

REFRIGERANT OPTIONS FOR CENTRIFUGAL CHILLERS

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Most of the important refrigerants used in air-conditioners, heat pumps, and refrigeration systems raise environmental concerns for their impacts on the stratospheric ozone layer, action as greenhouse gases contributing to global warming, or both. Additionally, refrigerant selections significantly affect operating efficiencies, which influence energy use and resulting emission of greenhouse gases from combustion of fuels. Selections also affect safety, durability, and costs. Nevertheless, good alternatives have been identified for most refrigerant applications. Refrigerant changes are particularly significant for China, which already is a major market and producer – and could become the biggest in the world in both roles – for refrigerants and also for air-conditioning and refrigeration equipment.

This paper focuses on the most commonly used refrigerant options for chillers – machines that cool water or brines for air-conditioning and industrial refrigeration systems – and specifically for the type used in large systems. Most of the traditional refrigerants for such equipment are being phased out for environmental protection, but the path forward is not clear for at least one very widely used refrigerant. The discussion begins with the international agreement to protect ozone in the stratosphere.

MONTREAL PROTOCOL

Hailed as the world's most successful environmental agreement, the Montreal Protocol stipulates measures to limit and ultimately phase out production of the chemicals that cause stratospheric ozone depletion. This landmark agreement, reached in 1987, stems from recognition in 1974 that the cause of ozone depletion is catalytic action by chlorine and bromine from release of man-made chemicals used for a number of purposes, including as refrigerants. The international accord represents the first time in history that entire classes of important chemicals are being eliminated for environmental protection. Its success already is confirmed. The United Nations Environment Programme (UNEP) concluded in 2003 that "global production and consumption of most ozone-depleting substances (ODSs) 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.”¹

The Montreal Protocol specifies control measures for ODSs.^{2,3} Among the control measures for developing countries – or more accurately those identified in Article 5(1), including China, based on prior levels of ODS use – are:

- Limitation of chlorofluorocarbon (CFC) “consumption” to not exceed the average level for 1995-1997 by July 1999.
- Reduction in CFC “consumption” to not exceed 50% of the average level for 1995-1997 by 2005.
- Reduction in CFC “consumption” to not exceed 15% of the average level for 1995-1997 by 2007.
- Phaseout of chlorofluorocarbon (CFC) “consumption” by 2010 with possible exception of essential-use exemptions.
- Limitation of hydrochlorofluorocarbon (HCFC) “consumption” to not exceed the level in 2015 starting in 2016.
- Phaseout of HCFC “consumption” by 2040.

“Consumption” is defined as production plus imports less exports and destruction, or effectively new additions to the amount of controlled substances in use. Note that the Montreal Protocol does not limit future use or recycling of chemicals once manufactured or imported, namely refrigerant inventories that are already in use or stockpiled prior to the reduction and phaseout dates. Existing equipment and future equipment manufactured and serviced with refrigerants produced in conformance with the Protocol can be used indefinitely, subject to national and local regulations where they exist. The Protocol also does not restrict use of chemicals as intermediates to manufacture other chemicals.

The schedule is more rapid for developed countries, namely:

- Phaseout of CFC “consumption” by 1996.
- Limitation of HCFC “consumption” starting in 1996 with successive reduction steps by 2004, 2010, 2015, and 2020 to not exceed 65%, 35%, 10%, and ½% of a calculated limit. That “cap” was determined from 1989 usage of CFCs and HCFCs. The last step, reduction to ½% starting in 2020, is intended to allow service of then existing equipment rather than continued production of new equipment using HCFCs.
- Phaseout of HCFC “consumption” by 2030 with possible exception of essential-use exemptions.

While China is not bound to these more stringent measures, they impact products exported from China to developed countries. Please note that each country determines its own specific ways to meet the Protocol requirements. The most common measures include scheduled phaseout dates for individual chemicals considering national requirements and alternatives, generally with early phaseout of those chemicals having high ozone depletion potential (ODP). Some countries, most notably those in Europe, have accelerated their schedules and already prohibit use and/or service of specified or all CFC and HCFC refrigerants.

CHILLER REFRIGERANTS

The commercial choices for centrifugal chillers today are among R-22, R-123, and R-134a. Like R-11 which it replaced, R-123 is the most widely used of these options based on its high thermodynamic efficiency and its low pressure, which lowers equipment costs, reduces leakage, and offers several safety advantages. However, it is an HCFC scheduled for phaseout despite having a very low ODP and an extremely low GWP.

Most of the rest use R-134a, a medium-pressure hydrofluorocarbon (HFC). R-134a is more widely applied in other uses, and it is likely to replace R-22 as the most widely used refrigerant overall (including applications other than centrifugal chillers).

Conversions of older R-114 (a CFC) chillers, primarily on military ships and especially on submarines, use R-236fa (a medium pressure HFC), but no manufacturer is marketing it for new chillers in stationery applications largely based on its high GWP.

While R-22 historically dominated in the very largest capacities with centrifugal compressors and still dominates in smaller chillers using positive displacement compressors, that picture is changing. Designs using R-134a in all capacities as well as R-407C and R-410A (both blends of HFCs) in small sizes are being introduced to replace those with R-22. A few small chillers employing positive-displacement compressors use R-404A (also a blend of HFCs); such use is primarily in Europe. Although the pressure-temperature characteristics of R-407C are similar to those of R-22, its use requires design modifications (for example elimination of flooded evaporators) to avoid composition shifts from blend fractionation. Some new designs for R-407C exploit its glide (range of temperatures in boiling and in condensing due to property differences in the blend's components), by using a Lorenz cycle to increase efficiency.

A growing, but still low number of small chillers use R-717 (ammonia) and – though much less frequently – hydrocarbons such as R-290 (propane), R-600 (n-butane), R-600a (isobutane), R-1270 (propylene), or blends of them. Acceptance is more common in Europe than elsewhere.

Absorption-cycle chillers typically use water and lithium bromide as the refrigerant and absorbent, respectively, in larger sizes and ammonia and water in smaller sizes. They account for less than 2% of large chiller shipments in North America, but are more commonly used in Asia owing to energy supply differences.

Table 1 summarizes the most widely used refrigerants in chillers.

Chillers using centrifugal compressors offer the highest capacities, spanning a range from 350 kW (100 refrigeration tons, RT) to more than 30 MW (8,500 RT). Those using positive displacement (scroll, reciprocating-piston, and screw) compressors range from 7 kW (2 RT) to 6 MW (1700 RT). Absorption chillers cover the range from 7 kW (2 RT) to 18 MW (5200 RT).

The largest of these chillers use turbo-compressors and specifically radial-flow turbine designs, commonly referred to as centrifugal compressors and therefore “centrifugal chillers.” These machines are very widely used in large buildings such as offices, hotels, hospitals, major stores, and multifamily residences. They also are used in central systems serving multiple buildings, such as for universities, medical and shopping centers, multipurpose complexes, and even in thermal utilities providing district cooling to city centers or neighborhoods. Their wide use stems from their very high efficiency, durability, and reliability as well as their low costs per unit capacity, both to acquire and to maintain them.

Table 1: Primary chiller refrigerants

compressor or cycle type	prior	current
centrifugal	R-11	R-123
	R-113	—
	R-12	R-134a
	R-114	R-236fa
	R-500	R-134a
	R-22	R-22
scroll, piston, screw	R-22	R-22, R-134a, R-410A R-407C R-404A
	R-717 (NH ₃)	R-717 (NH ₃)
absorption	H ₂ O/LiBr	H ₂ O/LiBr
	NH ₃ /H ₂ O	NH ₃ /H ₂ O

Of those refrigerants listed in table 1 for centrifugal chillers:

- R-11, R-12, R-113, and R-114 are CFCs and the R-500 blend includes a CFC as a component. All of them have high ODP and also high global warming potential (GWP).
- R-22 and R-123 are HCFCs with much lower ODP.
- R-134a and R-236fa are HFCs with approximately zero ODP, but notable and for R-236fa very high GWP.

Except for R-113, there are alternatives for the CFCs as shown in table 1. Its use was very limited, to broaden the capacity range of older centrifugal chillers, but the targeted capacities are now largely met with screw chillers.

Of the HCFCs, there are a number of good alternatives for R-22 including R-134a, which offers slightly higher efficiency, essentially zero ODP, and approximately 25% lower GWP. Reference 4 addresses the alternatives for R-22 in more detail.

The remaining HCFC, R-123, needs closer examination, starting with consideration of environmental properties.

ENVIRONMENTAL DATA

R-123 has the lowest ODP of commercialized CFC, HCFC, and the less common brominated refrigerants such as R-12B1 and R-13B1. It also has both the lowest GWP and shortest atmospheric lifetime of commercialized fluorochemical refrigerants (also including HFCs). With exception of R-11 and R-141b, both of which have much higher ODP and GWP and the latter of which

Table 2: Environmental properties of refrigerants for centrifugal chillers (based on references 7-9)

refrigerant	atmospheric lifetime (yr)	ODP	GWP (100 yr)
R-11	45	≡ 1.000	4,680
R-12	100	0.82	10,720
R-22	12.0	0.034	1,780
R-113	85	0.90	6,030
R-114	300	0.94	9,880
R-123	1.3	0.012	76
R-134a	14.0	~ 0.000	1,320
R-236fa	240	~ 0.000	9,650
R-245fa	7.6	~ 0.000	1,020
R-500	a	0.605	7,900

^a Atmospheric lifetimes are not given for blends since the components separate in the atmosphere. The atmospheric lifetimes of the components of R-500 are 100 and 1.4 yr.

is flammable, R-123 offers the highest thermodynamic and practical efficiencies among all chiller refrigerants also including ammonia, carbon dioxide, and hydrocarbons.⁴⁻⁶

Table 2 tabulates the latest scientific data, based on international assessments, for the atmospheric lifetime, ODP, and GWP for chiller refrigerants.

We cannot predict future problems precisely, but we should anticipate that some issues not yet recognized will emerge. Accordingly, scientists recommend prudent measures to avoid use or at least to avoid discharge of chemicals with long atmospheric lifetimes, knowing that they will accumulate with time. As such, short atmospheric lifetime provides an important hedge against atmospheric build-up of releases and against a lengthy recovery period after future responses. That position is a lesson learned from ozone depletion, for which full recovery will take more than a century due to atmospheric accumulation of the offending chemicals before recognition of and measures to correct the problem.

The Montreal Protocol addresses only the ozone issue. The Kyoto Protocol deals with climate change and specifically emissions of greenhouse gases, including refrigerants, that cause global warming.¹⁰ While the Kyoto Protocol is not yet in force and while it imposes no specific emission limits for developing countries, China will face very significant consequences from global warming. Climate change is much more complex than ozone depletion due to the causes involved, natural offsets, and uncertainties in sensitivities to both of them. Nevertheless, the majority of

scientists now agree both that warming is occurring and that the consequences are far more foreboding. The Intergovernmental Panel on Climate Change (IPCC), in which China participates, concluded in its latest assessment both that there is evidence that climate change has begun and that the origin is from human activities rather than from natural causes.

The present contribution of HFCs to total greenhouse gas emissions is small. It is less than 2% even expressed as equivalent carbon dioxide, with accounting for differences in global warming potential (GWP) between the substances involved. The portion from refrigerants is even smaller. Nevertheless, collective HFC impacts are growing much more rapidly, on a global basis, than the other gases addressed in the Kyoto Protocol. As such, future measures to specifically control HFCs cannot be ruled out; some already are in effect in Europe.

For a comparative sense of the environmental importance of ozone depletion and global warming, the United Nations Environment Programme (UNEP, the international organization behind the Montreal Protocol) concluded in its 2003 annual report that:

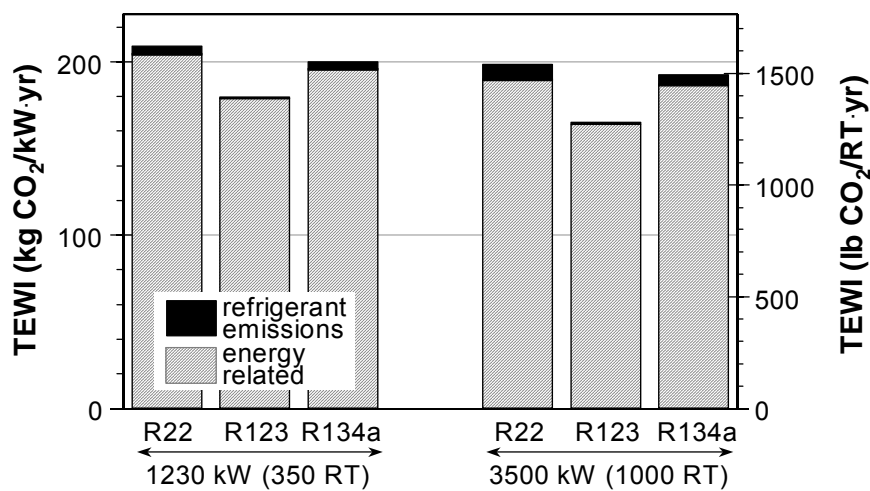
“Global production and consumption of most ozone-depleting substances (ODS) has peaked and is declining, leading scientists to cautiously predict a gradual recovery of the Earth’s ozone shield by the middle of the century. ... International efforts to achieve the same kind of success in tackling global climate change – which represents an even greater threat to human health and sustainable development – have been less successful.”¹¹

These conclusions are important for two reasons. First, they show that concerted efforts to reduce avoidable emissions, phaseout of CFCs in developing countries, and shifts away from highly emissive applications of ODSs such as for aerosol propellant and solvent uses were sufficient to reverse the trend in ODS releases. Specifically, total ODS releases already are declining even before phaseout of HCFC refrigerants, pointing to their comparatively small contribution. Second, the conclusions highlight the greater threat from global climate change that will demand more stringent actions in the future.

EFFICIENCY

In addition to their action as greenhouse gases, refrigerant selections also affect efficiency. In turn, efficiency influences resulting releases of carbon dioxide and additional greenhouse gases from combustion of fuels, either to generate electricity remotely or to power the chillers locally. Of refrigerants used in new centrifugal chillers, R-123 offers a 3-5% advantage in theoretical efficiency over alternatives.⁴⁻⁶ A survey by the Air-Conditioning and Refrigeration Institute (ARI) in the USA found that R-123 held a 9-20% efficiency advantage over R-22 and R-134a for the best available chillers.¹² Whereas larger performance improvements have occurred since then for R-123 chillers than for other refrigerants, the extent of the advantage also has increased. That does not imply that R-123 chillers always outperform others, since the ranges of available efficiencies overlap. It means that R-123 chillers hold a clear advantage when the highest efficiencies are sought.

This performance benefit translates to important distinctions in total equivalent warming impact (TEWI), life-cycle-warming impact (LCWI), or life-cycle climate performance (LCCP), all of which express the combined effects of refrigerant releases and larger effects from system energy use in terms of equivalent carbon dioxide emissions.



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Figure 1. Greenhouse gas emissions (expressed as equivalent carbon dioxide) per unit of cooling per year – TEWI – for the best available chillers in two representative capacities⁵

Figure 1 compares the TEWIs for the best available chillers by refrigerant. It includes emissions to power cooling tower and typical condensing water pumps. As shown, phaseout of R-123 would increase the net global warming impact for the best chillers by more than 14%.

R-245fa offers potential to approach R-123 efficiencies in large capacities, 3-15 MW_t (850-4300 RT), with use of multistage compressors.^{5,6,13} R-245fa is likely to cost more than other refrigerants, based on the manufacturing processes entailed, though such cost increases may be acceptable to achieve higher capacities in equipment initially developed for R-123. The decisive factor for R-245fa use by equipment manufacturers is likely to be assurance of long-term availability.

Suggested use of R-601 (n-pentane), R-601a (isopentane), or blends of them would be exceptionally dangerous. These hydrocarbons are highly flammable, and the charge quantities needed for centrifugal chillers could result in large explosions. Moreover, the subatmospheric pressure at which they operate risks air entry and the possibility of detonation when the hydrocarbon-air mixture is compressed. Beyond the safety issues, neither hydrocarbons nor R-717 (ammonia) matches the efficiency of R-123 at chiller operating conditions.^{4-6,13}

Although typical efficiencies are lower in China, the minimum efficiency levels used in many countries based on the widely adopted ANSI/ASHRAE/IESNA Standard 90.1 are as shown in Table 3:

Table 3: Minimum efficiency requirements for centrifugal chillers^a

<u>equipment type</u> capacity (kW)	COP ^b	IPLV ^b
<u>air-cooled, with condenser</u> all capacities ^c	2.80	3.05
<u>air-cooled, without condenser^d</u> all capacities	3.10	3.45
<u>water-cooled</u> <528 kW (<150 RT)	5.00	5.25
≥528 and <1055 kW (≥150 and <300 RT)	5.55	5.90
≥1055 kW (≥300 RT)	6.10	6.40

^a from ANSI/ASHRAE/IESNA Standard 90.1-2001¹⁴T for electrically-operated centrifugal chillers (the older ASHRAE/IESNA Standard 90.1-1999 specified the same minimum COPs effective 2001.10.29)

^b rated and certified in accordance with ARI 550/590-1998¹⁵

^c ASHRAE 90.1-2001¹⁴ actually shows minimum efficiencies for both <528 and ≥528 kW, but they are the same values.

^d for use with remote condensers

Both the full-load coefficients of performance (COPs) and the integrated part-load values (IPLVs) shown in the table reflect certified performance, determined at standardized conditions. Both indicators are important. Full-load COP indicates performance or comparative performance at peak operating conditions, when power demand is highest and electricity supplies are most heavily strained. IPLV suggests comparative performance on a seasonal basis including low-load conditions, though it cannot predict actual seasonal performance for most applications.

While any of the current refrigerants shown in table 1 can meet the minimum performance levels in table 3 (except for absorption chillers for which the performance criteria are different), the options are more limited at higher efficiencies. R-123 is the only refrigerant for which available products can exceed the minimum full-load COPs by even 20% for water-cooled chillers. Others can do so on an IPLV basis by using adjustable-speed drives to optimize part-load performance, but the inverter efficiency losses (typically 3-5%) worsen the full-load COP and add to the equipment and installation cost. Investing the same cost premium in a high performance, multi-stage, R-123 system yields higher efficiency gains in both full and part-load efficiency, and the adjustable-speed drive option is still available for even further part-load improvement.

IPLV is more indicative of seasonal energy use and, therefore, both of energy costs and of contributions to global warming from energy-related greenhouse gas emissions. Full-load COP is more indicative of peak energy demand, which determines the fuel mix for electricity generation at peak. It also impacts requirements for power generation, transmission, and distribution capacities (and therefore electricity demand costs), peak fuel use, and requirements for cooling towers or other heat rejection components. Peak fuel use, in turn, typically requires more expensive fuels and results in higher energy-related greenhouse gas emissions compared, for example, to electricity generated by hydroelectric dams on rivers.

The peak-load efficiency is particularly acute in eastern Chinese cities, for which growth and development have surpassed power supplies.^{16,17} Indeed, cities such as Shanghai already have experienced power shortages and “blackouts” (power disruptions) due to capacity shortages driven by air-conditioning loads. Resulting regulations on temperature control (minimum thermostat settings) in nonresidential buildings compromise both comfort and productivity. The same peak power savings can be obtained with mandates for higher efficiency, except that the efficiency approach would lower operating costs and energy-related greenhouse gas emissions. Of particular importance to China is that the life-cycle cost for more efficient chillers is much lower than the corresponding cost to increase power supplies.

ASSESSMENTS OF R-123

R-123 is one of the few controlled substances for which there is a clear environmental rationale for retention as a chiller refrigerant, even though it is an HCFC. Rigorous scientific studies show that continued use of R-123 in chillers would have a negligible impact on the stratospheric ozone layer (less than 0.001% of total chlorine-bromine loading), but that such use reduces greenhouse gas emissions significantly.^{6,13,18,19} Rather than negligible, the ozone impact actually would be favorable if used to retire alternatives with higher ODP, namely CFCs, earlier.

R-123 phaseout raises unique concerns since all identified alternatives for it compromise performance and/or safety.^{5,6} The clear solution would be to exempt R-123 from phaseout under the Montreal Protocol and associated national regulations. Such exemption could be restricted to production for use as a chiller refrigerant. The scientific justification for exemption is strong since R-123's impact on stratospheric ozone is indiscernible, its benefit in reducing global warming is significant, and its atmospheric lifetime is among the shortest for refrigerants.^{18,19}

The rationale for a reprieve for R-123 is documented not only in articles in the technical literature, including in some of the most prestigious scientific and engineering journals, but also in international assessments. The final conclusion of the 1998 World Meteorological Organization (WMO) “Scientific Assessment of Ozone Depletion,” part of an international effort prepared pursuant to the Montreal Protocol, states that “the issues of ozone depletion and climate change are interconnected; hence so are the Montreal and Kyoto Protocols ... decisions regarding controlling HFCs may affect decisions regarding the ability to phase out ozone-depleting substances.”²⁰

The Joint Intergovernmental Panel on Climate Change – Technical and Economic Assessment Panel (IPCC-TEAP) “Expert Meeting on Options for the Limitation of Emissions of HFCs and PFCs” in 1999 noted that “phaseout of HCFC-123 will increase ... global warming by 14-20% ... as contrasted to less than a 0.001% increase in peak bromine-chlorine loading.”²¹ Although controversial, the working group agreed and twice voted “that HCFC-123 use warrants examination for chillers based on its negligible impact on ozone depletion and strong benefit in reducing global warming.”²¹

The 2002 assessment “Report of the Refrigeration, Air-Conditioning, and Heat Pumps Technical Options Committee (RTOC),” prepared under the auspices of the United Nations Environment Program (UNEP), stated that “HCFC-123 has a favorable 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.”²²

Despite scientific recognition that R-123 warrants reconsideration from phaseout, there is no consensus among manufacturers or among advocates of non-fluorochemical refrigerants. Manufacturers of both R-123 itself and of chillers using it support reconsideration, while manufacturers of competing products oppose it for proprietary reasons, even though stated in other terms. Likewise, advocates of “natural” (non-fluorochemical) refrigerants often argue against use of any CFC, HCFC, or HFC.

CONCLUSIONS

International efforts to protect the stratospheric ozone layer are succeeding and recovery is underway. Alternatives exist for most chiller refrigerants. A key exception is R-123 – now the most widely used refrigerant in centrifugal chillers. As an HCFC, the Montreal Protocol currently requires its production phaseout by 2030 in developed and by 2040 in Article 5(1) countries, including China. R-123 phaseout raises unique concerns since all identified alternatives for it compromise performance and/or safety. Indeed, scientific studies and international assessments support the position that HCFC-123 use has a favorable overall impact on the environment attributable to its low ODP and very low GWP, very short atmospheric lifetime, low emission rates in chillers, and efficiency – the highest of all current options for chillers. Recognizing that there are no ideal refrigerants, needless elimination of options may cause more environmental harm than benefit. Independent of its ultimate fate, R-123 offers very important environmental and economic advantages for China for at least several more decades.

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