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Options and outlook for chiller refrigerants

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Abstract

This paper reviews the progression in refrigerants for chillers, from historical selections through current options and projections for the future. It examines the global environmental issues that catalyzed recent changes. It then discusses candidate refrigerants in the context of future availability (or phaseout) based on controls for environmental protection, efficiency, toxicity, flammability, and escalating future costs. It notes that negative marketing and conflicting claims, intended to discredit competitor's approaches, create confusion and retard replacement of older, less-efficient equipment. The result hurts the environment, increases costs, and stifles the chiller market. The paper concludes that most of the current anxiety with refrigerant selections is unwarranted. Engineers, building owners, and others involved in chiller decisions should revert to traditional chiller specifications based on cost, performance, local manufacturer support, service options, and reliability. Anticipating more stringent environmental regulations, they also should take all practical steps to reduce refrigerant releases and increase efficiency. The paper examines future refrigerant options for chillers. Noting that there are no ideal refrigerants and that none are likely to be found, it recommends scientific determination of acceptability rather than market manipulation. © 2002 Elsevier Science Ltd and IIR. All rights reserved.

Keywords: Air conditioning; Water chiller; Refrigerant; Survey

Frigorigènes utilisés dans les refroidisseurs d'eau : options et perspectives

Mots clés : Conditionnement d'air ; Refroidisseur d'eau ; Frigorigène ; Enquête

1. Introduction

Refrigerant selections were simple—or at least simpler—until late 1989. The choices for centrifugal (turbo) chillers were among R-11, R-12, R-22, and R-500. Special needs, such as serving low capacities or operating at high condensing temperatures for heat recovery, called for R-113 or R-114, respectively. Most engineers either did not specify a desired refrigerant or were amenable to alternatives in bid reviews. They simply stipulated the capacity, operating specifications, and required piping, power, and control features.

2. Prior options

R-11, a chlorofluorocarbon (CFC), captured the lead largely based on its efficiency and the cost advantages of low-pressure chillers. Approximately two of every three centrifugal installations used this refrigerant. More R-11

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chillers are in current use than all other centrifugals combined, even though their production ended in developed countries in 1994. This paradox results from the large quantity installed coupled with slow replacement and conversion rates.

The next most common choice was R-12, to extend the competitive centrifugal range to lower capacities and for cost advantages when high efficiency was not demanded. R-500 was introduced in centrifugal chillers to achieve the same capacities with 50 Hz motor speeds as obtained with R-12 at 60 Hz for similar designs. It later gained use in 60 Hz equipment to expand the range of capacities. 50 Hz power is standard in Europe, parts of Japan, and elsewhere in Asia; 60 Hz power is the norm in most of North America and the remainder of Japan.

Most chillers with scroll, piston, or screw (all positive displacement) compressors used R-22, a high-pressure hydrochlorofluorocarbon (HCFC). This versatile refrigerant also dominated in the largest chillers—those exceeding 5 MW_t (1400 tons)—using centrifugal compressors. A comparatively small number of systems—less than 10% of the total—used R-717 (ammonia) or absorption-cycle chillers. Most of the latter used water and lithium bromide as the refrigerant and absorbent, respectively.

3. Current options

The choices for centrifugal chillers today are among R-22 in both small and very large capacities, R-123, and R-134a. The balance between R-123 and R-134a is similar to that for R-11 and R-12. Nearly two-thirds of new installations use R-123, a low-pressure HCFC.

Most of the rest use R-134a, a medium-pressure hydrofluorocarbon (HFC). R-134a acceptance is notably higher in other uses, and it is likely to replace R-22 as the most widely used refrigerant overall.

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

While R-22 still dominates in smaller chillers using positive displacement compressors, that picture is changing. Designs using R-134a as well as R-407C and R-410A (both blends of HFCs) are being introduced to replace those with R-22. A few small chillers, notably in Europe, use R-404A (also a blend of HFCs). 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, 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, most using water/lithium bromide, account for less than 2% of total chiller shipments in North America. This fraction excludes the small ammonia/water chillers that compete with unitary air conditioners, but hold less than a 0.2% market share in that application. While there are signs of reviving interest in centrifugal chillers in Japan, absorption-cycle chillers are much more common than centrifugal chillers there. This local preference is largely due to differences in energy resources, resulting costs, and construction regulations.

4. What changed?

The equipment manufacturer, rather than the system design engineer or building owner, made the historical choice of refrigerants. Owners and engineers paid little more attention to this selection than to other internal components. Most based chiller selections on cost, performance, local manufacturer representation and service options, operating preferences, and perceptions of reliability. Where applicable, they excluded some refrigerants to skirt local requirements for special permits or operator attendance for specific refrigerants or equipment.

The *rules* changed in 1987 with international agreement to the Montreal Protocol [1], a landmark treaty to protect the stratospheric ozone layer. They changed again with subsequent amendments [2], notably so in 1990 and 1992, and the later Kyoto Protocol on climate change [3]. Future revisions to both environmental accords are virtually ensured by the unfolding science and political influences; these changes will spur still further control measures.

5. Environmental issues

The two driving issues, stratospheric ozone depletion and climate change, are both global.

5.1. Stratospheric ozone depletion

Ozone, a form of oxygen, absorbs incoming ultraviolet-B radiation from the sun, which otherwise would cause harm to humans, animals, and plants. A publication by M. J. Molina and F. S. Rowland in 1974 identified CFCs as the source of chlorine upsetting the equilibrium in natural ozone formation and destruction. This publication and subsequent investigations raised concern with thinning of the stratospheric ozone layer by chlorine and bromine from anthropogenic (man-made) compounds. These studies showed the potential for more serious ozone depletion, based on projected growth in the use of these chemicals.

The Montreal Protocol requires scheduled phase out of controlled substances. They include chemicals containing chlorine and bromine used as refrigerants, solvents, foam blowing agents, aerosol propellants, fire suppressants, and for other purposes.

5.2. Climate change

The prospect of global warming has a longer history. The mathematician J-B. Fourier identified the role of atmospheric gases in governing the atmospheric and ground level temperatures in 1827. He was responsible for the analogy to their action like a "greenhouse." A publication by S. Arrhenius in 1896 warned that emissions of carbon dioxide from growing use of fossil fuels would increase the natural greenhouse effect.

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 more foreboding.

Unlike ozone depletion, some locations may benefit from climate change. Unfortunately, warming will foster the spread of diseases and large populations living near sea level are at risk from flooding due to rising sea levels. Also, rapid changes will harm most crops and other plant life.

Key scientists, such as J. D. Mahlman at the National Oceanic and Atmospheric Administration (NOAA), argue that we already have committed to a doubling—and may see a quadrupling—of atmospheric carbon dioxide by the year 2100. It is the greenhouse gas of primary concern.

Another NOAA scientist who has been at the forefront of the ozone issue, D. L. Albritton, provides a unique insight. He suggests that historians may view the response to stratospheric ozone depletion as a necessary apprenticeship, to prepare for the more difficult issue of climate change.

The debate on environmental issues ranges from denial or elaboration of climate change benefits to warnings of grave doom. In its latest assessment, the Intergovernmental Panel on Climate Change (IPCC) concluded that there is discernible evidence that climate change has begun.

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 global warming potential (GWP) differences. The portion from refrigerants is even smaller. Nevertheless, collective HFC impacts are growing more rapidly, on a global basis, than the other gases addressed in the Kyoto Protocol.

5.3. Others

One lesson from ozone depletion and climate change is that chemical emissions can build up before problems are recognized or proven.

There are growing concerns with the accumulation of persistent chemical pollutants (PCPs) and their impacts on ecosystems. One aspect of the problem is a threat to limited potable water supplies.

Another concern is with nitrogen loading from intensive fertilizing in agriculture, fuel combustion, and widespread cultivation of legumes. Part of the resolution will require efficiency improvements for all energy uses, including chiller operation.

Air pollution, affected by fossil fuel uses such as those to power refrigeration systems, and resource utilization are likely to continue as concerns. They will escalate with growing world population—now past 6 billion and growing—and with economic and industrial development.

We cannot predict future problems precisely, but we should anticipate that some will emerge. Accordingly, we must take prudent measures to avoid upsets to nature and discharge of chemicals with long lifetimes, knowing that they or their decomposition products will accumulate with time.

6. Refrigerants

While refrigerants contribute to the cited environmental concerns, their role is comparatively small. One distinction from other uses of the same chemicals is that refrigerants do not have to be released to perform their function. In fact, avoiding such releases improves system performance and lowers costs. The problem is not with refrigerants inside systems, but with their release!

Refrigeration offers essential societal benefits. Some are making intemperate locations habitable, enabling food storage and transportation, enabling production and storage of medical and pharmaceutical materials, and preventing the spread of disease. Refrigeration also makes many important production processes possible, increases worker productivity, and provides comfort.

Refrigerants are the most essential component of refrigeration systems. The heat removed to evaporate the refrigerant is what provides the cooling.[1] Separation of the refrigerant from the air or other substance being

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[1] There are other ways to provide refrigeration such as use of magnetocaloric or thermoacoustic processes or exploitation of the Seebeck effect. These approaches warrant further research, but are not currently practical except in specialty applications, such as magnetocaloric systems at temperatures approaching absolute zero. The discussion herein addresses the Joule-Thomson effect, which is by far the most widely used based on performance and versatility.

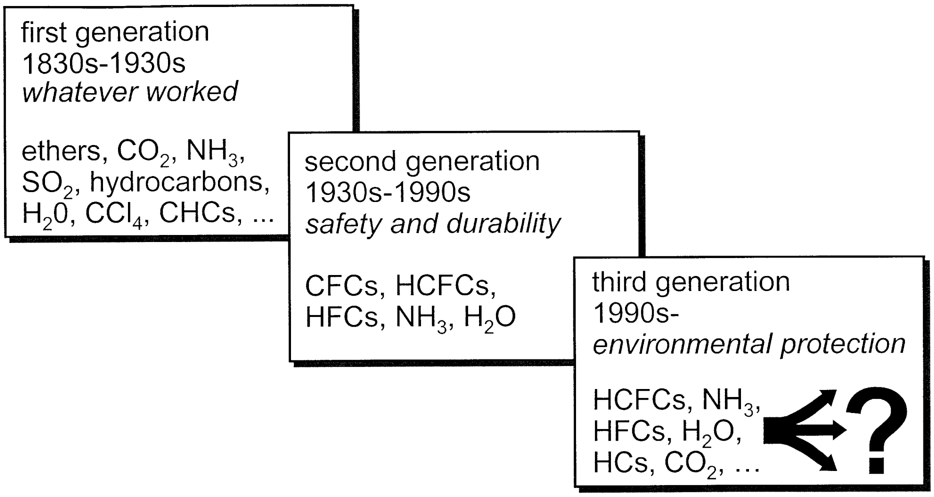

Fig. 1. Refrigerant progression.

cooled requires some form of a heat exchanger—an evaporator—to isolate the refrigerant.

The remaining components in a refrigeration circuit simply enable cycling of the refrigerant. A compressor (or a combination of an absorption–desorption circuit and a solution pump) raises the refrigerant pressure, to enable heat rejection at a warmer temperature. A condenser reliquifies the refrigerant so it can be boiled, or evaporated, again. A throttling device, such as an expansion valve or orifice, meters the flow to separate the high- and low-pressure sides of the circuit.

Everything else in a refrigeration system controls operation at varying load and heat rejection conditions, transports heat from the location served to the evaporator, transports condenser heat to rejection devices, supplies energy to drive the system, or functions to improve the safety, durability, and reliability of the system.

Almost any fluid can be used as a refrigerant, usually by a phase change. The real distinctions are in stability, safety, performance, and compatibility.

6.1. Refrigerant history

The first century of refrigerant use was dominated by innovative efforts with familiar fluids—“whatever worked”—in almost prototypical machines. The goals were to provide refrigeration and, later, durability. Nearly all of the early refrigerants were flammable, toxic, or both, and some also were highly reactive. Accidents were common. For perspective, propane was marketed as *the odorless safety refrigerant.*

The second generation of refrigerants stemmed from a 1928 search for safer refrigerants, to enable broader use in domestic refrigerators. T. Midgley, Jr., and his associates A. L. Henne and R. R. McNary, scoured property tables for candidates deemed to be stable, neither toxic nor flammable, and having a desired boiling point.

The result called their attention to previously unused organic fluorides, but data deficiencies forced another approach. Midgley turned to the periodic table of the elements. He quickly dismissed those yielding insufficient volatility. He then eliminated those resulting in unstable and toxic compounds as well as the inert gases, based on their low boiling points. He was left with just eight elements: carbon, nitrogen, oxygen, sulfur, hydrogen, fluorine, chlorine, and bromine. They clustered at an intersecting row and column of the periodic table of the elements, with fluorine near the center.

Repeated screenings by others, with newer data and techniques, have converged on the same findings regarding the suitability of *Midgley's elements*. Interestingly, all of the refrigerants used before 1928 were made up of just seven of the eight elements—all but fluorine. References [4–7] elaborate on the history. The refrigerant generations discussed above are summarised in Fig. 1.

6.2. Ideal refrigerants

In addition to having the desired thermodynamic properties, an ideal refrigerant would be nontoxic, nonflammable, and completely stable inside a system. It also would be environmentally benign-even with respect to decomposition products-and abundantly available or easy to manufacture. It would be self-lubricating and compatible with other materials used to fabricate and service refrigeration systems. It would be easy to handle and detect, and not require extreme pressures, either high or low.

There are additional criteria, but no current refrigerants are ideal even based on the partial list. Chemical and thermophysical analyses reveal conflicts in desired molecular makeup and properties, which virtually preclude the possibility that ideal refrigerants exist or can be synthesized [4].

Fig. 2 illustrates the trade-offs inherent to organohalides, and specifically among compounds containing chlorine, fluorine, and hydrogen in addition to carbon. Increasing the hydrogen content shortens atmospheric lifetime, but makes the substance flammable. Increasing the fluorine content reduces miscibility, to the point that HFCs and perfluorinated (fully fluorinated) refrigerants usually require synthetic lubricants for oil return. Increasing the chlorine content generally increases toxicity. There are, however, many forms of toxicity such as lethality, cardiac sensitization, carcinogenicity, and mutagenicity as well as anesthetic, reproductive effects, and respiratory effects. Some toxicities are physical in nature and others are chemical; chlorine content is only one of many determining variables.

Increasing the fluorine or chlorine content increases atmospheric stability, which lengthens atmospheric lifetime. As illustrated in Fig. 3, increasing the chlorine content in refrigerant molecules generally increases the ozone depletion potential (ODP). Compounds that contain no bromine or chlorine have ODPs that are nearly zero. Likewise, increasing the fluorine count generally raises the global warming potential (GWP). Substituting hydrogen tends to shorten the atmospheric lifetime. Compounds with very short lives will have low ODPs, since most emissions will decompose before reaching the stratosphere. They also will have low GWP values, since their atmospheric persistence will be comparatively short in duration.

7. Selection criteria

With recognition that there are no ideal refrigerants and that none is likely to be found, users must work with available candidates. Choosing among them is frustrating because the future acceptability of the choices appears uncertain. Moreover, informed selection requires examination of diverse factors. They range from environmental and safety considerations to performance and compatibility issues.

The equipment manufacturers that incorporate refrigerants in products portray their own picks as the only logical selections. Chemical manufacturers and independent service companies also engage in market promotion, but have less at stake in the refrigerant selection. Not surprisingly, conflicting, misleading, and sometimes incorrect information has flooded the marketplace. The result is an air of fear, uncertainty, and doubt (FUD). The targeted *FUD factors* include:

- Future availability (or phaseout) based on controls for environmental protection
- Efficiency
- Toxicity
- Flammability, and
- Escalating future costs.

7.1. Future availability

R-22 and R-123 are both scheduled for phaseout under the Montreal Protocol and implementing national regulations. The Protocol calls for ceasing their production by

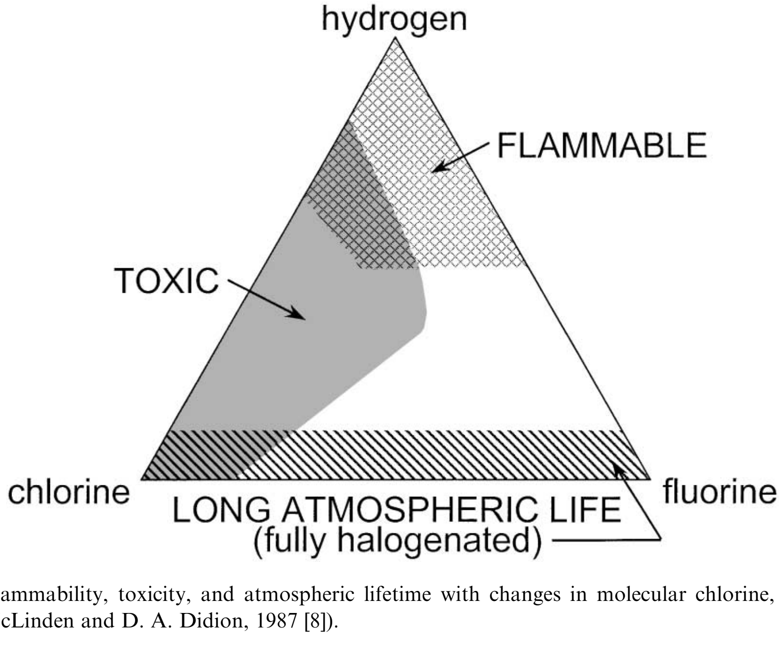

Fig. 2. Trade-offs in flammability, toxicity, and atmospheric lifetime with changes in molecular chlorine, fluorine, and hydrogen content (from M. O. McLinden and D. A. Didion, 1987 [8]).

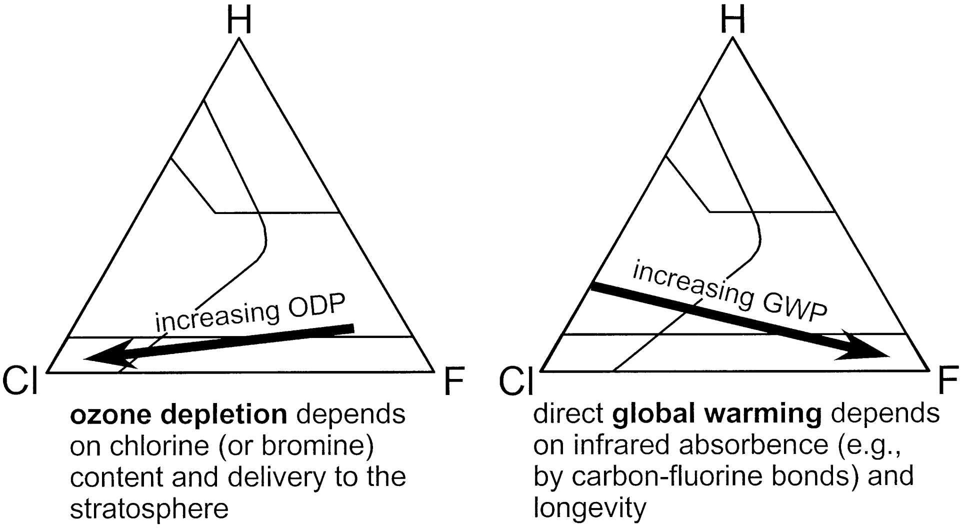

Fig. 3. Chlorination and fluorination impacts on ozone depletion and global warming potentials [4].

2030 in industrialized countries and by 2040 in developing countries. It further stipulates reduction steps as the ODP-weighted sums of all HCFCs together. National regulations impose the same or earlier deadlines for use in new equipment, for production or import, and—in extreme cases—for all uses. These dates generally are earlier or much earlier for R-22, based on its higher ODP.

The primary HCFC concern actually lies with releases of R-141b and R-142b from their use as foam blowing agents. This application is inherently emissive, and their ODPs, 0.086 and 0.043 respectively, are high for HCFCs. By contrast, refrigerant use in chillers results in very low releases [9], and the ODPs of R-22 and R-123 are much lower, 0.034 and 0.012, respectively.

Rigorous analyses show that the impact of R-123 from refrigerant use on ozone depletion is negligible, with less than a 0.001% contribution to the peak [10]. Further studies indicate that its environmental benefits outweigh its ozone impact and justify reconsideration of its phaseout [4,9,10,11,12,13].

While the scientific justification for a reprieve for R-123 is strong, the political aspects are harder to predict. Production is allowed for another three decades (four in developing countries) even without reconsideration. The refrigerant quantities needed to service both existing and new R-123 chillers should be available for at least several additional decades. Note that R-11 production was halted in developed countries in 1994 or earlier, yet service inventories remain high. Refrigerant recycling from equipment retirements and replacements, which the Montreal Protocol allows, should provide more than adequate amounts at affordable costs. The key is proper tightening and maintenance to reduce the quantity needed for service.

HFCs are not controlled by the Montreal Protocol since their ODPs are nearly zero. HFC emissions are regulated under the Kyoto Protocol, but this treaty has not entered into force and may not do so unless amended to address measures by developing countries.

The present form of the Kyoto Protocol specifies reduction targets for emissions based on a GWP-weighted basket of six specified gases or groups, which include HFCs. HFCs are a small fraction of the total, but are the component that is increasing the fastest.

There is no way to forecast whether specific production caps will be imposed in the future. Some countries—notably in Europe—are moving unilaterally toward restrictions on and even bans of some HFC uses. Equipment manufacurers have avoided R-236fa in new equipment based on its very high GWP of 9400 (compared to 120 and 1600 for R-123 and R-134a, respectively).

Fig. 4 contrasts the ODPs and GWPs for key single-compound refrigerants. It suggests several points worth noting.

First, the CFCs warranted control both as ozone depleters and greenhouse gases.

Second, only two of the refrigerants shown offer both very low (or near zero) ODP and GWP, namely R-123 (an HCFC) and R-152a (an HFC). R-152a is fairly easy to ignite and, therefore, only used for refrigerant purposes as a blend component (notably in the R-401 series of service fluids and in R-500).

Third, a very different picture might have emerged had measures addressing global warming been implemented before those for ozone depletion. The left—ODP—side of the plot shows why the framers of the Montreal Protocol focused first on CFCs, allowed HCFCs as transition fluids, and deemed HFCs long-term solutions. The right—GWP—side suggests a different outcome had global warming been addressed first. Compounds probably would have been considered individually rather than by coarse composition groups. It is highly likely that R-123 then would have survived the second cut, for ODPs, with fewer remaining options and recognition of its environmental benefits. They are discussed further below.

Given the compelling rationale for and possibility of a reprieve for R-123, and recognizing that some parties already are seeking stiffer controls on HFCs, the air-conditioning and refrigeration industry needs to make a clear case for scientific determinations. They require integrated assessments of all environmental issues, taking both favorable and unfavorable impacts into account.

7.2. *Efficiency*

Almost any volatile substance can be used as a refrigerant. Moreover, different fluids can offer the same coefficient of performance (COP) in theoretical cycles adapted with cycle modifications for individual fluid properties [4,15–16]. However, attainable performance differs among individual fluids in simple cycles [4]. The differences are even larger in practical equipment [4,9,10].

Of refrigerants used in new centrifugal chillers, R-123 offers a 3-5% advantage in theoretical efficiency over alternatives. A survey by the Air-Conditioning and Refrigeration Institute (ARI) in November 1996 found that R-123 held a 9–20% efficiency advantage for the best available equipment [17]. Whereas larger performance improvements have occurred since then for R-123 than others, the differences have 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) which express the combined effects of refrigerant releases and larger effects from system energy use in terms of equivalent carbon dioxide emissions.

Fig. 5 compares the TEWIs for the best available chillers by refrigerant. It includes emissions to power cooling tower and typical condensing water pumps. It is based on the calculation methods and data in refs. [4] and [10] as well as prior studies identified therein. The GWP values used were taken from the latest international assessment. As shown, phaseout of R-123 would increase the net global warming impact for the best chillers by 14–20%.

7.3. *Toxicity*

R-22, R-123, R-134a, and most common refrigerants have low or very low acute (short term-single exposure as in unplanned releases) dermal and inhalation toxicity. None of them are carcinogens, reproductive or developmental toxicants, genotoxins, or respiratory irritants. The exception is R-717 (ammonia). It is corrosive to skin and eyes. It also is a respiratory irritant, but its odor gives warning of leaks.

All of those cited except R-717 (ammonia) and R-718 (water) are cardiac sensitizers. All can act as asphyxiants.

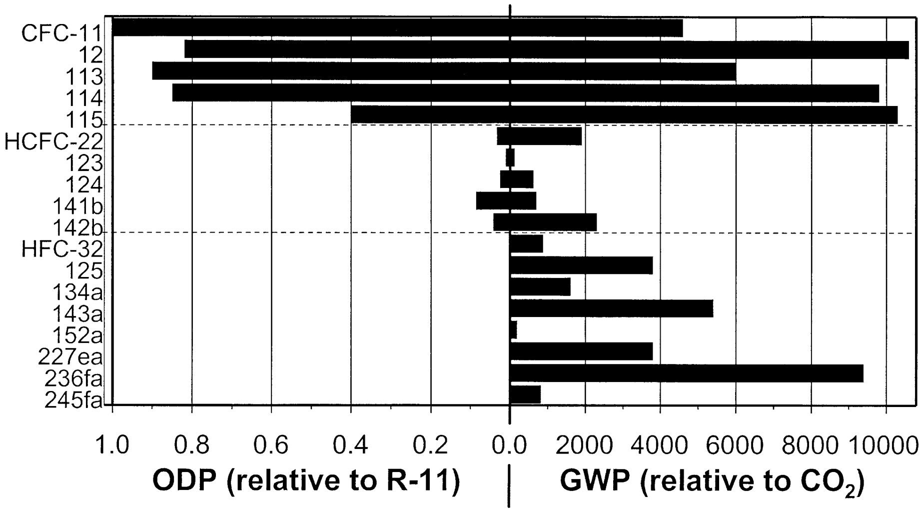

Fig. 4. Ozone depletion potential (ODP) contrasted to global warming potential (GWP) for key single-compound refrigerants (based on data from reference [14]): CFCs generally have high ODP and GWP. HCFCs generally have much lower ODP and GWP. HFCs offer near-zero ODP, but some have comparatively high GWPs.

Of those mentioned, all pose fairly low occupational risks to technicians and others who work with or near them, usually characterized as chronic (long-term, repeated exposure). R-123 is more toxic than R-22 and R-134a, as reflected in both their permissible exposure limits (PELs) or consistent indices and by their safety classification under ASHRAE Standard 34 (*Designation and Safety Classification of Refrigerants*) [18]. R-717 (ammonia) is even more toxic, but none of them qualifies as a "highly toxic" or even as a "toxic" substance under federal regulations in the USA or in most local construction (building, fire, and mechanical) codes [19].

All of these refrigerants can be used safely with proper equipment and system design and adherence to recommended service practices. ASHRAE Standard 15 (*Safety Code for Mechanical Refrigeration*) [20] and the building, fire, and mechanical codes identify minimum safety requirements.

Toxicity indices alone do not describe relative risk. Most such indices and exposure limits are expressed as concentrations in dimensionless form, such as ppm v/v (parts per million by volume), or dimensional equivalents (mass per unit volume). Because of differences in volatilities, ruptures or other releases of the same amounts of low- and high-pressure refrigerants result in different airborne concentrations at room temperature. With a normal boiling point of 27.8 °C (82.0 °F), most of the R-123 would condense on the floor as a liquid and the airborne concentration would be low. Conversely, R-22 or R-134a would have higher initial concentrations, but they would dissipate more quickly. Since the driving force in a leak is pressure, the amount of refrigerant that would escape for the same size leaks would be higher with high-pressure refrigerants than for low-pressure fluids.

For perspective, R-123 is safer or significantly safer than R-11, which it replaced, by most measures. R-134a is one of the least toxic refrigerants commercialized. While all of them pose risks if used improperly, the most dangerous part of working on refrigeration systems is getting to and from the job site. The chances of death from a refrigerant exposure, excluding intentional abuse, is more than twenty times less than of being killed by lightning. This record should improve with current use of refrigerant leak detectors and compliance with updated safety standards and codes.

As to the FUD debate, R-22 did cause malignant tumors in rats during toxicity tests. Both R-123 and R-134a—the latter only at very high concentrations—caused increased incidence of benign (nonmalignant) tumors in rats late in life, following chronic exposures. Repeated toxicological evaluations based on further mechanistic and other tests have concluded that these results are not relevant to and do not pose unusual risks in humans. The claims of a volunteer dying and being resuscitated in human tests of R-134a and R-227ea grossly distort what happened. Subsequent investigations found that the reactions were caused by the way the tests were performed, and not by chemical action. Multiple tests on animals and humans at higher concentrations, as well as unintentional exposures, corroborate the findings.

References [19,21,22] provide further information on refrigerant toxicity.

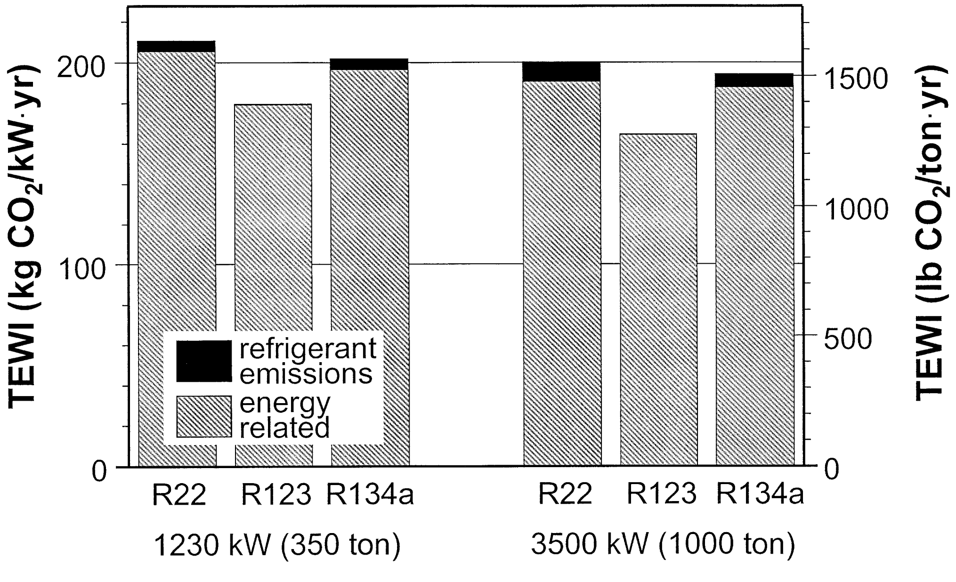

Fig. 5. Greenhouse gas emissions (expressed as equivalent carbon dioxide) per unit of cooling per year-TEWI-for the best available chillers in two representative capacities.

7.4. Flammability

None of the cited chiller refrigerants except ammonia and the hydrocarbons are flammable by the tests generally used to classify refrigerant safety. Ammonia's flammability is moderate, and it does not ignite easily. R-123 and R-236fa are used commercially as fire suppressants.

Except for water, all of the cited refrigerants warrant greater care for fires from failures involving aerosols of the compressor lubricants in pressurized refrigerants. This comment is particularly true for refrigerants that are flammable or have low flame-suppression capability.

7.5. Future costs

The short answer on future refrigerant costs is that they need not be high. The refrigerant component of total system costs or even equipment costs is small. The strategic approach to reducing the costs of refrigerants for service is to minimize the need for make-up. The keys are factory and field tests for leaks in new equipment, adherence to manufacturer recommendations for preventative maintenance and service practices, technician training, and prompt responses to leak indicators. They include the need to add refrigerant, use of leak detectors, and increased run-time for purges.

8. Chiller wars

The term *chiller wars* describes the marketing campaigns, or FUD campaigns, that emerged in the 1990s based on refrigerant and equipment selections.

Every chiller application warrants evaluation for unique factors, but some generalizations hold for most. The following comments respond to some of the FUD espoused in marketing.

Low-pressure designs usually offer lower costs, particularly for chillers with high efficiencies. They require purge devices to remove air that leaks in, but subatmospheric operation reduces refrigerant losses (air leaks in rather than refrigerant out). Assertions that purge venting (discharge of the removed air) also releases refrigerants are largely a vestige of the past. The contention predates the near-zero losses of current condensing purges, and especially those that vent through a charcoal or other recovery canister.

High-pressure chillers often are more compact, facilitating replacements where space or access is tight. They generally offer lower equipment—not operating—cost for low-efficiency designs.

R-22, R-123, and R-134a are all acceptable choices. While R-22 designs will be the next class to be retired, stocked supplies of R-22 and recycled amounts should satisfy service needs for current and new chillers for many years. Contentions that users will face shortages or be held hostage to escalating prices are overstated. As for R-11, R-12, and other CFCs or blends containing CFCs (such as R-500 and R-502), the keys are tightening systems to minimize losses, improving service practices, and managing current inventories including those in use. These measures are essential for all refrigerants, not just those facing earlier production phaseout.

R-717 (ammonia) also warrants consideration. It is an excellent refrigerant in appropriate applications. Examples include industrial processes, such as food and beverage processing and warehousing, and refrigeration of ice rinks. Ammonia is not suitable in locations where accidental releases would threaten public safety.

Absorption-cycle chillers typically are larger and more expensive, but offer lower operating costs when driven by otherwise wasted heat or low-cost heat or fuels. They also offer a strategy to reduce peak electric demand charges where of concern. The efficiencies of absorption chillers are comparatively lower than vapor-compression counterparts, resulting in higher or much higher TEWI, LCWI, or LCCP in most locations and applications.

There is an old quandary about a partially filled glass. The philosopher debates whether it is *half full* or *half empty*; the engineer thinks the glass is *too big for the need.* Half truths on refrigerants should evoke a similar response. The answer is not whether they are *half correct* or *half incorrect*, but that they usually *do not address the appropriate question.*

9. Future chiller refrigerants

Newer designs using R-134a, R-407C, R-410A, other blends, or R-717 (ammonia) will replace R-22 in coming years. R-134a will remain in use, and it will dominate in the limited market for very large capacities, chillers exceeding 15 MW_t (4300 ton).

The difficult transition will be to replacements for R-123, since all identified alternatives for it compromise performance and/or safety [4,9,10]. The clear solution would be to exempt R-123 from phaseout under the Montreal Protocol and 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.

R-245fa offers potential to approach R-123 efficiencies in large capacities, 3-15 MW_t (850-4300 ton), with use of multistage compressors. Its commercialization as a refrigerant is still uncertain. Such use will depend on broad market acceptance as a foam-blowing agent, to reach affordable production levels. Even then, R-245fa is likely to cost more than other refrigerants, based on the manufacturing processes entailed. The decisive factor for 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, subatmospheric operation risks air entry and the possibility of detonation when compressed. Beyond the safety issues, neither hydrocarbons nor R-717 (ammonia) matches the efficiency of R-123 at chiller operating conditions, as shown in Refs. [4 and 9]

10. Conclusions

Most of the current anxiety with refrigerant selections is unwarranted. Engineers, building owners, and others involved in chiller decisions should revert to traditional chiller specifications based on cost, performance, local manufacturer support, service options, and reliability. Anticipating more stringent environmental regulations, they also should take all practical steps to reduce refrigerant releases and increase efficiency.

The FUD campaigns have retarded replacement of older, less-efficient, leak- and failure-prone equipment. That result hurts the environment, increases costs, and stifles the chiller market.

Further recognizing that there are no ideal refrigerants and that none are likely to be found, all involved must insist on scientific determination of acceptability rather than market manipulation. Failing that, industry infighting will invite a return to less safe options that exacerbate climate change. Those options also will worsen other looming issues, such as nitrogen loading, through lowered efficiency and the resulting requirement for higher energy use.

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