

# COMPARATIVE EFFICIENCIES AND IMPLICATIONS FOR GREENHOUSE GAS EMISSIONS OF CHILLER REFRIGERANTS

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## ABSTRACT

This paper summarises analyses of refrigerant options for chillers. It presents tabulated global warming potentials and other environmental data for candidate refrigerants. The paper discusses briefly the historic progression in refrigerant release reductions and presents analyses to compare the efficiencies of historic and current refrigerant options. The 28 refrigerants addressed include chlorofluorocarbon (CFC), hydrochlorofluorocarbon (HCFC), hydrofluorocarbon (HFC), hydrocarbon (HC) and inorganic (such as ammonia) fluids. The paper discusses the relative importance of the refrigerant-related and energy-related components of chiller emissions

**Keywords:** refrigerants, air conditioning, refrigeration, chillers, efficiency, global warming

Chillers are refrigeration machines that cool water, other heat transfer fluids, or process fluids by a vapor-compression (modified reverse-Rankine), absorption, or other thermodynamic cycle. Their most common use is in central systems in large buildings or complexes, such as offices, campuses, shopping centers, hospitals, hotels, and military installations. The chilled water (or less commonly a brine or other heat-transfer fluid) is piped through the building or buildings to other devices, such as zoned air handlers, that use the cooled water or brine to air condition (cool and dehumidify) occupied or controlled spaces. By their nature, both efficiency and reliability are critical attributes of chillers.

Such machines typically are the core of central systems to air condition large office, commercial, medical, entertainment, residential high-rise, and similar buildings or clusters of buildings. Both large central and interconnected plants, generally with multiple chillers in each, are common for shopping centers; university, medical, and office campuses; military installations; and district cooling systems. Chillers range in thermal capacity from approximately 10 kW (3 ton) to exceeding 30 MW (8,500 ton), with a more common range of 300 kW (85 ton) to 14 MW (4,000 ton). Larger systems typically employ multiple chillers, with some installations exceeding 300 MW (85,000 ton) of cooling.

Both mechanical vapor-compression and absorption systems employ refrigerants. Absorption cycles are differentiated from mechanical compression systems by use of heat-driven, chemical absorption processes to raise the refrigerant pressure. The most common working fluids for absorption chillers are ammonia as refrigerant with water as the absorbent in small capacities, and water as the refrigerant with lithium bromide or much less commonly lithium chloride as the absorbent in large systems. Fuel prices or peak-electric demand avoidance justify absorption chillers in some applications, and they are common in countries with unique energy circumstances, such as Japan, and in countries with inadequate electric power infrastructures. Mechanical vapor-compression dominates in most locations based on significant advantages in efficiency, size, and equipment cost. Fluorochemicals are the most common refrigerants, but ammonia, hydrocarbons, and other fluids are options subject to limitations discussed below.

Refrigerant selections influence global warming two ways, directly by releases acting as a greenhouse gas (GHG) and

indirectly by emissions associated with energy use. Of the two, the energy-related component typically has a much larger impact and can exceed 99% of the total.

The refrigerant-related component can be determined by summing initial, operating, intermittent, and ultimate retirement losses weighted by the appropriate global warming potential (GWP). The majority of refrigerant releases occur on site – at the point of use – from leakage, servicing, and averaged releases from failures or catastrophic discharges from accidents and failures. Upstream emissions associated with manufacture, packaging and repackaging, transport, storage, and equipment charging as well as downstream losses associated with ultimate recovery and disposal occur only once in the life of the refrigerant use. They constitute a small fraction, compared to the operating and intermittent service and failure losses, when annualised for an application with a typical life of 20-30 years.

The energy-related impact results from operation and is, therefore, influenced by the chiller efficiency and thus by the refrigerant choice. The energy-related GHGs usually are released at the power plants that provide the electricity, or less commonly the steam or hot water, used to power air conditioning and refrigeration systems. The releases can be largely on-site in the case of engine, turbine, heat-driven systems, and direct-fired systems, but even they typically use some remotely generated electricity for controls, pumps, fans, and similar auxiliary devices. Summed over many hours of operation, the energy-related carbon dioxide, nitrous oxides, and other GHGs from fuel use far overshadow the refrigerant-related GHG impact for current equipment.

Whereas prior efforts focused on reduction of refrigerant releases and design improvements, the refrigerant selection now has greatest overall influence on the GWP of direct releases, the leakage and similar loss rates, and the equipment efficiency. The following discussion addresses the ways refrigerant selections influence GHG emissions for chillers.

## ENVIRONMENTAL IMPACTS AND USES OF CHILLER REFRIGERANTS

Table 1 (see end of this paper) summarises the atmospheric (combined tropospheric and stratospheric) lifetimes, ozone depletion potentials (ODPs), and global warming potentials (GWPs) of historic, common, and candidate refrigerants. The

GWPs shown include those for integration time horizons (ITHs) of 20, 100, and 500 years as well as the net GWPs for 100 years with inclusion of offsetting effects of stratospheric ozone depletion. While shorter ITH emphasises near-term impacts and discounts long-term consequences of the carbon-dioxide reference, longer ITH captures total warming impacts more completely [1]. Some investigators advocate use of absolute (essentially infinite) global warming potentials to minimise the influence of the reference basis [1].

Of the tabulated refrigerants, chlorofluorocarbon (CFC) R-11 was the most common historical choice for large chillers employing centrifugal turbo-compressors, based both on its efficiency and the cost advantages of low-pressure designs. Other CFCs also were used. R-12 came into acceptance, particularly for installations with low annual operating hours, R-113 to enable centrifugal chiller efficiencies in small capacities, and R-114 for specialty uses such as industrial heat pumps, heat-recovery chillers, and to meet unique requirements in submarines. R-500 (a refrigerant blend that includes the CFC R-115) was first introduced to attain the same capacity in equipment operating at 50 Hz motor speeds as with R-12 at 60 Hz; it gained further acceptance for capacity improvement. These CFCs were replaced for environmental protection primarily with hydrochlorofluorocarbon (HCFC) R-123 and hydrofluorocarbon (HFC) R-134a. HFC R-236fa has limited use to retrofit naval equipment. HCFC R-22 dominates in small systems using positive displacement (scroll, reciprocating piston, and screw) compressors, while inorganic R-717 (ammonia) enjoys wide use in industrial applications, especially with screw compressors, and limited use for space conditioning, notably in Europe. Use of R-290 (propane), R-1270 (propylene), and other hydrocarbons is extremely limited in chillers due to safety concerns. R-134a and to a lesser extent R-410A (an HFC blend) are replacing R-22 in screw and large scroll chillers, while R-410A is replacing it in chillers using reciprocating piston and small scroll compressors. Other HFC blends, notably R-404A and R-407C, are less commonly used, primarily in small chillers and then mostly for retrofit service. A slew of blends based on HCFCs, HFCs, and in some cases small fractions of HCs – to enable continued use of mineral oil lubricants – offer further options as service fluids.

The formerly anticipated replacement for R-123, HFC R-245ca, was abandoned based on flammability concerns, discussed below. Despite aggressive and sustained promotion by one chemical manufacturer, equipment manufacturers have not or not yet embraced the isomer R-245fa due to its higher pressure, lower efficiency particularly in single- and even two-stage designs, high cost, concerns with long-term availability (viewed as contingent upon sustained use as a blowing agent), and other factors. Several companies have tested R-245fa, but only one manufacturer is known to be actively considering its use as a refrigerant at this point, for a special design strategy.

The most common chiller refrigerants in new equipment are R-22 and R-410A in small chillers, R-134a in mid-size chillers, and R-123 and R-134a in large, centrifugal chillers. R-717 (ammonia) is widely used in industrial refrigeration, especially in the food and beverage industries, but less so in non-industrial chillers. The ammonia/water (refrigerant/absorbent) pair dominates in small absorption chillers while most large machines use water/lithium bromide.

## REFRIGERANT EMISSIONS

Annual losses exceeded 30% of the installed refrigerant in some equipment in the past. Current equipment and practices limit leakage rates to less than ½% per year in the best chillers. Reference [8] documents extensive changes in equipment design and installation, service, and recovery practices to reach this release level. Figure 1 depicts the progression in release reductions, which was spurred by concerns with stratospheric ozone depletion and global climate change.

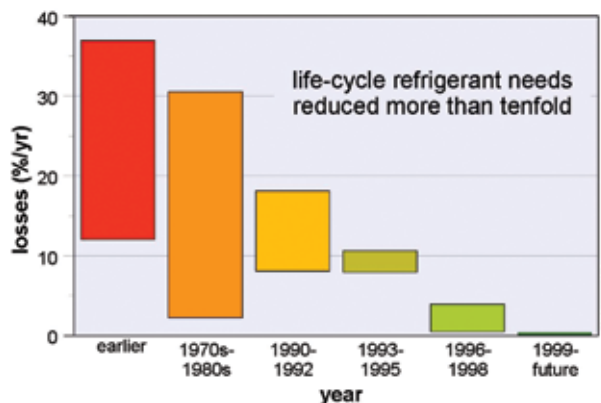


Figure 1 - progression in refrigerant release reductions for chillers [8]

Use of low-pressure refrigerants further reduces leakage rates for two reasons. First, such rates are driven by pressure differentials between the internal and external sides of refrigerant circuits, so lower pressure leads to much lower losses when inevitable leaks or infrequent ruptures happen. Similar benefits occur in service hose connections and disconnections, in handling accidents, and in container leaks during packaging, transportation, and storage.

Second, leaks in equipment or equipment components that operate below atmospheric pressure result in air being sucked in rather than refrigerant leaking out. While such operation requires a purge device to remove any air and moisture that leaks in, monitoring the purge operation serves as an early warning system of developing leaks so they can be repaired before refrigerant loss occurs.

Early mechanical, thermal, and similar low-efficiency purges offset the low-pressure leak minimisation by releasing significant refrigerant amounts along with purged air. Newer condensing purges – especially those coupled with self-regenerating filters to remove even trace quantities of refrigerant from removed air – reduce refrigerant release to near-zero levels measured in grams over equipment life rather than in kg per year (in ounces over equipment life rather than in pounds per year).

Reference [9] reports analyses of release data, from three sources, for nearly 6000 low-pressure chillers that were carefully monitored for periods as long as 8 years. The resulting data substantiate the reductions in refrigerant losses. Manufacturers also claim dramatic reductions for chillers using high-pressure refrigerants, but corroborating studies are needed. These claims generally extrapolate laboratory estimates of joint leakage. They generally exclude service losses, equipment failures, catastrophic losses such as fires in buildings, and the upstream and downstream losses that are included in the low-pressure data cited.

## REFRIGERANT EFFICIENCIES

Mechanical systems for air conditioning, refrigeration, ventilation, and space and water heating represent the largest fraction of electricity use in commercial and institutional buildings. The total for them in the USA amounts to 48% – nearly half – of all electricity use for these buildings [10]. The fraction for cooling alone is 26%, as shown in Figure 2.

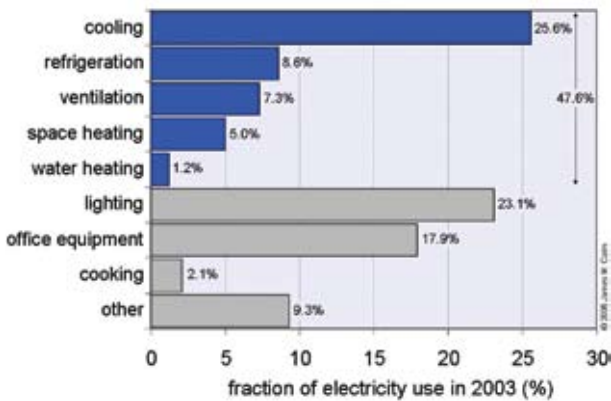


Figure 2 – electricity use in commercial buildings in the USA (based on data from reference [10])

The resulting energy-related emissions can be reduced with lowered cooling demands, efficient equipment, and operating strategies that maximise system performance. Based on their operating profiles, even small efficiency improvements translate to significant reductions in GHG emissions.

Thermodynamic cycle analyses offer insight into the comparative efficiencies of refrigerants in vapor-compression cycles. Essentially similar efficiency can be achieved by all refrigerants with sufficient cycle modification and optimisation to exploit or compensate for refrigerant differences [11]. However, each element of added complexity increases costs, refrigerant charge (amount), the potential for leaks, and thermodynamic irreversibilities [12]. Each addition also reduces the system's reliability. Hence, refrigerants with high efficiencies in simple cycles have an inherent advantage to improve efficiencies at lower costs and with lower system risk of environmental harm [12].

Table 2 (see end of this paper) updates prior efficiency comparisons for candidate refrigerants for chillers using newer, refined property data. Figure 3 depicts the results for the ideal cycle case.

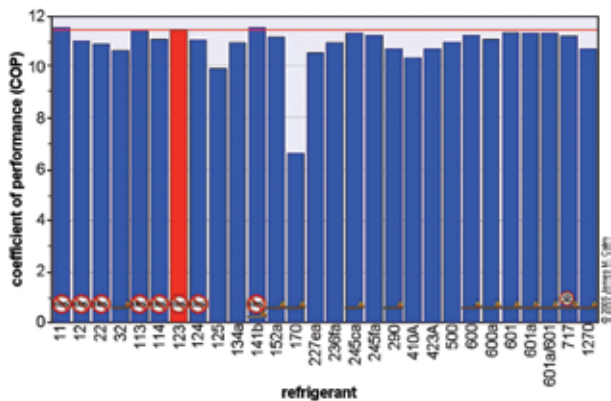


Figure 3 – comparative efficiencies of chiller refrigerants in ideal cycles for standard rating conditions (based on data in Table 2). Burning matches identify flammable refrigerants.

## DIFFERENCES AMONG PRIOR STUDIES

Reference [12] provided consistent performance calculations at standard rating conditions for both ideal and typical cycles for 16 refrigerants. Reference [8] updated the efficiency tabulations using refined thermodynamic property models and provided comparisons for 24 refrigerants.

Reference [19] reported similar comparative performance for nine refrigerants, though calculated at slightly different operating conditions. In a later publication [20], the same author suggests contrary findings regarding the comparative efficiencies of candidate refrigerants. Table 3 (see end of this paper) summarises the cited efficiencies for those identified as the top performance contenders in these studies. Except for the reference [20] findings, the normalised COPs in Table 3 show that there is reasonable consistency both in the comparative efficiencies and in the refrigerant efficiency rankings despite the differences in operating conditions analyzed.

Examination of the findings from reference [20] reveals different underlying assumptions, namely that postulated differences in heat transfer for the refrigerants examined leads to different temperature lift requirements for them. The assumptions are based on calculations using basic relations for laminar film condensation and for film heat flux per unit area for plain tubes. The approach disregards two pertinent considerations. First, it assumes plain rather than enhanced surfaces for the heat exchanger tubes. Surface enhancement is the norm in large chillers, and refrigerant-specific optimisation largely overcomes the suggested heat transfer differences. Second, differences in heat transfer performance can be compensated with increased or decreased surface area to achieve consistent lift requirements.

Table 4 (see end of this paper) shows the lift differences assumed in reference [20]. It shows a combined advantage of 1°C (1.8°F) or 3.1% for R-601 (n-pentane) compared to R-123. While this advantage is small, it exceeds the combined approach temperatures (sum of the evaporator approach temperature and the condenser approach temperature) for the best commercially available R-123 chillers [21], so it is impossible for R-601 to have that advantage for the most efficient chiller designs. Nevertheless, this assumed difference biases the result and explains the conflicting efficiency rankings between reference [20] and both reference [19] and the other studies, including the present paper. Tables 2 and 3 show more indicative comparisons driven by differences in the thermodynamic properties of the refrigerants with recognition that design optimisation, and specifically heat exchanger optimisation, can overcome small differences in transport properties that lead to small differences in heat transfer.

The Maclaine-Cross [20] study also concludes that the pentane isomer blend, R-601a/601 (37.0/63.0), can be substituted for R-11 and that R-601 can be substituted for R-123 with use of adjustable speed drives (ASDs) to increase the impeller speeds by 38 and 43%, respectively. The electronics in ASDs introduce 3-4% efficiency losses that are not addressed.

## FLAMMABILITY

Flammability is a severe concern for centrifugal chillers for three reasons. First, the refrigerant quantity used (charge size) exceeds 100 kg and for large machines can exceed several tonnes. That is quite different from household refrigerators, which typically use hydrocarbon refrigerant amounts of less

than amounts of less than 50 g or under 100 g for large sizes. That amount will not cause the extensive damage that would result in a fire or explosion with the much larger refrigerant charge needed for a chiller.

Second, the refrigerant circuit in a refrigerator is factory brazed or welded as the small compressor normally does not require field service and the tubing size is small enough to allow field brazing if service is needed. In contrast, the large compressors, and especially the centrifugal compressors that offer much higher efficiency than the rotary (and reciprocating) piston compressors typically used in refrigerators, do need periodic service. As such, some threaded and flanged joints are needed. Even with use of adhesive sealants, replacement of flared fittings with threaded fittings incorporating o-rings, and similar measures to minimise leakage [8], some leaks still occur.

And third, the most efficient refrigerant options for centrifugal chillers identified in Table 2 and Maclaine-Cross [20], namely R-11, R-113, R-123, R-141b, R-601 (n-pentane), R-601a (isopentane), and the pentane isomer blend R-601a/601 (37.0/63.0), all operate at sub-atmospheric pressures, at least in the "low-side" (evaporation side) of the cycle. Accordingly, air would be sucked in rather than refrigerant leaked out for typical leaks. While accumulated air would be removed by the purge system, prior compression of the hydrocarbon-air mixture would be exceptionally dangerous, particularly if the purge device failed for any reason. Diesel engine ignition is achieved by compression of fuel-air mixtures. For perspective, pentane isomers are used in fuels while R-123 is commercially used as a fire suppressant, as a halon alternative.

## OZONE DEPLETION AND GLOBAL WARMING CONSIDERATIONS

The analyses summarised above indicate that R-123 is the most efficient option for centrifugal chillers other than R-11 and R-141b. These two options, a CFC and an HCFC respectively, both have much longer atmospheric lifetimes and higher ODPs and GWPs than R-123, by factors of 35, 83, and 62 respectively for R-11 and factors exceeding 7, 7, and 9 respectively for R-141b. Both R-11 and R-141b have been phased out of commercial production in developed countries, the latter from primary use as a foam-blowing agent rather than as a refrigerant.

Both R-11 and R-123 enable economic use of multistage compression with direct drives. The multistage-economiser approach boosts efficiency by 3-7% depending on the number of stages. The direct drive avoids a 2-4% loss in mechanical efficiency inherent to gears. Combined with the 4.5% difference in theoretical efficiency, the best R-123 chillers offer 14% higher efficiency over R-134a designs. Most R-134a chillers have COPs lower than 6.5 and the best models still cannot achieve 6.8 despite extensive improvement efforts. Commercially available R-123 chillers can exceed COPs of 7.4. Some models reach 7.8, and improvement to 8.0 is likely. That translates to 14-15% higher efficiency with anticipated increase to 18% or higher. The actual benefit is compounded with additional energy savings from reduced loads on associated condensing water pumps and cooling towers.

There are additional options to improve seasonal chiller performance. One is use of adjustable speed drives to reduce compressor and pump speeds at part loads, but their use increases peak electrical demands by 3-4%. The same approaches can be used with all refrigerants, including R-123.

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The advantages of R-123 in terms of short atmospheric lifetime, very low GWP (comparable to or even lower than hydrocarbons on a net-GWP basis), and reduced emissions are all highly advantageous environmentally. Nevertheless, R-123 “consumption” (effectively production) is slated for phaseout by 2030 in developed countries and by 2040 in Article 5(1) countries pursuant to the Montreal Protocol. Use in new equipment will end in most developed countries by 2020 and already has stopped in Europe. Simply put, R-123 is lumped with all other HCFCs despite its unique environmental and other qualities. Prior studies show the impact on stratospheric ozone from R-123 use in chillers – even with exemption from phaseout – to be less than 0.001% of total chlorine-bromine loading [9, 22]; that impact is indiscernible and potentially eliminated with any resulting acceleration of CFC retirements.

There is no common denominator to equate the demerits of ozone depletion and global warming, but four factors suggest reconsideration of the scheduled R-123 phaseout. First, ozone depletion will not be discernibly increased and ozone layer recovery will not be retarded with an exemption for R-123 for chiller use [9, 22]. Second, R-123 use offers a significant opportunity to reduce GHG emissions (as discussed above and in references [8] and [9]). Third, the very short atmospheric lifetime of R-123 offers a hedge in case future unforeseen problems are discovered, in contrast to the long recovery period from prior release of chemicals with long lifetimes [22]. Despite production phaseout more than a decade ago in developed countries, prior releases of CFCs still – and will for many decades to come – retard recovery of the stratospheric ozone layer. And fourth, there neither are nor can be ideal alternatives that offer high efficiency, zero ODP, zero or near-zero GWP, safety, and stability, so some compromise is needed among these objectives [12].

## CONCLUSIONS

R-123 remains the best current option to reduce the substantial global warming contributions from chiller use for air conditioning and refrigeration. As demonstrated above and as stated in the 2002 assessment Report of the Refrigeration, Air-Conditioning, and Heat Pumps Technical Options Committee (RTOC) [23], prepared under the auspices of the United Nations Environment Program (UNEP):

“HCFC-123 has a favourable overall impact on the environment that is attributable to five factors: (1) a low ODP, (2) a very low GWP, (3) a very short atmospheric lifetime, (4) the extremely low emissions of current designs for HCFC-123 chillers and (5) the highest efficiency of all current options.”

This international assessment cites studies showing that “continued use of HCFC-123 in chillers would have imperceptible impact on stratospheric ozone while offering significant advantages in efficiency, thereby lowering greenhouse gas emissions from associated energy use.” The importance of these findings is highlighted by the latest UNEP Annual Report [24]:

“Global production and consumption of most ozone-depleting substances (ODS) has peaked and is declining, leading scientists to cautiously predict a gradual recovery of the Earth’s ozone shield by the middle of the century... International efforts to achieve the same kind of success in tackling global climate change – which represents an even greater threat to human health and sustainable development – have been less successful.” ■

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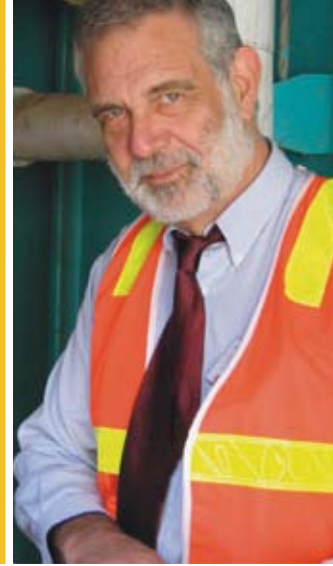
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#### About the author

James M Calm is an engineering consultant specialising in heating, air conditioning, and refrigerating systems. Much of his work involves the application and safety of alternative refrigerants. He is a Fellow of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), a member of the American Society of Mechanical Engineers (ASME), and an elected member of both Sigma Xi (honorary society for research) and Tau Beta Pi (honorary society for engineering). He holds bachelor and master of science degrees from Tufts University and holds multiple registrations as a professional engineer.

**See overleaf for tables.**

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**Table 1 — environmental data for historical, current and candidate chiller refrigerants**

Refrigerant*	Atmospheric Lifetime	ODP <sup>b</sup>	Direct GWP for Indicated ITH <sup>b</sup>			Met GWP <sup>c</sup> 100yr (2102)	
			20yr	100yr	500yr	minimum	maximum
R-11	45	1	6330	4680	1630	-524	3660
R-12	100	0.82	10340	10720	5230	7660	10120
R-22	12.0	0.034	4850	1780	552	1420	1710
R-32	4.9	~0	1800	543	169	543	543
R-113	85	0.90	6150	6030	2700	2470	5330
R-114	300	0.94	7560	9880	8780		
R-123	1.3	0.012	257	76	24	-44	53
R-124	5.8	0.026	1950	599	186	450	570
R-125	29	~0	5970	3450	1110	3450	3450
R-134a	14.0	~0	3370	1320	410	1320	1320
R-141b	9.3	0.086	2120	713	222	-109	552
R-152a	1.4	~0	411	122	38	122	122
R-170 (ethane)		~0		~20		~20	~20
R-227ea	34.2	~0	5760	3660	1200	3660	3660
R-236fa	240	~0	7620	9650	7700	9650	9650
R-245ca	6.2	~0	2200	682	212	682	682
R-245fa	7.6	~0	3180	1020	316	1020	1020
R-290 (propane)		~0		~20		~20	~20
R-410A <sup>d</sup>		~0	3900	2000	640	2000	2000
R-423A <sup>d,e</sup>		~0	4500	2400	790	2400	2400
R-500 <sup>d</sup>		0.605	7700	7900	3900	5685	7501
R-600 (n-butane)		~0		~20		~20	~20
R-600a (isobutane)		~0		~20		~20	~20
R-601 (n-pentane)		~0		~20		~20	~20
R-601a (isopentane)		~0		~20		~20	~20
R-601a/601 (37.0/63.0) <sup>d</sup>		~0		~20		~20	~20
R-717 (ammonia)		~0		<1		<1	<1
R-1270 (propylene)		~0		~20		~20	~20

a reference [2]

b data from references [3-5]; ODP values are modeled values; GWPs for blends are values calculated by the author based on component data

c references [6] and [3]

d R-410A is R-32/125 (50.0/50.0), R-423A is R-134a/227ea (52.5/47.5),e and R-500 is R-12/152a (73.8/26.2). The numbers preceding the parentheses indicate the components and the numbers inside the parentheses identify the percentages by mass [2].

e Standard designation pending [7]

(Tables continued overleaf)



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**Table 2 — comparative refrigerant efficiencies at standard chiller rating conditions**

Conditions	Ideal cycle a,b			Typical conditions b,c		
	(°C)	(%)	(°F)	(°C)	(%)	(°F)
Average evaporating temperature	6.7		44.0	5.0		41.0
Superheat	0.0		0.0	1.0		1.8
Average condensing temperature	29.4		85.0	35.0		95.0
Subcooling d	0.0		0.0	5.0		9.0
Isentropic compressor efficiency		100			80	
Motor efficiency		100			95	
Control and other power use		0			0	
Refrigerant e	COP (kW/kW)	Specific power (kW/ton)		COP (kW/kW)	Specific power (kW/ton)	
R-11	11.56	0.30		6.58	0.53	
R-12	11.03	0.32		6.29	0.56	
R-22	10.92	0.32		6.18	0.57	
R-32	10.64	0.33		5.97	0.59	
R-113	11.41	0.31		6.52	0.54	
R-114	11.08	0.32		6.34	0.56	
R-123	11.42	0.31		6.52	0.54	
R-124	11.04	0.32		6.31	0.56	
R-125	9.93	0.35		5.68	0.62	
R-134a	10.93	0.32		6.24	0.56	
R-141b	11.55	0.30		6.58	0.54	
R-152a	11.17	0.31		6.35	0.55	
R-170 (ethane)	6.62	0.53		f	f	
R-227ea	10.54	0.33		6.04	0.58	
R-236fa	10.94	0.32		6.26	0.56	
R-245ca	11.32	0.31		6.47	0.54	
R-245fa	11.24	0.31		6.43	0.55	
R-290 (propane)	10.73	0.33		6.14	0.57	
R-410A g	10.35	0.34		5.86	0.60	
R-423A g,h	10.73	0.33		6.14	0.57	
R-500 g	10.97	0.32		6.25	0.56	
R-600 (n-butane)	11.24	0.31		6.42	0.55	
R-600a (isobutane)	11.09	0.32		6.34	0.56	
R-601 (n-pentane)	11.37	0.31		6.50	0.54	
R-601a (isopentane)	11.32	0.31		6.47	0.54	
R-601a/601 (37.0/63.0) g	11.34	0.31		6.49	0.54	
R-717 (ammonia)	11.21	0.31		6.24	0.56	
R-1270 (propylene)	10.72	0.33		6.10	0.58	

- a Conditions are those for standard chiller ratings for water-cooled chillers [13].
- b Calculations were made with CYCLE\_D 3.0 [14] and property data updates and additions (R-601 and R-601A) based on REFPROP fluid models from [15-18]
- c Conditions approximate those typically encountered on the refrigerant side of water-cooled chillers. The “typical” efficiencies shown can be exceeded by optimizing subcooling and superheat, employing multiple stages, or using similar cycle modifications. Likewise, poor designs do not meet them.
- d Typical subcooling varies by refrigerant; the level shown is a representative selection for comparisons.
- e [2]
- f Condensing temperature exceeds the critical point; practical use requires major cycle modifications.
- g R-410A is R-32/125 (50.0/50.0), R-423A is R-134a/227ea (52.5/47.5),h and R-500 is R-12/152a (73.8/26.2). The numbers preceding the parentheses indicate the components and the numbers inside the parentheses identify the percentages by mass [2].
- h Standard designation pending [7]

**Table 3 — reported and normalised theoretical COPs at chiller operating conditions**

Study	Refrigerant				
	R11	R 123	R 601 n-pentane	R 601a isopentane	R 601a/601 (37.0/63.0)
<b>Reported COPs</b>					
Calm (this paper)					
ideal cycle	11.56	11.42	11.37	11.32	11.34
typical conditions	6.58	6.52	6.50	6.47	6.49
Maclaine-Cross [19]					
without superheat	7.52	7.46	7.40	7.36	
with 20 K (36 °F) superheat	7.66	7.42	7.31	7.24	
Maclaine-Cross [20]	7.68	7.48	7.68	7.54	7.69
Normalised COPs <b>(relative to R-123 in %)</b>					
Calm (this paper)					
ideal cycle	101.2	100.0	99.6	99.1	99.3
typical conditions	100.9	100.0	99.7	99.2	99.5
Maclaine-Cross [19]					
without superheat	100.8	100.0	99.2	98.7	
with 20 K (36 °F) superheat	103.2	100.0	98.5	97.6	
Maclaine-Cross [20]	102.7	100.0	102.7	100.8	102.8

**Table 4 — differences in temperature lifts in Reference [20] efficiency comparisons**

Study	Refrigerant				
	R11	R 123	R 601 n-pentane	R 601a isopentane	R 601a/601 (37.0/63.0)
condensing temperature (°C)	36.69	37.00	36.51	36.64	36.56
evaporating temperature (°C)	4.28	4.00	4.51	4.36	4.45
temperature lift (°C)	32.41	33.00	32.00	32.28	32.11
condensing temperature (°F)	98.04	98.60	97.72	97.95	97.81
evaporating temperature (°F)	39.70	39.20	40.12	39.85	40.01
temperature lift (°F)	58.34	59.40	57.60	58.10	57.80
normalised temperature lift (relative to R-123 in %)	98.2	100.0	97.0	97.8	97.3
normalised temperature lift (relative to R-601 in %)	101.3	103.1	100.0	100.9	100.3



*Image courtesy of Australian Greenhouse Office*