

Emissions and Environmental Impacts from Air-Conditioning and Refrigeration Systems

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Abstract

The impacts of air conditioning and refrigeration systems on stratospheric ozone are primarily linked to release of ozone-depleting refrigerants. Their contributions to global warming stem both from release of refrigerants and from emission of greenhouse gases (GHGs) for associated energy use. Because the energy-related component has a significantly higher warming impact, phaseout of hydrofluorocarbon (HFC) refrigerants with less efficient options will increase net GHG emissions. The same conclusion applies for perfluorocarbon (PFCs), though they are less commonly used as refrigerants. Integrated assessment of ozone depletion, global warming, and atmospheric lifetime provides essential indications in the absence of ideal refrigerants, namely those free of these problems as well as safety, stability, compatibility, cost, and similar burdens. This paper examines the trend in refrigerant losses from chiller use. It documents both substantial progress in release reductions and the technical innovations to achieve them. It contrasts the impacts of current refrigerants with alternatives and with the chlorofluorocarbons (CFCs) they replaced. The paper also summarizes thermodynamic and environmental comparisons of options to show that phaseout decisions based on chemical composition alone, without regard to attributes of individual substances, can result in greater environmental harm than benefit.

1 Introduction

The final conclusion of the latest Scientific Assessment (WMO, 1999), the fourth in a series by an international panel of leading scientists since adoption of the Montreal Protocol, recognizes that:

“The issues of ozone depletion and climate change are interconnected; hence, so are the Montreal and Kyoto Protocols.”

This conclusion is based on meticulous consideration of the underlying atmospheric science and extensive sets of supporting data (WMO, 1999). It also follows intuitively from recognition that the phenomena of ozone depletion and climate change involve the same atmosphere (Albritton, 1997).

The primary global environmental impacts from air-conditioning and refrigeration (ACR) systems arise from emissions of refrigerants and of gases associated with energy use. Those gases usually are released at the power plants that provide the electricity, steam, or hot water used to manufacture, transport, install, operate, service, and ultimately dispose the equipment and ancillary devices. They can occur on-site when the equipment is driven by engines or turbines or with use of direct-fired absorption cycles. Of the total, releases of refrigerants and of combustion emissions to provide operating power dominate. Specifically, discharge or leakage of stable refrigerants containing chlorine, bromine, and – though generally negligible – other halogens affects the stratospheric ozone equilibrium. Likewise, both the common refrigerants and the combustion products, notably carbon dioxide (CO₂) and to a lesser extent nitrous oxide (N₂O), act as GHGs. Refrigerant releases have multiple effects, variously including ozone depletion following breakdown, direct action as GHGs, and efficiency reduction leading to increased energy use. The performance reductions occur with departures from the optimal charge or – for refrigerant blends – charge and composition. Hence, the critical issues in addressing stratospheric ozone depletion and climate change for ACR systems come down to selection of refrigerants that minimize impacts, reducing their release, and increasing net efficiencies to lower energy-related GHG emissions.

The severe consequences of ozone depletion are being averted through international adherence to the Montreal Protocol. The levels of chlorine and bromine reaching the stratosphere, referred to as chlorine-bromine loading (CBL), have peaked or are now peaking, and the ozone layer has begun or soon will start to recover (WMO, 1999). The outlook for global warming and the severity of its consequences are far more threatening. Even if releases stopped for all other GHGs, carbon dioxide emissions from energy use still would increase in concert with foreseen economic improvement in developing countries and with population growth (IPCC, 1996). Whereas the net carbon dioxide impact overshadows the combined effects of all other GHGs, reduction in energy demands and efficiency improvement are crucial. As a minimum, no changes that decrease efficiency can be deemed acceptable.

The functional measures of the Montreal and Kyoto Protocols, beyond those addressing scientific assessments and international assistance, differ. The Montreal Protocol restricts the production of the individual chemicals of concern, leading to their ultimate phaseout for most uses (UN, 1987; UNEP, 1996). The Kyoto Protocol imposes national limits on emissions of important GHGs, but does so by a collective approach encompassing six specific gases or groups of gases (UN, 1997). The most critical gas among them is CO₂. Although they have a much lower impact, namely 1.6% of the total for the USA at present (EIA, 1998), HFCs and PFCs as groups constitute two of the six GHGs in the Kyoto Protocol “basket.” Some studies project that their impact will reach 4-10% of the global total by 2100 and double that if not controlled (Ko et al., 1993).

The focus of the present meeting, and this paper, is on options to limit emissions of HFCs and PFCs, both of which are among the primary alternatives to ozone-depleting substances. This paper addresses the measures taken and available to minimize their release, with emphasis on the refrigerants used in chillers.¹ Such measures include design changes and enhancements to reduce leakage, regulations to reduce intentional and unintentional discharges, and use of alternatives. In doing so, the paper focuses on the trades in refrigerant selection to balance actions as ozone-depleting substances (ODS), impacts as GHGs, and impacts on release of other GHGs to power the systems.

2 Refrigerant Emission Reductions

A number of studies have compiled data or estimated losses from centrifugal chillers, as summarized in table 1. Some of the dates shown reflect inferences by the author for studies that did not specifically identify this information. The dates for conversions, from CFCs to either R-123 or R-134a, indicate when the conversion was performed.

The terminology of *initial*, *annual* (which includes both *operating* and annualized *intermittent*), and *disposal* losses is explained in Calm et al. (1999). All of them are expressed as a fraction of the operating refrigerant quantity, or *charge*. The disaggregation is useful to assess the timing of emissions and their impacts. Briefly:

- *Initial*: This group includes all losses associated with making equipment functional, and specifically those associated with manufacturing, performance and leak testing, transportation, installation, initial charging, field leak testing, and initial start up. These losses are very small, except in cases where a significant leak is discovered or a failure occurs during start up.
- *Operating*: Unlike the initial losses, which occur once in the life of a machine, the operating losses are recurring. They include both leakage and purge releases.
- *Intermittent*: Also recurring, these releases include those from maintenance (for example in disconnecting hoses and opening systems for major service procedures), accidents, failures, unin-

¹ Chillers are refrigeration machines that cool water, other heat transfer fluids (*brines*), or process fluids by a vapor-compression (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 brine 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.

Table 1: Chiller refrigerant losses (%/yr)

time frame and, if applicable, location (study)	initial	annual	disposal
earlier anecdotal data (Fischer et al., 1991)	—	12 - 37	—
1970s - 1980s Japan (Miyasaka, 1989)	—	2.2 - 18	—
1970s - 1980s USA (Hummel et al., 1991)	—	7.4-10.2	—
1980s USA, “historical” (Calm, 1993)	—	8	10
1987-1989 France (Climafort, 1998; Sauer, 1998)	—	12.6 - 30.6	—
1990 (UNEP 1991)	—	8 - 15	—
1990s, “parametric” (Fischer et al., 1991)	—	0 - 16	0 - 5
1990-1992 (Climafort, 1998; Sauer, 1998) ^a	—	15.3 - 18.2	—
1991 USA, “current” (Calm, 1993) ^a	—	4	5
1993-1995 France (Climafort, 1998; Sauer, 1998) ^a	—	7.9 - 10.7	—
late 1990s, “parametric” (Sand et al., 1997)	—	½ - 4	5
1996 USA (Calm et al., 1999) ^a	0.7 ^b	1.0 ^{b,c}	1.5 ^b
1992-1997 (Trane 1997) ^a	—	0.46%	—
1999 USA, manufacturer claims	—	<0.1 - <0.5 ^d	—
projected ~2000, “future” (Calm, 1993)	~0	<½	<½
<u>refrigerant conversions</u>			
1989-1993 USA (Clark, 1999)	—	0-154 ^e	—
1996 USA (Calm et al., 1999) ^a	0.7-3.5 ^b	1.0 - 10 ^{b,c}	1.5 ^b
1992-1997 (Trane 1997) ^a	—	0.62%	—

^a actual releases since 1991 are increasingly lower than indicated due to use of make-up rates as a proxy to determine loss rates (see discussion in text)

^b includes adjustments for *upstream* losses (see discussion in text)

^c annual sum of *operating* and *intermittent* losses

^d claims do not elaborate the specific losses included or how they were determined

^e several converted machines had repeated, catastrophic losses: The average for operation from 1994 through 1998 was 3.2 %/yr with exclusion of the four worst machines.

tentional venting, technician errors, and nonspecific causes.

- *Disposal*: This amount accounts for the refrigerant lost at equipment retirement, a one-time event per machine.

The progression of leak data in table 1 shows a clear trend in release reduction, by as much as two orders of magnitude in several decades. This remarkable achievement was driven, for the most part, by growing environmental awareness, market economics including manufacturer competition to claim reduced emissions, and anticipation of refrigerant shortages and future regulations. Historical loss rates were very low in small, sealed systems (factory charged and tested circuits with hermetic compressors). Examples include window air conditioners, other appliances, packaged terminal air conditioners and heat pumps, and water-source heat pumps. Disposal losses typically were 100% for them, but recovery is becoming the norm and now is required in most developed countries. Progress also was made in unitary equipment and other ACR product groups, but some still have high loss rates. Higher losses still occur with automotive air conditioners, transport refrigeration, and systems employing field-installed piping, such as supermarket (commercial refrigeration) systems.

Most of the data from before 1990 is necessarily from chillers employing CFCs. They were used in more than 95% of centrifugal chillers, led by R-11 in approximately two-thirds. There is no reason to expect differences in leakage rates by chemical composition (for example, between CFCs, hydrochlorofluorocarbons or HCFCs, and HFCs) for equipment fabricated with similar materials and technologies. Different loss rates are likely for R-717 (ammonia) based on the materials and fabrication differences. One distinction that is likely to influence emission rates is dissimilar operating pressures.

Climafort (1998), Dazin (1998), Hummel (1991), and Sauer (1998) document higher losses, by as much as 50%, in older chillers using low-pressure refrigerants. These differences are consistent with expectations based on old purge designs, which vented appreciable refrigerant quantities along with the air removed, but they are not indicative of current and projected practice. Low-pressure chillers and refrigeration systems fitted with condensing purges coupled with vapor recovery systems, for purge venting, should offer a small advantage. Leaks, when they occur, in the subatmospheric portion of such systems generally will suck air in, rather than release refrigerants. The purge device removes this air. A small amount of refrigerant vapor accompanies the air, but the purge condenses most of this refrigerant and returns it to the chiller. The vapor recovery canister (commonly a tank filled with activated charcoal) absorbs most of the remainder for recovery in periodic processing. The majority of R-11 and R-113 (both CFCs) retrofits and new R-123 (an HCFC) chillers employ purge and vapor recovery systems; the same advantage is expected with low-pressure HFCs or hydrofluoroethers.

Whereas the driving force in a leak is pressure differential, a shift to high-pressure refrigerants – whether HFCs, hydrocarbons (HCs), ammonia, or others – is likely to increase releases when leaks occur. There is little difference in loss rates in new, tight equipment based on design compensation, but the available data and anecdotal accounts for high-pressure refrigerants point to higher releases when failures do occur. A tiny leak will increase purge run time with almost no refrigerant loss in a low-pressure machine, but the same small opening will discharge increasing refrigerant amounts with increasing operating or standby pressure. The full refrigerant charge may be lost in a high-pressure system before a leak or rupture is detected or attended to.

The common practice of using refrigerant additions (*make-up*) and removals as a proxy for actual releases, which are difficult to measure, introduces three errors that exaggerate emissions. First, some of the make-up refrigerant in low-pressure chillers offsets amounts removed in purge venting, even though very small in tight chillers. Most of the vented refrigerant is or could be – as discussed below – recovered, but recovery usually is left out of the accounting. The actual releases, therefore, may be as much as 25% lower for low-pressure chillers where the recovery tanks are correctly reprocessed. Second, some of the initial and early make-up amounts do not reflect actual losses. The portion of the refrigerant that is not recovered from factory testing remains inside the chiller, dissolved in the lubricant or absorbed in other materials. This amount reduces startup charge requirements. Likewise, some early additions reflect original undercharging rather than actual releases. Third, replacements for contaminated refrigerants, such as from motor burn-outs or high acid levels, do not imply releases when the old refrigerant is recovered for reclaim or disposal.

A fourth error partially offsets the first three, in the majority of studies, namely omission of *upstream* losses. This term refers to fugitive emissions in manufacturing, packaging, repackaging in distribution, transportation, storage, and handling of the refrigerant before use, including amortization of associated catastrophic losses in transportation, distribution, and storage accidents. In short, it accounts for all releases of the refrigerant prior to its introduction into equipment for use. Although it is a small fraction of the total for the container sizes used for large chillers, this adjustment can be appreciable for some ACR applications. As an example, upstream losses may exceed 25% in small containers for consumer use to “top off” the charge in automobile air conditioners.

Future emissions are likely to be reduced to or less than the low levels projected by Calm (1993) by the improvements discussed below. Those levels were determined through a survey of the product develop-

ment and engineering departments of equipment manufacturers. The results are supported by proprietary data obtained for more than 4000 chillers.

3 Changes to Reduce Refrigerant Releases

The preceding discussion summarizes remarkable reductions in refrigerant losses in the last two decades, typically by factors exceeding ten over the life of a chiller. Such dramatic decreases required hundreds of modification in the design, manufacture, and service of chillers. Some of the key changes were:

SEALS AND JOINTS

- design changes to minimize the number of joints in refrigerant circuits: Modifications and use of special assemblies enabled ten-fold or greater reductions.
- replacement of flared and other mechanical connections with brazed connections: While brazed joints increase the cost of fabrication, they are not prone to loosening with vibration and service errors.
- augmentation of threaded joints with o-rings: Addition of o-ring seals on the threaded joints that cannot be eliminated, for service or other access needs, lowers seepage.
- use of new gasket materials: A new class of flat gasket materials provides tighter seals, in some cases at lower sealing pressures. Similarly, systematic screening tests identified materials that are more durable and that absorb less refrigerant.
- augmentation of flat face gaskets with silicone beads: This change increases the local pressure in places where it is difficult to achieve high sealing pressure due to bolting patterns.
- replacement or augmentation of gaskets and o-rings with adhesive sealants: The new sealing materials reduce losses.

PURGE SYSTEMS

- use of condensing purges: Older purges used a variety of thermal, buoyancy, and pressure methods to separate air from refrigerants in low-pressure chillers and in subatmospheric operation of medium- and even high-pressure systems, at low or very low temperatures, for refrigeration. Modern purges cool the removed air below the boiling point of the refrigerant, separate the two, and return the condensed liquid refrigerant to the chiller or refrigeration machine. Condensing purges typically use a small, hermetic refrigeration circuit, but greatly reduce the refrigerant quantity released in venting the purged air. Other designs use lubricants or other fluids cooled by the chiller itself instead of separate refrigeration circuits; they are simpler, but cannot run when the chiller is off.
- use of vapor recovery systems in purge venting: Even though the amount of refrigerant released by condensing purges is very small, it can be reduced to virtually none by passing the air through a material that absorbs any residual refrigerant vapor before its discharge. Typical systems employ activated charcoal pellets in tanks, which are then reprocessed to recover the refrigerant. A new approach will be introduced in the next year, to promote wider use, with in situ processing and recovery as part of the annual maintenance.

SERVICE

- incorporation of on-board refrigerant storage or means for charge recovery during service: Some designs include receivers or provisions to isolate the refrigerant in the evaporator or condenser, so some internal service procedures can be performed without having to remove the charge from the chiller. Others facilitate recovery into and recharge from permanently connected or portable storage systems. Both strategies are effective in containing the refrigerant during service.

- introduction of, and in some countries requirements for, refrigerant recovery equipment: Utilization of such equipment enables reuse of the refrigerant, often after passing it through filter-driers to clean it, and reduces the likelihood of intentional venting.
- use of cylinders instead of drums to transport and store low pressure refrigerants: Although they have a higher first cost, use of cylinders of the type commonly used for high-pressure refrigerants enables service technicians to draw vacuums on emptied containers to extract any residual refrigerant. The older drums would buckle when evacuated, so some refrigerant was lost each time one was disposed. Moreover, the bungs used to open and close those drums were more leak-prone than protected cylinder valves. The cylinders can be returned for reuse, which also reduces other waste.
- shift from scheduled lubricant changes to when needed: By reducing the frequency of oil changes, both the dissolved refrigerant and lubricant quantities are conserved. Periodic oil analyses and chemical monitoring assure lubricant integrity with reduced chemical use, waste, and disposal burdens.
- increased diagnostic measures in preventative maintenance: Checking for conditions that suggest the likelihood of imminent failures, such as periodic eddy-current testing of heat exchanger tubes, enables corrective actions before failures and associated refrigerant releases occur.
- license requirements for technicians: Some countries, states, and local jurisdictions require that technicians servicing specified equipment obtain licenses to do so. Candidates usually must demonstrate training through prescribed courses, testing, apprenticeship, or some combination of them. Such requirements provide a limited assurance of competence and frequently also verify awareness of environmental protection measures.
- education and training of technicians: A number of associations, manufacturers, and labor unions have instituted training programs, often culminating in proficiency testing, to improve the qualifications of technicians who install and service ACR equipment. Such programs improve the prospect that technicians learn the procedures necessary to minimize failures and to perform their tasks with lowered refrigerant losses.
- increasing role of manufacturers in service operations: Whereas most chiller systems were installed and serviced by independent companies in the past, and sometimes by the staffs of building owners and/or managers, equipment manufacturers have increased their roles in and technical support for service operations. Similarly, both manufacturers and a greater number of independent laboratories now offer chemical analyses of refrigerants and lubricants, to improve maintenance and to identify imminent failures. These shifts improved both the likelihood and the competence of preventative maintenance.

OTHER CHANGES

- use of enhanced heat transfer surfaces: Although the primary incentive for this change is to improve efficiency, it also reduces internal volumes, thereby lowering the refrigerant charge size and the amount lost in catastrophic failures and *upstream* releases. Related advances in heat exchanger design, such as in tube-bundle configuration and spray nozzle placement, and – in some chillers – shifts to compact plate heat exchangers provide similar benefits.
- design changes to extend service intervals: Some refrigerant, such as that trapped under gaskets or absorbed by motor insulation materials, is lost each time equipment is opened even with recommended pump-down procedures. By reducing service frequencies through design modifications and use of more durable materials, some refrigerant releases are avoided.
- design changes to reduce failures and extend equipment life: As an example, manufacturers changed the baffle designs and materials inside shell-and-tube heat exchangers, which are the type most widely used in water-cooled chiller condensers and most chiller evaporators, to re-

duce tube vibration and wear. Doing so minimizes one cause of potential leaks. Similarly, manufacturers also strengthened tube headers in heat exchangers and improved the fabrication methods to attach tubes; both of these changes improve initial tightness and reduce the likelihood of future leaks.

- manufacturing advances: Modern extrusion and other fabrication methods improve the integrity of refrigerant circuits. The seamless copper or other tubes used today, as an example, are less prone to failure than welded tubes of the past.
- factory tests: The majority of manufacturers now check all assemblies (not just random samples) for leaks with helium mass spectrometers or other methods that are capable of detecting even very small leaks. These methods are more sensitive, reliable, and economical than older methods that used more primitive refrigerant detectors, air bubbles, or soap solutions. Manufacturers check all completed chillers in the best cases.
- use of leak detectors: Although promoted to improve technician safety in refrigeration machinery rooms, use of detectors set at very low concentration levels provides an early warning of incipient leaks, before significant refrigerant losses occur. Both leak detectors and microcomputer controls, discussed below, can be connected to remote annunciators or phone dialers to notify technicians of leaks. New fire and mechanical regulations in some locations require remote annunciation, at constantly attended locations staffed with trained personnel, to assure that detector alarms are heeded.
- microcomputer control of operation: Computerized control systems have become the norm for chillers and other sophisticated ACR equipment in the last 15 years. Tracking of critical operating parameters enables detection of failures before their severity increases refrigerant losses and other damage. These microcomputers also monitor run time, purge operation, and refrigerant leak detectors to facilitate preventative maintenance and alert technicians of service needs and impending failures. Their primary benefit is to optimize operation, particularly in installations with multiple chillers, to attain the highest operating efficiencies and, thereby, reduce energy use and related GHGs. As the technologies advance, some of these systems are incorporating anticipatory logic and schedules to project future loads and optimally control operation, for example with integrated thermal storage. Moreover, the computerized controls enable remote supervision and intervention by service technicians and trained supervisory staffs, technicians, and engineers.
- bearing advances to reduce or eliminate compressor lubricants: Reducing or eliminating lubricant needs also reduces or eliminates release of the refrigerant dissolved in the oil when changed. New approaches including magnetic, advanced hydrostatic, ceramic, permanently lubricated, and other bearing technologies are being tested that may completely eliminate the need for compressor oils and oil changes. Some of these developments have been announced and others probably will be within the next two years.
- regulations to prohibit intentional venting: While deliberate release of refrigerants during service or upon equipment retirement historically was common in smaller systems, it was not a common practice in large chillers, for which the refrigerant amounts and costs already justified recovery measures. The regulations have some impact for chillers, for example to limit releases when the quantities taken from containers in charging do not fully empty them or when components are serviced (e.g., system cleaning after a hermetic motor burnout).
- regulations to require repairs when refrigerant make-up amounts exceed prescribed thresholds: Such regulations assure that chronic leaks are repaired or that the equipment involved is taken out of use or replaced. Again, chiller operating economics generally assured the same results, but the restrictions address the worst cases and increase the penalties for deferring prudent service and replacements.

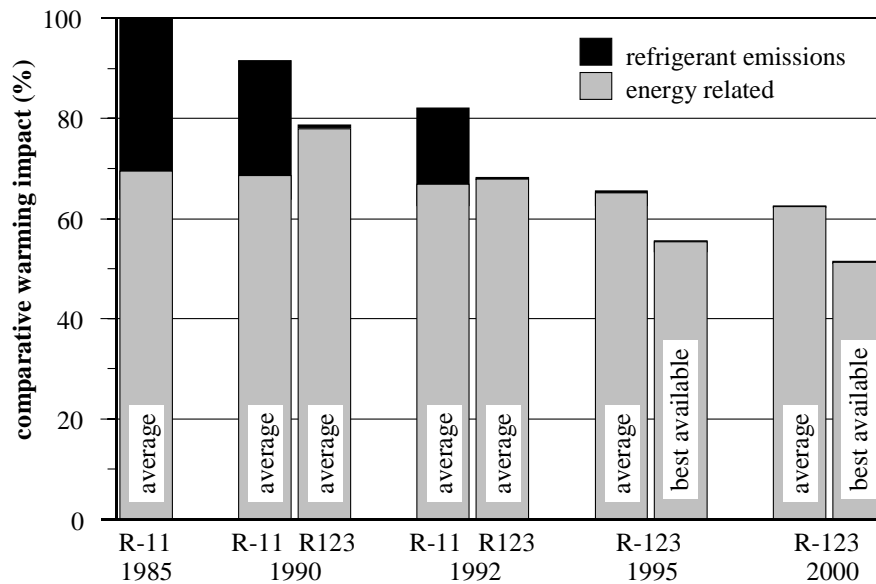


Figure 1: Progression and projection for comparative warming impacts (relative TEWIs) for centrifugal chillers for 1985-2000 with replacement of R-123 for R-11

This list of technology, service, and regulatory advances to reduce emissions suggests a revolution, rather than evolution, in measures to reduce refrigerant releases. Moreover, this list highlights only the key changes; there were many others.

The measures to reduce refrigerant releases are not limited to CFCs, HCFCs, HFCs, and PFCs. Many of them also are applicable to ammonia, carbon dioxide, hydrocarbons, water, and other nonfluorocarbon refrigerants. Their release could increase flammability or toxicity hazards, risk pressure injuries, degrade system reliability, or exacerbate other environmental problems. For example, hydrocarbon emissions may contribute to local smog formation; such releases will be concentrated in urban areas in which smog problems are most acute. Released ammonia that is washed into surface water by rain is highly toxic to aquatic life. And most importantly, loss of refrigerant from vapor-compression machines, or air leaks into subatmospheric equipment, reduces operating efficiency and thereby increases energy use and GHG emissions.

4 Efficiency and Warming Impacts

Figure 1 shows the consequences of reduced emissions, both refrigerant and energy-related, from centrifugal chillers on GHG emissions. The data shown are for 1750 kW (500 ton) R-11 and R-123 chillers. Approximately 60% of the centrifugal chillers installed in the years shown used these refrigerant. Similar conclusions can be drawn for replacement of R-12 with R-134a for the same time frame, although the absolute emissions both start and end at higher levels. The underlying analyses, commonly described as *total equivalent warming impact* (TEWI) analyses, and data are detailed in Calm (1993) and Calm and Didion (1997). The only change herein is recalculation with the refrigerant global warming potentials (GWPs) from the latest scientific assessment (WMO, 1999). The updated GWPs for the four cited refrigerants, namely R-11, R-12, R-123, and R-134a, for 100-year integration were increased from 3800, 8100, 90, and 1300 relative to CO₂ to 4600, 10600, 120, and 1600, respectively.

R-11 dominated in centrifugal chillers almost since its introduction. Refrigerant losses were high; they often exceeded 15% of the total charge each year, as shown in figure 1 for 1985. Small efficiency gains appeared by 1990, but more significant gains were introduced in system tightening and improved purge technologies. Figure 1 shows the resultant drop in impacts from emissions. R-123 use also had begun, though the first machines – essentially R-11 designs with materials changes for compatibility – yielded

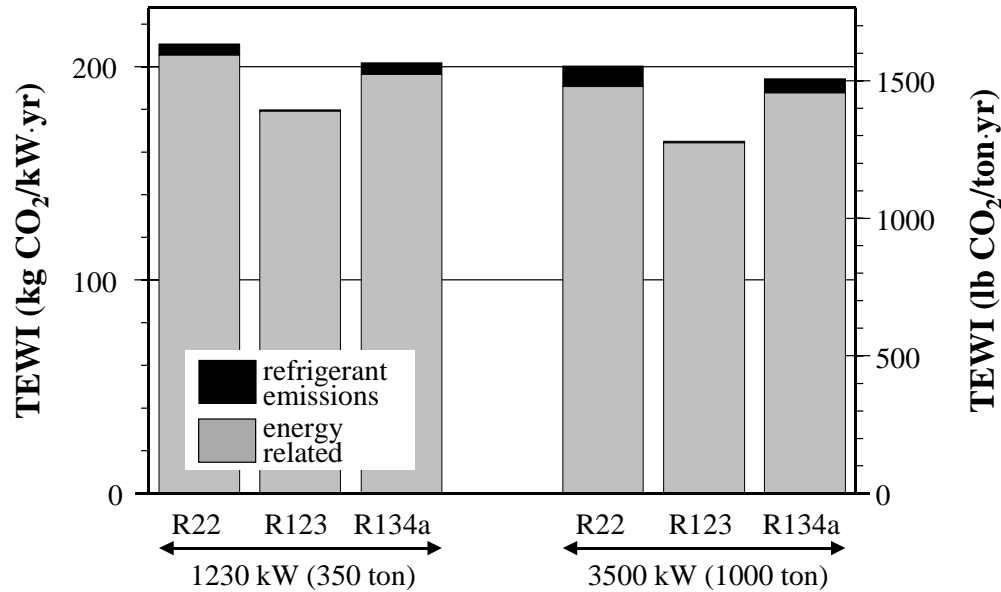


Figure 2: Greenhouse gas emissions (expressed as equivalent carbon dioxide) per unit of cooling per year – TEWI – for the best available chillers in two representative capacities

14-16% lower efficiency. The direct warming impact of R-123 emissions is barely visible, owing to the difference in GWPs, a decrease of more than 97%.

Release reductions continued both by equipment tightening and improved service practices, as discussed above. By 1992, the last year in which R-11 chillers were manufactured for domestic use in the United States, net refrigerant emissions for machines of comparable capacities were half of those in 1985 and before. These reductions offer several benefits beyond reduced global warming. They also lower the impact on ozone depletion. The ozone depletion potential (ODP) and GWP of a chemical only are relevant for the portion that is released. Refrigerant that does not escape, and is recovered for reuse or safe disposal, does not harm the environment. Reduced losses also eliminate the need for makeup, thereby saving other resources and lowering costs, improving safety, and avoiding performance losses from insufficient refrigerant charge.

Figure 1 also shows the dramatic improvements made by 1995 in R-123 chiller optimization, leading to higher practical efficiency than available with the retired R-11 designs. This achievement, and subsequent further gains, are all the more impressive since R-11 holds a small theoretical efficiency advantage over R-123 (Calm and Didion, 1997).

Further improvements in performance followed and will continue, but the pace will slow as gains approach theoretical limits. Coupled with emission reductions and the lower GWPs of R-22, R-123, and R-134a, the best chillers in 1995 reduced net global warming impacts by approximately 45% compared to typical machines a decade earlier. This fraction will exceed 48% by the year 2000 as shown in figure 1.

Figure 2 illustrates the comparative magnitudes of warming impacts from emission of refrigerants and use of energy by water-cooled chillers. The efficiencies used in this example were the highest commercially available in late 1996, as determined by an industry survey (ARI, 1996). The survey was restricted to equipment with certified performance ratings, and the submissions were verified. Once again, the analyses are explained by Calm and Didion (1997), but were updated herein with the new GWP data cited above (R-22 increased from 1500 to 1900 on a consistent basis).

As shown in figure 2, the direct effect of refrigerant emissions amounts to only 3-5% of the annual total for chillers using R-22, which has the highest GWP of the three refrigerants shown. These fractions drop

to approximately 3% with R-134a and to less than 0.2% with R-123, which also offers the lowest energy-related impact based on its efficiency.

From a comparative warming or TEWI perspective, phaseout of the HCFCs and HFCs provides only a small gain in the refrigerant-related warming component for chillers with low refrigerant releases. There is far greater opportunity in efficiency improvement. The same conclusion holds true for most other air-conditioning and refrigeration products as well. Two exceptions are mobile air conditioners and supermarket refrigeration systems. They have high loss rates, but their energy-related impacts still dominate over those from refrigerant releases.

Table 2 summarizes efficiency limits in theoretical cycles for current and candidate refrigerants (Calm and Didion, 1997). Theoretical efficiency limits alone do not govern practical efficiencies. Other properties such as viscosity, thermal conductivity, and resulting heat transfer coefficients may have significant impacts on overall performance. Likewise, cycle design impacts performance. Increased subcooling may reduce the efficiency distinctions for some refrigerants in simple cycles, as seen by examination of the data presented. Notwithstanding these cautions, the performance data summarized in the table imply comparative limits to achievable performance.

As shown, neither ammonia nor the hydrocarbons match the efficiencies of the best fluorochemical options. Such comparisons strongly suggest that the fluorochemical refrigerants be retained to reduce global warming, until comparable or superior efficiencies can be demonstrated without them and without compromising occupant safety. To avoid any misinterpretation, there are applications where ammonia and hydrocarbons offer advantages, but nobody should infer that they are similarly attractive in all refrigerant uses. Ammonia already is widely used in food and beverage processing and storage. One hydrocarbon option that holds promise, but which is not frequently mentioned, is ethane (R-170) for use in ultra-low temperature systems with small charge sizes. Ethane's efficiency appears to be low in table 2 because chiller operating conditions are near its critical point temperature. That is not the case for extremely-low temperatures, where high GWP fluids (primarily CFCs, PFCs, and blends of them) are common. R-601 (n-pentane) and its isomers offer both high efficiency and low-pressure operation at chiller conditions, but they are highly flammable and pose a considerable safety risk in the quantities needed by large chillers.

Calm and Didion (1997) present a detailed analysis that shows that there are no *ideal* refrigerants. Such fluids would offer zero ozone depletion, zero global warming, high efficiency, very low toxicity, and no flammability – even without practical constraints such as cost, materials compatibility, and chemical and thermal stability. The referenced paper also provides a rationale based on thermodynamics and chemical composition to suggest that the elusive ideal refrigerant probably does not exist.

5 Necessary Refrigerant Compromises

Most first generation refrigerants (1830s-1930s, selected based on availability and thermal suitability) were retired for safety reasons. Some, such as ammonia and hydrocarbons, survived or were later revived for limited applications in which their risks were manageable, such as industrial or small-charge systems (see Calm and Didion, 1997, for elaboration). Most second generation refrigerants (1930s-1990s, selected for safety, durability, and performance) have been or are being retired to protect the stratospheric ozone layer. The criteria for third generation refrigerants (“alternative refrigerants”) include both safety and environmental issues. Whereas the first generation lasted approximately 100 years and the second approximately 60, care is needed in dismissing options with minor defects if manageable. The third generation will be more vulnerable as the global population increases, industrial and economic development expands, and environmental understanding increases. These considerations demand greater attention to atmospheric lifetime to ensure that we not repeat the error made with CFCs and halons, namely releasing large quantities of long-lived compounds before we discover their impacts. Likewise, far more attention is needed to containment and recycling instead of phaseout.

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	COP (kW/kW)	specific power (kW/ton)	COP (kW/kW)	specific power (kW/ton)	COP (kW/kW)	specific power (kW/ton)
R-11	11.52	0.31	6.58	0.53		
R-12	10.99	0.32	6.29	0.56		
R-22	10.88	0.32	6.18	0.57		
R-32	10.60	0.33	5.97	0.59		
R-113	11.37	0.31	6.52	0.54		
R-114	11.04	0.32	6.34	0.56		
R-123	11.38	0.31	6.52	0.54		
R-124	11.00	0.32	6.31	0.56		
R-125	9.88	0.36	5.68	0.62		
R-134a	10.89	0.32	6.24	0.56		
R-141b	11.51	0.31	6.58	0.54		
R-152a	11.13	0.32	6.34	0.56		
R-170 (ethane)	6.58	0.54	e	e		
R-236fa	10.90	0.32	6.26	0.56		
R-245ca	11.29	0.31	6.47	0.54		
R-245fa	11.19	0.31	6.42	0.55		
R-290 (propane)	10.73	0.33	6.14	0.57		
R-410A	10.40	0.34	5.91	0.60		
R-500	10.92	0.32	6.24	0.56		
R-600 (n-butane)	11.19	0.31	6.42	0.55		
R-600a (isobutane)	11.05	0.32	6.34	0.56		
R-601 (n-pentane)	11.33	0.31	6.50	0.54		
R-717 (ammonia)	11.17	0.31	6.24	0.56		
R-1270 (propylene)	10.68	0.33	6.10	0.58		

^a Conditions are those for standard chiller ratings for water-cooled chillers (ARI, 1998).

^b Calculations were made with CYCLE_D 2.0 (Domanski et al., 1999) and R-601 data (McLinden, 1999)

^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 Condensing temperature exceeds the critical point; practical use requires major cycle modifications.

There is no common denominator to equate the demerits of ozone depletion and global warming. It is clear, however, that a 13-19% increase in global warming to switch from R-123 to R-134a, at the best

performance levels, is more significant than a 0.002% or lower peak impact on ozone depletion (Wuebbles and Calm, 1997; Calm, Wuebbles, and Jain, 1999). This comparison is more dramatic for newer data, namely increases of 14-20% in carbon equivalent GHG emissions versus less than a 0.001% increase in peak CBL. The new comparison employs efficiency improvements since 1996 and reduced refrigerant release rates, both of which are evident in figure 1. It combines them with updated ODP values and new GWP data (WMO, 1999). Moreover, four factors increase the importance of the comparison. First, correction is underway for ozone depletion (Wuebbles and Calm, 1997; WMO, 1999). Second, ozone depletion will not be discernibly increased with a reprieve for R-123 (Calm, Wuebbles, and Jain, 1999), which has an ODP of only 0.012 and atmospheric lifetime of 1.4 yr (WMO, 1999). Third, recovery of the ozone layer will not be retarded with a reprieve for R-123 (Wuebbles and Calm, 1997; Calm, Wuebbles, and Jain, 1999). And fourth, the options to adequately address global warming are far more limited, and a reprieve for R-123 is one of them (Calm and Didion, 1997; Calm, Wuebbles, and Jain, 1999).

It is highly probable that HCFC-123 and possibly other short-lived CFC replacements would have survived restrictions for stratospheric ozone protection had the global warming response occurred first. With keener awareness of the more-limited options remaining (Wuebbles and Calm, 1997), the framers of the Montreal Protocol might then have been more cautious in rejecting chemicals with indiscernible ozone impacts and offsetting environmental benefits.

Likewise, phaseout of HFCs from chiller use for very small benefits in direct (refrigerant-related) warming impacts at the expense of greater CO₂ and N₂O emissions will increase rather than decrease net warming.

The key distinction that makes most ACR applications, and especially chillers, unique from other HCFC, HFC, and PFC uses is that the refrigerant is used in closed systems with very low life-cycle release rates. Most of the refrigerant can be, and is being, recovered upon ultimate equipment retirement. A second difference, at least for HCFC-123 and HFCs, is that abandoning these proven options would increase the GHG emissions from associated energy use.

6 Conclusions

Historic releases of refrigerants from centrifugal chillers have been dramatically reduced from annualized (amortizing initial and disposal losses) rates of 8-37 %/yr to less than – or significantly less than – 1 %/yr. The refrigerant needs for make-up in old chillers far exceeded those for initial charging, amounting to more than ten full charges over the operating life in the worst cases. By contrast, more than three-quarters of the original charge can be recovered for re-use or safe disposal when current equipment reaches retirement; that fraction exceeds 90% in the best systems. On average, the lifetime refrigerant needs for chillers have been reduced more than tenfold.

Most of the technologies applied to achieve these loss reductions also can be applied in smaller ACR equipment. The driving forces for the changes in large chillers was economics, including competitive marketing advantage, and growing environmental awareness.

The importance of a refrigerant's ODP or GWP diminishes with very low losses. For refrigerants with low ODP and low GWP, the most damaging environmental effect from refrigerant losses is suboptimal operation resulting in increased energy use and, thereby, increased emission of CO₂ and other GHGs to power the system. Suboptimal efficiency thus exacerbates climate change even with zero-GWP refrigerants.

Any refrigerant substitution that lowers overall efficiency is likely to have more adverse impact than benefit based on net global warming impacts (e.g., life-cycle GHG emissions or TEWI).

Phaseout of R-123 – the most-widely used refrigerant in centrifugal chillers today – as an HCFC will increase HFC use, and therefore HFC releases, but more importantly will significantly increase global warming with lowered operating efficiencies for no discernible benefit in stratospheric ozone protection.

An integrated assessment of ozone protection, climate change, local environmental and safety issues, and the likelihood of future environmental concerns suggests the need for distinction between short-lived, low-ODP chemicals and those with high ODPs, particularly in low-emission applications such as R-123 in chillers.

Whereas no ideal refrigerants exist, care is needed to not dismiss options with minor flaws without examination of their net environmental advantages.

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