	25	1.0060			6
125	Pentafluoroethane	101.3	25	1.0072			6
134a	1,1,1,2-tetrafluoroethane	101.3	25	1.0125			6
142b	Chlorodifluoroethane	94.2	27.2	1.013			3
143a	Trifluoroethane	86.1	25	1.013			3
		101.3	25	1.0170			6
170	Ethane	101.3	0	1.0015			1
236fa	1,1,1,3,3,3-hexafluoropropane	101.3	25	1.0121			6
245fa	1,1,1,3,3-pentafluoropropane	101.3	25	1.0066			6
290	Propane	a	b	1.009	440[c]	105.3	2
404A	R-125/143a/134a (44/52/4)	101.3	25	1.0121			6
407C	R-32/125/134a (23/25/52)	101.3	25	1.0113			6
410A	R-32/125 (50/50)	101.3	25	1.0078			6
500	R-12/152a (73.8/26.2)	a	b	1.024	470[c]	76.45	2
507A	R-125/143a (50/50)	101.3	25	1.0119			6
508A	R-23/116 (39/61)	a	–30	1.12			5
		a	0	1.31			5
		101.3	25	1.0042			6
508B	R-23/116 (46/54)	a	–30	1.13			5
		a	0	1.34			5
		101.3	25	1.0042			6
717	Ammonia	101.3	0	1.0072			1
		a	0		0.82		4
729	Air	101.3	0	1.00059			1
744	Carbon dioxide	101.3	0	1.00099			1
		101.3	b		0.88		4
1150	Ethylene	101.3	0	1.00144			1
		101.3	22.8		1.21		4

Notes:
a = saturation vapor pressure
b = ambient temperature
c = measured breakdown voltage, volts/mil

References:
1 CRC (1987)
2 Beacham and Divers (1955)
3 Fuoss (1938)
4 Charlton and Cooper (1937)
5 Data from E.I. DuPont de Nemours & Co., Inc.
6 Gbur (2005)

Table 8 Velocity of Sound in Refrigerant Vapors

Refrigerant	Pressure, kPa	Temperature, °C 10	50	100
		Velocity of Sound, m/s		
11	100	b	144.52	156.06
12	100	145.94	156.20	167.93
	1000	b	136.60	156.04
	1500	b	b	148.45
22	100	177.08	188.81	202.24
	1000	b	173.97	193.09
	1500	b	163.78	187.56
23	100	199.83	212.33	226.78
	1000	188.21	204.92	222.29
	1500	180.89	200.66	219.83
32	100	235.50	250.33	267.05
	1000	212.11	236.68	258.78
	1500	b	228.18	254.02
113	100	b	119.64	130.01
114	100	118.04	127.18	137.39
123	100	b	134.30	145.46
	1000	b	b	b
	1500	b	b	b
124	100	133.96	143.96	155.12
	1000	b	b	139.55
	1500	b	b	128.84
134a	100	157.21	168.39	180.99
	1000	b	146.88	168.59
	1500	b	b	160.87
143a	100	174.73	186.74	200.45
	1000	b	168.36	189.26
	1500	b	156.00	182.68
404A	100	161.39	172.60	185.37
	1000	b	155.51	178.05
	1500	b	143.93	168.98
407C	100	173.85	185.72	199.20
	1000	b	169.30	189.38
	1500	b	158.12	183.56
410A	100	192.84	205.56	220.06
	1000	170.15	192.17	211.92
	1500	b	183.78	207.24
502	100	152.01	162.45	174.43
	1000	b	147.40	165.17
	1500	b	136.70	159.59
507A	100	160.32	174.45	184.14
	1000	b	154.67	174.00
	1500	b	143.34	168.04
508A	100	161.68	172.35	184.74
	1000	149.98	164.89	180.22
	1500	142.71	160.67	177.84
508B	100	166.23	177.14	189.76
	1000	154.64	169.74	185.31
	1500	147.46	165.55	182.94
600	100	204.59	219.88	236.83
	1000	b	b	206.17
	1500	b	b	181.53
600a	100	205.58	220.45	237.15
	1000	b	b	210.17
	1500	b	b	190.26
717	100	422.02	450.44	482.17
	1000	b	430.71	470.71
	1500	b	417.84	463.93
744	100	262.37	278.69	297.64
	1000	253.98	273.23	294.31
	1500	248.95	270.12	292.48

Source: *NIST Standard Reference Database 23*, v.7.0 (Lemmon et al. 2002)
b = Below saturation temperature.

SAFETY

Tables 1 and 2 summarize toxicity and flammability characteristics of many refrigerants. In ASHRAE *Standard* 34, refrigerants are classified according to the hazard involved in their use. The toxicity and flammability classifications yield six safety groups (A1, A2, A3, B1, B2, and B3) for refrigerants. Group A1 refrigerants are the least hazardous, Group B3 the most hazardous.

The safety classification in ASHRAE *Standard* 34 consists of a capital letter and a numeral. The capital letter designates a toxicity class based on allowable exposure:

- Class A: Toxicity has not been identified at concentrations less than or equal to 400 ppm by volume, based on data used to determine threshold limit value/time-weighted average (TLV/TWA) or consistent indices.
- Class B: There is evidence of toxicity at concentrations below 400 ppm by volume, based on data used to determine TLV/TWA or consistent indices.

The numeral denotes flammability:

- Class 1: No flame propagation in air at 21°C and 101 kPa
- Class 2: Lower flammability limit (LFL) greater than 0.10 kg/m^3 at 21°C and 101 kPa and heat of combustion less than 19 000 kJ/kg
- Class 3: Highly flammable as defined by LFL less than or equal to 0.10 kg/m^3 at 21°C and 101 kPa or heat of combustion greater than or equal to 19 000 kJ/kg

LEAK DETECTION

Leak detection in refrigeration equipment is of major importance for manufacturers and service engineers.

Electronic Detection

Electronic detectors are widely used in manufacture and assembly of refrigeration equipment. Instrument operation depends on the variation in current flow caused by ionization of decomposed refrigerant between two oppositely charged platinum electrodes. This instrument can detect any of the halogenated refrigerants except R-14; however, it is not recommended for use in atmospheres that contain explosive or flammable vapors. Other vapors, such as alcohol and carbon monoxide, may interfere with the test.

The electronic detector is the most sensitive of the various leak detection methods, reportedly capable of sensing a leak of 0.3 g of R-12 per year. A portable model is available for field testing. Other models are available with automatic balancing systems that correct for refrigerant vapors that might be present in the atmosphere around the test area.

Bubble Method

The object to be tested is pressurized with air or nitrogen. A pressure corresponding to operating conditions is generally used. If possible, the object is immersed in water, and any leaks are detected by observing bubbles in the liquid. Adding a detergent to the water decreases surface tension, prevents escaping gas from clinging to the side of the object, and promotes formation of a regular stream of small bubbles. Kerosene or other organic liquids are sometimes used for the same reason. A solution of soap or detergent can be brushed or poured onto joints or other spots where leakage is suspected. Leaking gas forms soap bubbles that can be readily detected.

Leaks can also be determined by pressurizing or evacuating and observing the change in pressure or vacuum over a period of time. This is effective in checking system tightness but does not locate the point of leakage.

UV Dye Method

A stable UV-fluorescent dye is introduced into the system to be tested. Operating the system mixes the UV dye uniformly in the

Table 9 Comparative Refrigerant Performance per Ton of Refrigeration

Refrigerant No.	Chemical Name or Composition (% by mass)	Evaporator Pressure, MPa	Condenser Pressure, MPa	Compression Ratio	Net Refrigerating Effect, kJ/kg	Refrigerant Circulated, g/s	Liquid Circulated, L/s	Specific Volume of Suction Gas, m^3/kg	Compressor Displacement, L/s	Power Consumption, kW	Coefficient of Performance	Compressor Discharge Temp., °C
170	Ethane	1.608	4.639	2.88	161.71	6.10	0.0219	0.0338	0.206	0.365	2.7	323
744	Carbon dioxide	2.254	7.18	3.19	133.23	3.88	0.0064	0.0168	0.065	0.192	2.69	343
1270	Propylene	0.358	1.304	3.64	286.17	3.46	0.0070	0.1299	0.449	0.220	4.5	315
290	Propane	0.286	1.075	3.76	277.90	3.53	0.0073	0.1562	0.551	0.218	4.5	309
502	R-22/115 (48.8/51.2)	0.343	1.312	3.83	105.95	9.43	0.0079	0.0508	0.479	0.228	4.38	311
507A	R-125/143a (50/50)	0.379	1.459	3.85	110.14	9.07	0.0089	0.0508	0.461	0.239	4.18	308
404A	R-125/143a/134a (44/52/4)	0.365	1.42	3.89	114.15	8.75	0.0086	0.0537	0.470	0.237	4.21	309
410A	R-32/125 (50/50)	0.478	1.872	3.92	167.89	5.84	0.0056	0.0545	0.318	0.222	4.41	324
125	Pentafluoroethane	0.403	1.561	3.87	85.30	11.41	0.0098	0.0394	0.449	0.244	3.99	304
22	Chlorodifluoromethane	0.295	1.187	4.02	162.67	6.13	0.0052	0.0779	0.478	0.214	4.66	326
12	Dichlorodifluoromethane	0.181	0.741	4.09	117.02	8.49	0.0066	0.0923	0.784	0.212	4.7	311
500	R-12/152a (73.8/26.2)	0.214	0.876	4.09	139.68	7.08	0.0063	0.0939	0.665	0.212	4.66	314
407C	R-32/125/134a (23/25/52)	0.288	1.26	4.38	163.27	6.11	0.0054	0.0805	0.492	0.222	4.5	321
600a	Isobutane*	0.088	0.403	4.58	263.91	3.76	0.0069	0.4073	1.533	0.215	4.62	303
134a	Tetrafluoroethane	0.163	0.767	4.71	148.03	6.71	0.0056	50.1214	0.814	0.216	4.6	310
124	Chlorotetrafluoroethane*	0.0088	0.443	5.03	117.83	8.41	0.0063	0.1711	11.439	0.214	4.62	303
717	Ammonia	0.235	1.162	4.94	1103.1	0.90	0.0015	0.5117	0.463	0.210	4.76	372
600	Butane*	0.056	0.283	5.05	292.24	3.53	0.0062	0.6446	2.274	0.218	4.74	303
11	Trichlorofluoromethane	0.02	0.125	6.25	155.95	6.36	0.0043	0.7689	4.891	0.197	5.02	316
123	Dichlorotrifluoroethane	0.016	0.109	6.81	142.28	7.02	0.0048	0.8914	6.259	0.204	4.9	306
113	Trichlorotrifluoroethane*	0.007	0.054	7.71	122.58	7.84	0.0051	1.6818	13.187	0.200	4.81	303

*Superheat required.

oil/refrigerant system. The dye, which usually prefers oil, shows up at the leak's location, and can be detected using an appropriate UV lamp. Ensure that the dye is compatible with system components and that no one is exposed to UV radiation from the lamp. This method is often more effective for liquid leaks than for vapor.

Another, more expensive method is to use dispersive and nondispersive infrared analyzers. Although these analyzers are expensive, they can not only find the refrigerant leak but also identify the refrigerant.

Ammonia Leaks

Ammonia can be detected by any of the previously described methods, or by bringing a solution of hydrochloric acid near the object. If ammonia vapor is present, a white cloud or smoke of ammonium chloride forms. Ammonia can also be detected with indicator paper that changes color in the presence of a base.

EFFECT ON CONSTRUCTION MATERIALS

Metals

Halogenated refrigerants can be used satisfactorily under normal conditions with most common metals, such as steel, cast iron, brass, copper, tin, lead, and aluminum. Under more severe conditions, various metals affect properties such as hydrolysis and thermal decomposition in varying degrees. The tendency of metals to promote thermal decomposition of halogenated compounds is in the following order:

(least decomposition) Inconel < 18-8 stainless steel < nickel < copper < 1040 steel < aluminum < bronze < brass < zinc < silver (most decomposition)

This order is only approximate, and there may be exceptions for individual compounds or for special use conditions. The effect of metals on hydrolysis is probably similar.

Table 10 Swelling of Elastomers in Liquid Refrigerants at Room Temperature, % Linear Swell

Refrigerant Number	Polyisoprene (Sulfur Cure)	Polychloroprene	Butyl Rubber	Styrene Butadiene Rubber	Nitrile Rubber	Fluoroelastomer
22	10.2	6.1	3.9	9.8	51.4	33.2
123	48.0	15.3	16.3	40.8	83.7	31.6
124	5.8	2.8	3.2	4.1	45.9	29.0
142b	10.2	6.5	6.2	7.3	8.7	31.8
32	2.7	1.0	1.0	2.0	8.3	23.2
125	4.2	2.7	2.6	3.6	3.9	11.7
134a	1.2	1.2	0.6	1.0	5.1	25.6
143a	1.9	1.2	1.3	1.5	2.0	13.6
152a	4.2	3.0	1.7	2.8	8.8	3.91

Magnesium alloys and aluminum containing more than 2% magnesium are not recommended for use with halogenated compounds where even trace amounts of water may be present. Zinc is not recommended for use with CFC-113. Experience with zinc and other fluorinated compounds has been limited, but no unusual reactivity has been observed under normal conditions of use in dry systems.

Ammonia should never be used with copper, brass, or other alloys containing copper. Further discussion of the compatibility of refrigerants and lubricants with construction materials may be found in Chapter 5 of the 2006 *ASHRAE Handbook—Refrigeration*.

Elastomers

Linear swelling of some elastomers in the liquid phase of HCFC and HFC refrigerants is shown in Table 10. Swelling data can be used to a limited extent in comparing the effect of refrigerants on elastomers. However, other factors, such as the amount of extraction, tensile strength, and degree of hardness of the exposed elastomer, must be considered. When other fluids (e.g., lubricants) are present in addition to the refrigerant, the combined effect on elastomers should be determined. Extensive test data for compatibility of elastomers and gasketing materials with refrigerants and lubricants

Table 11 Diffusion of Water and R-22 Through Elastomers

Elastomer	Diffusion Rate	
	Water[a]	R-22[b]
Polychloroprene	970	4.63
Nitrile rubber	150	69.4
Chlorosulfonated polyethylene	620	1.85
Butyl rubber	58	1.04
Fluoroelastomer	—	12.7
Polyethylene	167	—
Natural	1940	—

Adapted from Eiseman (1955).
[a]75 µm film, 100% rh at 38°C. Water diffusion rate is in micrograms per second per square metre of elastomer.
[b]Film thickness = 25 µm; temperature = 25°C. Gas at 101.3 kPa and 0°C. Diffusion rate in cubic centimetres of gas per second per square metre of elastomer.

are reported by Hammed et al. (1994). Diffusion of fluids through elastomers is another consideration; Table 11 shows the diffusion rate of water and R-22 through elastomers.

Plastics

The effect of a refrigerant on a plastic material should be thoroughly examined under conditions of intended use, including the presence of lubricants. Plastics are often mixtures of two or more basic types, and it is difficult to predict the refrigerant's effect. Swelling data can be used as a general guide of effect, but, as with elastomers, the effect on properties of the plastic should also be examined. Extensive test data for compatibility of plastics with refrigerants and lubricants are reported by Cavestri (1993), including 23 plastics, 10 refrigerants, 7 lubricants, and 17 refrigerant/lubricant combinations. Refrigerants and lubricants had little effect on most of the plastics. Three plastics (acrylonitrile-butadiene-styrene, polyphenylene oxide, and polycarbonate) were affected enough to be considered incompatible. In a separate study by DuPont Fluoroproducts, two additional plastics (acrylic and polystyrene plastics) were determined to have questionable compatibility with HCFC and HFC refrigerants.

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