GLOBAL WARMING IMPACTS OF CHILLERS

Once the high GWP CFCs are eliminated, global warming will more readily be reduced through efficiency improvements and emission reductions than by refrigerant substitutions

By JAMES M. CALM, PE,
Engineering Consultant,
Great Falls, Va.

Most discussion of refrigerant impacts on the environment has focused on protection of stratospheric ozone. The now-familiar Montreal Protocol, as revised last November at a meeting in Copenhagen, provides a clear mandate for transition to alternatives that do not deplete the earth's ozone layer. Coupled with reductions in refrigerant emissions, substitution of fluids with low or zero ozone-depletion potential (ODP) minimize or, for the latter, eliminate damage to the ozone layer. With retirement of the chlorofluorocarbon (CFC) refrigerants that once dominated in chillers for air conditioning systems, including R-11, R-12, R-113, R-114, and R-500 (which contains R-12), questions surface on other environmental concerns for the alternatives.

Near-term chiller options

The primary options for the near term are substitution of hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) refrigerants, though even the former are scheduled to be phased out, and use of absorption-cycle chillers. R-22, R-123, and R-134a—a high-pressure HCFC, a low-pressure HCFC, and a medium-pressure HFC, respectively—are the most widely used options. Ammonia (R-717) and propane (R-290) also are candidates, but their use is limited by inherent flammability and, for ammonia, toxicity concerns. Both, however, warrant consideration for industrial use and, where adequate safety can be assured, also in chillers in isolated machinery rooms.

Other potential refrigerants are being investigated, including additional HFCs, ethers, ketones, and inorganic chemical compounds. They will require at least three and more probably five to seven years for commercialization once proven feasible. This delay results from the time needed for toxicity and other safety studies, identification and qualification of compatible materials and lubricants, performance and durability testing, both product and process engineering, and production startup.

The most widely used refrigerant/absorbent pairs for absorption equipment are ammonia/water in small capacities and water/ lithium bromide for larger units. Some use also has been made of water/lithium chloride, but it has been less successful due to corrosive effects. While many other working fluids have been proposed, the cited pairs are the only commercialized options.

Limited opportunities exist to address latent cooling loads with

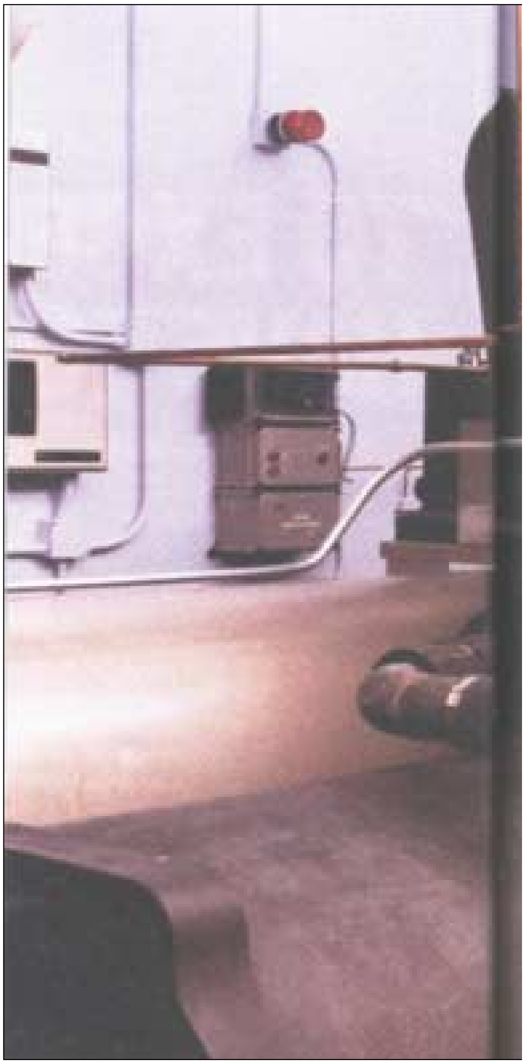


Photo courtesy of The Trane Company

desiccant dehumidification systems and sensible cooling loads, particularly in dry climates, with evaporative cooling. Other cited technologies that avoid the refrigerants of concern range from magnetic and thermoacoustic heat pumps to Stirling and the related Vuilleumier machines. Although the subjects of ambitious research programs, these technologies are not ready for, and in some cases may never reach, commercialization for technical, safety, or economic reasons.

The primary near-term options for commercial and institutional applications, then, are vapor compression-cycle chillers using R-22, R-123, and R-134a and absorption-cycle chillers using ammonia/water in capacities generally below 60 tons and water/lithium bromide in larger sizes. The vapor-compression machines can be driven by electric motors, gas and/or diesel engines, and steam turbines though the electric version is by far the most widely used. Table 1 summarizes the primary applications of alternative refrigerants in vapor-compression equipment for heating, refrigeration, and air conditioning.[1] Although R-22 and R-123 will be phased out by 2030 under the recently revised Montreal Protocol and national restrictions such as the 1990 Clean Air Act Amendments in the United States, they remain critical transition options. The phaseout dates in the Protocol and Clean Air Act were selected to allow for normal retirement of new equipment using these fluids, to enable accelerated phaseout of the CFCs, and for time to develop and introduce successor fluids and technologies.

TABLE 1—Primary refrigerant uses in vapor-compression equipment. (Refrigerants shown in parentheses are under consideration, either for new equipment or to service existing machines, but are not yet commercially available.)

Application	Current/former	Near-term alternative(s)
Air conditioners	HCFC-22	HCFC-22
Heat pumps	HCFC-22	HCFC-22
Chillers	CFC-11, CFC-113	HCFC-123[1]
	CFC-12, R-500	HFC-134a[1]
	CFC-114	(HCFC-124, E-134)
	HCFC-22	HCFC-22[1]
Refrigerators/freezers	CFC-12	HFC-134a, (blends)[2]
Commercial refrigeration		
Low temperature	R-502	HCFC-22, blends[1]
Medium temperature	CFC-12	HFC-134a, HCFC-22[1]
High temperature	CFC-12, HCFC-22	HFC-134a, HCFC-22
Mobile air conditioners	CFC-12	HFC-134a
Transport refrigeration	CFC-12	HFC-134a

[1]Ammonia—R-717—and, for industrial applications, propane—R-290—may be used in some applications subject to safety considerations.

[2]A propane/isobutane (R-290/600a) blend is being investigated in Europe, as is HFC-152a in China; neither is regarded as probable in the United States due to concerns with flammability.

Global warming

Concern has been raised with the potential of alternative refrigerants to act as "greenhouse gases," thereby contributing to global warming. The average temperature at the surface of the earth would be lower by approximately 34 C (61 F) were it not for the gases that make up the atmosphere. Those with the ability to absorb infrared energy trap this component of sunlight, leading to the higher temperatures on which we depend. The global warming issue relates to changes in the atmospheric composition that may lead to increased greenhouse effect. An indicator of the ability of a gas to trap heat is its global warming potential (GWP), a relative measure generally referenced either to R-11 for similarity to the ODP or more commonly to carbon dioxide—the primary greenhouse gas. The former measure is sometimes referred to as the halocarbon GWP (HGWP) for distinction.

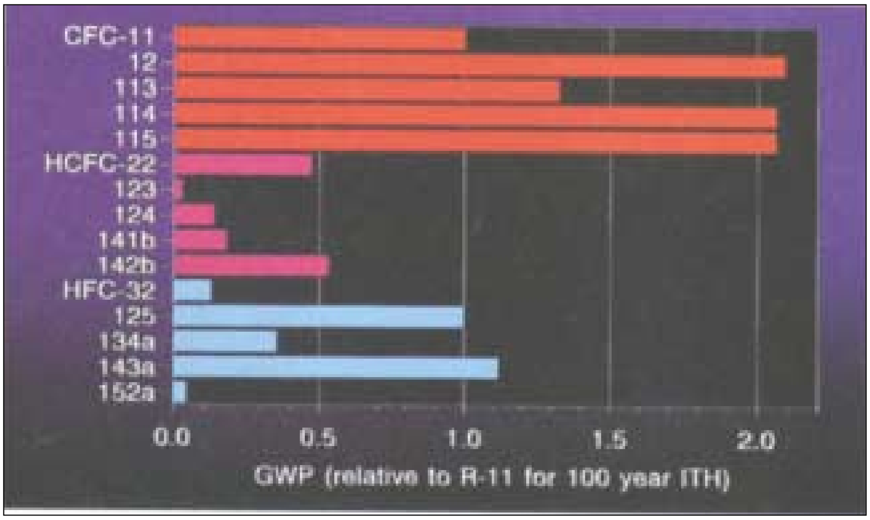
The greenhouse gas mechanism is different from the primary function of glass in a greenhouse. The glass admits sunlight while reducing convection (heat movement by air circulation). Greenhouse temperatures usually are controlled by opening windows or using ventilation fans. By contrast, greenhouse gases actually absorb the infrared energy radiated by the earth, to offset incoming solar energy, changing the equilibrium and resulting in global warming. There are no windows to open or fans to use for planetary cooling. In fact, once the planet warms, glaciers and polar caps may melt, leading to reduced reflection of sunlight and further warming.

Much is still unknown about the mechanisms leading to equilibrium. Among them are increases in cloud formation as temperatures rise—and thus increased reflection of incoming sunlight—and natural sinks for greenhouse gases. Two potential sinks are absorption of carbon dioxide by oceans and increased conversion through photosynthesis from faster plant growth, nurtured by high carbon dioxide levels. Debate exists both on the desirability of warming, since some scientists hold that we may be approaching another ice age, and on whether such warming has actually begun. It is clear, however, that either a rapid change in global temperature or warming sufficient to melt the polar ice caps, causing sea levels to rise, would be catastrophic.

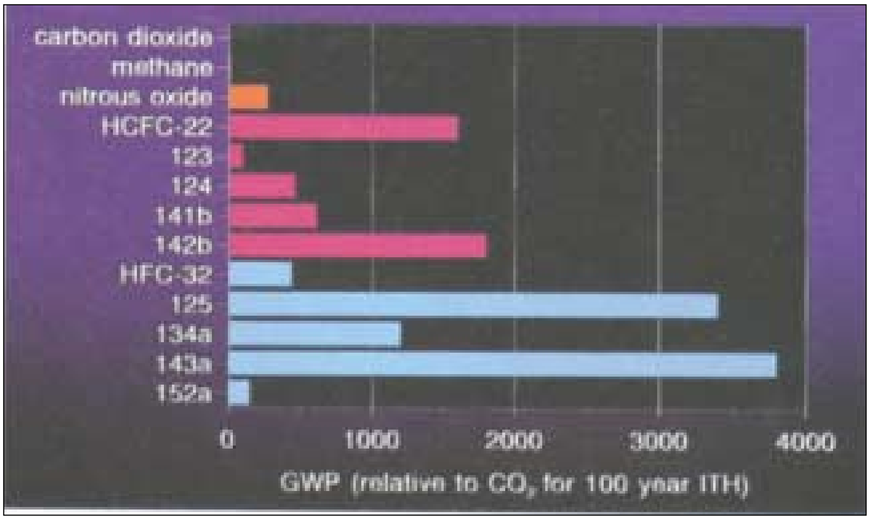
The specter of global warming, therefore, raises a second environmental concern with refrigerants. Some authorities count it as the fourth, including safety and energy use, which were the reasons for the introduction of the CFC family of chemicals. Taxes based on GWPs similar to those based on ODPs for the CFC refrigerants have been proposed for refrigerants.

Direct and indirect effects

While the alternative refrigerants generally yield much lower GWPs than CFCs, as shown in Fig. 1,[2,3] their direct warming effect, as with greenhouse gases, is much higher than that from carbon dioxide and other atmospheric gases (Fig. 2[2,3]). The



1 Global warming potentials (GWPs) of CFC, HCFC, and HFC refrigerants (based on data from Reference 3).

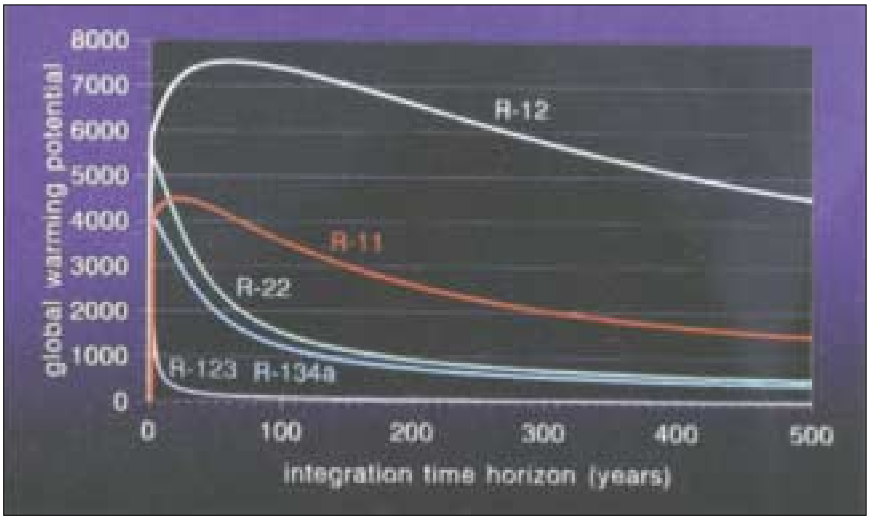


2 GWPs of HCFC and HFC refrigerants relative to carbon dioxide (based on data from Reference 3).

[1]*Superscript numerals indicate references listed at the end of this article.*

HFCs, while offering a solution for the ozone-depletion problem, generally have high GWP values. The two shown with low GWPs, namely R-32 and R-152a, are both flammable. R-152a has been used as a component of R-500, a nonflammable azeotropic blend, for several decades. Unsuccessful attempts were made to commercialize R-32 in the 1960s, and it is now being tested as a blend component in a number of alternative refrigerants under development.

The direct effect (chemical action as a greenhouse gas) alone, however, is misleading. The thermodynamic properties of a refrigerant limit the efficiency that can be attained in a heat pump or refrigeration machine. Since the efficiency governs the amount of power required for a specific thermal load, the selection of refrigerants also impacts the greenhouse gases, most notably carbon dioxide, released in supplying the required power. The warming stemming from combustion emissions to provide power is referred to as the indirect, or energy-related, effect. Atmospheric scientists use the term *indirect effect* to refer to the impact of greenhouse gases produced in the atmosphere by chemical reactions with an emission. The effect of this secondary chemistry is of much lesser magnitude and is not further discussed in this article.



3 Impact of time horizon (ITH) selection on GWP (based on data from Reference 2).

Total equivalent warming

Whereas the direct effect is a property of a refrigerant indicated by a GWP, the indirect effect depends on its use. Release rates, efficiency, duration of operation, and similar application-specific variables are all pertinent. By expressing both the direct (chemical) and indirect (energy-related) effects as equivalent carbon dioxide emissions, we can calculate a net effect referred to as the total equivalent warming impact (TEWI) for each use of refrigerants.

Prior studies have quantified the warming impacts of refrigerants as equivalent carbon dioxide impacts, based on emission rates and carbon dioxide-based GWPs.[4] A perspective published by Du Pont Chemicals illustrated the relative impacts of direct and indirect effects by expressing both as the amount of carbon dioxide emissions resulting in equivalent global warming.[5] The most widely cited study of net warming impacts was performed by the Oak Ridge National Laboratory and Arthur D. Little, Inc.[6] It was jointly sponsored by the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS, a consortium of chemical manufacturers) and the U.S. Dept. of Energy (DOE).

The AFEAS/DOE analyses concluded that replacement of CFCs with HCFCs or HFCs would reduce the TEWI by 10 to 98 percent, depending on the application (including nonrefrigerant uses such as foam blowing and cleaning solvent). One finding specific to air conditioners, chillers, and refrigeration (applications in which the refrigerant is used in a closed system) was that the indirect effect dominated over the direct. A critical implication is that substitution of fluids on the basis of GWP alone, without consideration of the efficiency that can be practically achieved with alternative fluids, may increase rather than decrease the net warming impact.

EPRI study

A study by the author, sponsored by the Electric Power Research Institute (EPRI), extended the prior investigations by examining several additional facets. First, updated GWP values, as shown in Figs. 1 and 2, were used. The new data reflect shorter integration time horizons (ITH)—100 rather than 500 years—and revised estimates of the atmospheric lifetimes of refrigerants. Second, the greenhouse gas emissions from electricity generation and associated power losses in transmission and distribution were recalculated based on current and projected utility data. Third, chiller load profiles were addressed in the calculations. Fourth, the analyses were repeated on a regional basis to examine variations in fuel use. And fifth, the impacts of improved equipment efficiency and refrigerant management practices were examined.

Integration time horizon

Gases in the atmosphere decay with time as they are broken apart by sunlight or react with other compounds. Molecular char-

continued on page35

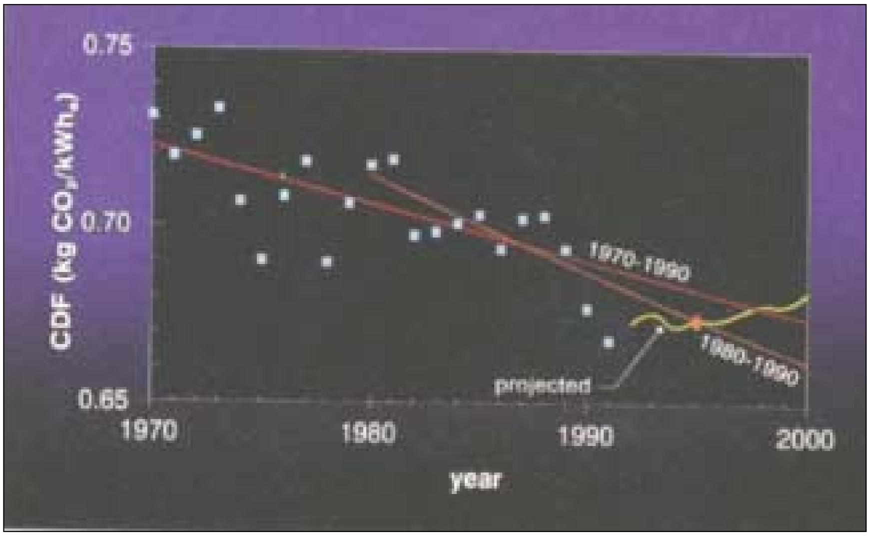
continued from page 31

acteristics determine the ability of a gas to absorb infrared energy, a component of sunlight. Both its trapping strength (resulting in its impact, or radiative forcing) and atmospheric lifetime impact its ability to act as a greenhouse gas and hence its global warming potential. The analysis period, or integration time horizon (ITH), used to calculate the GWP impacts the outcome. Fig. 3[2,3] shows the change in GWP as a function of ITH. As indicated, GWP values increase for refrigerants, particularly those with short atmospheric lifetimes, such as R-123, R-134a, and R-22, as the ITH is reduced. Shorter ITH values accentuate their impact by disregarding increasing portions of the warming effect of carbon dioxide.

Whereas long ITH values indicate the cumulative effects on climate, short time horizons emphasize immediate influences. Too short an ITH can be misleading, however, due to the inertial effects of the world's oceans and other energy exchanges with the surface; the lag in climate response is 10 to 100 years, depending on the specific change. The findings reported in this article are based on 100-year ITH values to provide a balanced presentation consistent with recommendations of the Intergovernmental Panel on Climate Change.

Energy data

Whereas the AFEAS/DOE study based its analyses on historical generation and estimated losses for transmission and distribution, the present analyses are based on the projected fuel mix for the United States in 1995. Net greenhouse emissions have fallen steadily as the efficiency of power plants (or, in utility parlance, their generation heat rates) improved. Similarly, generation using nonfossil energy sources, including nuclear and hydro and to a lesser extent geothermal, wind, and solar, has increased.



4 Historical and projected carbon dioxide factors (CDFs) for generation of electricity.

Fig. 4 illustrates the historical trend in carbon dioxide emissions from power generation. The quantity shown is the carbon dioxide factor (CDF)—the ratio between emissions and electricity generated. Regression lines are plotted both for the last two decades and for the last decade, clearly showing that improvement has been more rapid in recent years than for the longer period. A sharper decline is evident for the last three years, but similar cyclical declines are evident for earlier years as well. Fig. 4 also shows projected CDF values based on forecast fuel mixes and loads. The increase toward the end of the century reflects increasing power needs that will be met primarily by added gas turbines, reducing the generation share of nonfossil fuels.

1995 projections were selected for consistency with the chiller performance projections developed for the AFEAS/DOE study.[7] The 1980-1990 regression and the generation forecast yield the same CDF value for that year.

Both the electricity and gas requirements for chillers examined in this study were adjusted to account for losses and uses in transmission and distribution. The loss factors used were based on actual data, again as summarized by the DOE based on utility reports.

Load profiles

Whereas the AFEAS/DOE study used uniform efficiency and power generation data, the present study adjusted the calculations to reflect both seasonal loads on chillers and daily load profiles. Both are important since the fuel mix and, therefore, greenhouse gas emissions from combustion change to meet demand peaks resulting in large part from cooling loads.

For example, hydroelectric power, which does not contribute to global warming, is most abundant in the winter and spring, but the highest cooling loads generally occur in the summer. Gas turbines, widely used to meet peak generation needs, produce less carbon dioxide per kilowatt-hour of electricity generated than do coal-fired plants. While some adjustments to reflect typical load and generation profiles are offsetting, their introduction was important to enable the regional analyses discussed later.

Assumptions

Most of the operating assumptions used in the present study were consistent with those in the AFEAS/DOE analyses. The refrigerant loss rates for both service and ultimate disposal were based on estimates provided by air conditioning and refrigeration manufacturers. Except as indicated for the analysis of emission management, the loss rates used reflect current rather than achievable practices. Equipment lives and load factors were based on the AFEAS/DOE data although the latter also were varied to examine comparative warming for chillers installed to meet peak cooling loads. The chiller efficiency and refrigerant charge quantities were based on industry inputs to the AFEAS/DOE study.[7,8] Details on data and assumptions for the analyses, as well as further results, will be provided in a report in preparation.[9]

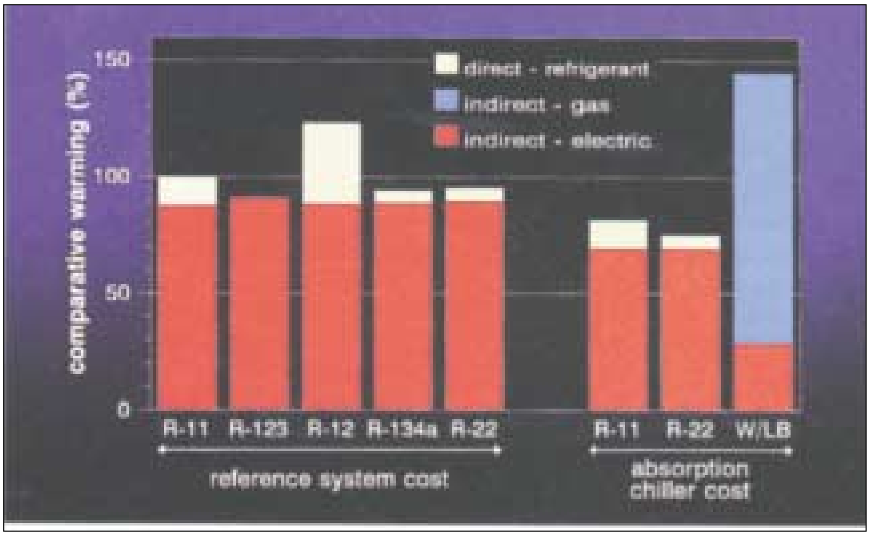
Findings

Fig. 5 compares the net equivalent warming impacts for electric vapor-compression chillers using R-11, R-123, R-12, R-134a, and R-22 and for a gas-fired, double-effect absorption chiller (labeled W/LB to indicate water/lithium bromide). The R-22 machines used either a centrifugal or competitive screw compressor; all of the other vapor-compression chillers analyzed used centrifugal compressors. The energy required by cooling towers and condenser water pumps also was included since this use is impacted by the chiller efficiency. Power for chilled water pumps and air handlers or terminal-device fans was excluded since it was assumed to be independent of chiller type. The net warming of the R-11 chiller was used as the reference level (*i.e.*, set to 100 percent) in this and subsequent figures to simplify comparisons on a relative basis.

The figure shows that all three alternative refrigerants—R-22, R-123, and R-134a—yield lower net warming than R-11 and significantly less than R-12. The efficiencies analyzed for the alternative refrigerants were slightly lower than for the CFCs, but the lower GWP of the refrigerants more than offset the difference.

Two conclusions can be drawn:

- As in the AFEAS/DOE study, the effect of the indirect (energy-related) components of warming far exceeds that from the direct (refrigerant) effect.
- All of the vapor-compression machines yielded lower net warming impact than the direct-fired, double-effect absorption chiller. The latter results in 45 percent higher TEWI than the R-11 chiller and 50 to 60 percent higher TEWI than the vapor-compression chillers using the three cited alternative refrigerants.



5 Net warming impacts for 300-ton vapor-compression and direct-fired, double-effect absorption chillers. Both standard and high-performance R-11 and R-22 machines are shown. Values for this and the succeeding figures include the combined effect of chillers and associated cooling tower fans and condenser water pumps.

Fig. 5 also shows two very high-performance chillers using R-11 and R-22. Although not commercially marketed, these machines feature performance levels that are estimated by chiller manufacturers as the minimums attainable at the fabrication costs of direct-fired, double-effect absorption chillers.[7] The production costs of vapor-compression and absorption chillers differ primarily due to the large increase in heat-transfer surface required for the latter, partly offset by the compressor cost. The objective of the comparison is to illustrate the further reduction in global warming from performance improvement achievable at the same cost premium as switching to absorption chillers.

A note is warranted on the efficiencies used for the chillers. They were obtained as industry consensus values for input to the AFEAS/DOE study, based on detailed analyses and in some cases measurements by equipment manufacturers.[7] All but one of the firms that provided the chiller data market both vapor-compression and absorption machines. The approach used based the efficiencies on consistent fabrication costs since a range of performance levels can be produced with each of the refrigerants.

The two cost levels shown in Fig. 5 correspond to those for the reference (R-11) system and for the more expensive absorption chiller. Significant strides have been made with all of the alternative refrigerants. Moreover, the costs of these fluids, which affect chiller costs, are now more favorable relative to those of the CFCs because of production advances and increasing CFC excise taxes. The small decrease in efficiency for the HCFCs and HFCs relative to the CFCs would no longer appear with newer data, and the relative efficiencies for the three alternative fluids might be changed slightly.

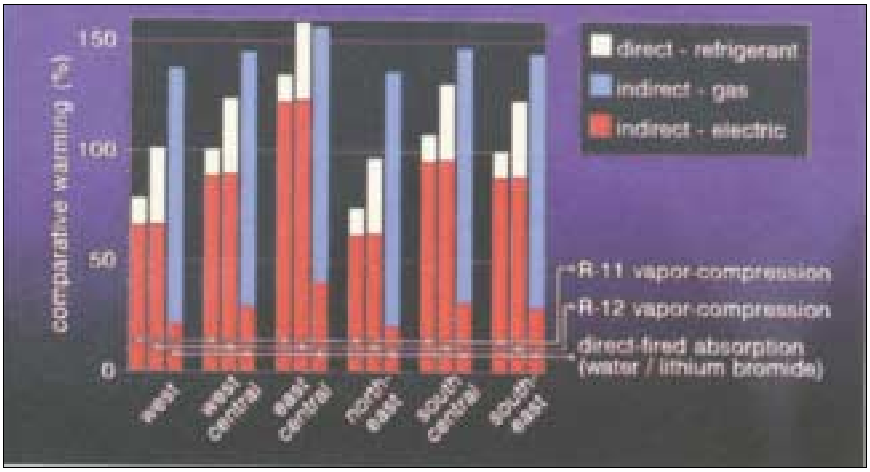
A triple-effect absorption chiller, which should improve the performance of direct-fired chillers, is under development but is not commercially available. Actual data on its performance and costs were not available for inclusion in the comparisons, but its net warming impact would still be higher than for the vapor-compression machines based on its announced performance goal.

Regional analyses

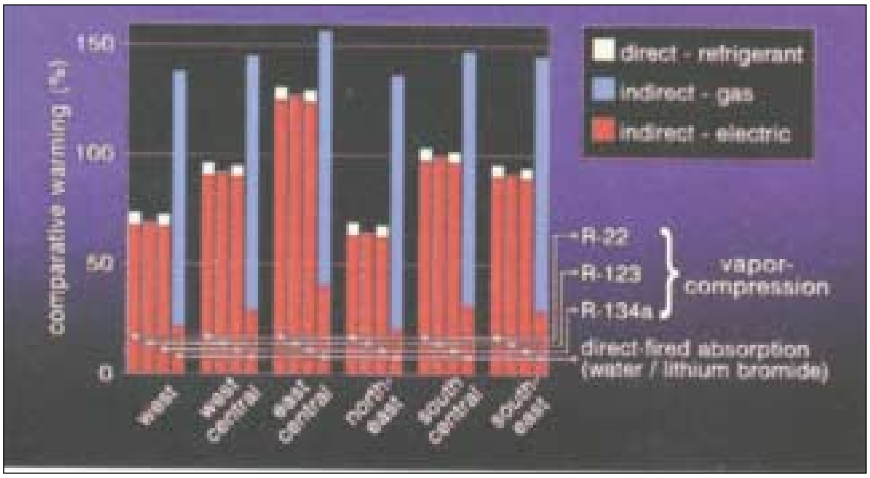
Figs. 6 and 7 summarize similar analyses by region of the country (Fig. 8—derived from Reference 10) based on local fuel mixes for electricity generation. Fig. 6 compares the double-effect absorption chiller to the vapor-compression models being phased out to protect the ozone layer. Fig. 7 repeats the comparison for the near-term alternative refrigerants.

With one exception—the east-central region—all of the electric vapor-compression chillers yielded lower comparative net warming than the direct-fired absorption machine. The exception involves R-12 centrifugal chillers in the region of the country with highest dependence on coal-fired electricity generation; R-12 centrifugal chillers will no longer be marketed in the United States by the time this article is published. The comparative warming in this region was lower for all of the other vapor-compression chillers examined.

As shown in Fig. 7, the direct-fired absorption chiller increased net warming by 20 to 110 percent compared to electric vapor-compression chillers using refrigerants that minimize or eliminate



6 Regional warming impacts for R-11, R-22, and direct-fired, double-effect absorption chillers.



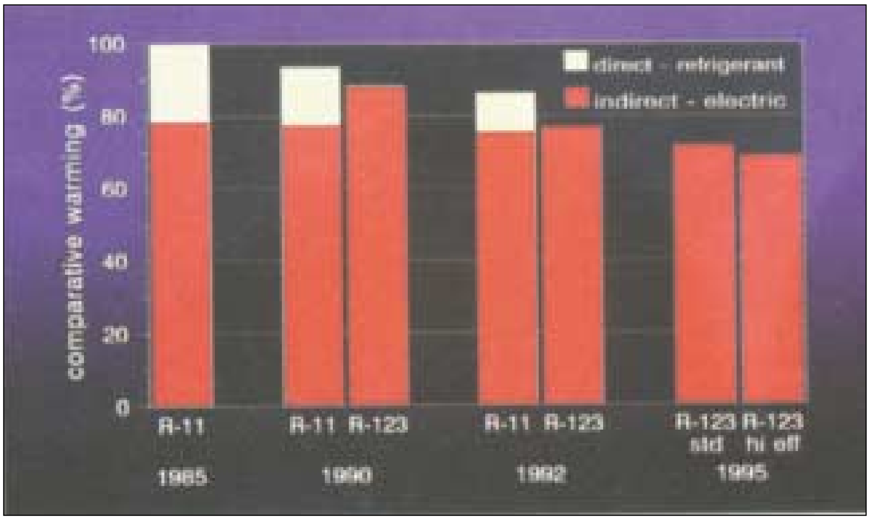
7 Regional warming impacts for alternative refrigerants and direct-fired, double-effect absorption chillers.

ozone depletion, depending on the region and refrigerant. Similar results were found in other chiller capacities examined.

A sensitivity analysis was performed to examine the impact of the chiller operating period. As operation decreased from 20 percent load factor (1750 hr per yr) to 5 percent (440 hr per yr), the average warming detriment of using the absorption chiller was 30 to 60 percent. This case gives an indication of global warming impact for potential use of absorption chillers to meet peak cooling demands. As the load factor was increased to 35 percent (3000 hr per yr), representative of a chiller in a central plant used all year, the detriment grew to 55 to 60 percent higher warming.

The east-central region was examined separately as the worst case for carbon dioxide emissions from power generation. The absorption machine results in 5 to 20 percent higher comparative warming for peak cooling loads. The breakeven point, compared to an R-123 centrifugal chiller, is for less than 17 hr of operation per year, for which it is difficult to conceive selection of the more expensive absorption option. The number of operating hours for equivalent impact is even lower for the other regions.

The regional analyses not only suggest the advantages of the alternative refrigerants in different portions of the United States but also provide an indication for international comparisons. The results from the northeast, based on a comparatively high nuclear power fraction (36 percent of annual generation), give an indication for countries with similar (*e.g.*, Finland, Germany, and Spain) and even higher (*e.g.*, Belgium, France, and Taiwan) nuclear shares. The results for the west region provide an indication for countries with similar and higher (*e.g.*, Austria, Brazil, Canada, Colombia, Norway, Switzerland, and Venezuela) hydroelectric shares. The east-central region is indicative of countries with high coal dependence (*e.g.*, Australia, Poland, South Africa, and the United Kingdom).



9 Net warming impacts with reduced refrigerant losses and equipment performance improvement calculated for constant (1995) generation fuel mix and losses.

Warming reduction

Two means beyond changing refrigerants are available to reduce global warming from chillers. The first is reduction of refrigerant emissions. The ODP and GWP of a refrigerant are irrelevant while it remains in the chiller; the problems stem only from refrigerant losses. One chiller manufacturer has announced a "near-zero" emissions chiller that will be available by mid-1993.[11] The reduction is achieved by upgrading the construction (*e.g.*, improving gasket materials and fittings), purge unit performance, leak testing techniques, and refrigerant handling and recovery methods. Annual losses are projected to be less than 0.5 percent of the total charge, compared to more than 25 percent in the past. Much of the earlier losses stemmed from service practices rather than actual leaks. ASHRAE publishes a guideline on reduction of refrigerant emissions, and though it is written for CFCs, most of it also is applicable to other refrigerants.[12]

The second means is performance improvement. As shown in the preceding analyses, the indirect (energy-related) effect far surpasses the direct (chemical) effect. Electric vapor-compression chillers with *COP*s of 4.7 to 6.0 (0.75 to 0.58 kW per ton) are available for the 300-ton size. The cost increase for the high-performance machines is 10 to 20 percent over the average—still considerably less than the premium for absorption chillers.

Fig. 9 shows the trend in performance and emission reduction for low-pressure chillers based on typical performance and emission levels for 1985, 1990, and 1992 as well as projections for 1995. Both annual and disposal losses have fallen in the same period, resulting in approximate halving of the direct contribution to warming without change in refrigerant. The amount of refrigerant used per kW$_t$ (ton) of capacity also is falling with improved designs. An earlier study of refrigerant charge in air conditioning equipment showed charge quantity reductions in all classes of equipment examined based on surveys of older, current, and projected equipment. Reductions as high as 40 percent have occurred compared to equipment installed approximately 17 years ago, largly stemming from the use of enhanced heat-exchange surfaces and the consequent reduction in required internal volume.[8] Returning to Fig. 9, a similar reduction in the direct warming component also is evident for the R-123 chillers although this warming component is much lower in mag-

8 Regions used for analyses of generation fuel impacts (based on data from Reference 10).

nitude than for the R-11 machines simply based on the much lower GWP.

Comparing the performance of the R-11 machines for 1985 and 1992, typical performance has improved from a *COP* of 5.25 to 5.50 (0.67 to 0.64 KW per ton) at standard rating conditions. The indirect component of warming has fallen nearly proportionately to the efficiency improvement. The difference lies in the component of energy use for the cooling tower for the actual cooling load since no improvement was introduced for this energy use in the analyses. A more dramatic improvement appears in the R-123 chillers since the initial designs were based on equipment optimized for R-11. As equipment was reoptimized for R-123, the performance difference between the R-123 and R-11 machines approached the difference based on theoretical performance of the two refrigerants.

With anticipated design improvements, the 1995 products should further reduce energy use and resultant indirect warming. The two R-123 chillers shown for 1995 reflect standard and high-efficiency models. The difference in net warming of the two chillers, both using the same refrigerant, is larger than the difference among the three alternative refrigerants—R-22, R-123, and R-134a—in Fig. 5. This comparison clearly shows that once the high-GWP CFCs are eliminated, far greater opportunity exists to reduce global warming by efficiency improvement or emission reduction than by refrigerant substitution. Another way to view the result is that the small impact of direct warming effect from refrigerant emissions is equivalent to less than a 0.1 to 1.1 percent change in efficiency, depending on refrigerant, once service and disposal losses are reduced and CFCs eliminated.

Similar results to those shown in Fig. 9 also would result for chillers using R-22 and R-134a. The performance improvement between 1990 and 1992 was more dramatic for R-123, however, due to initial differences in the equipment optimized for R-11, particularly with regard to heat transfer.

Conclusions

R-22, R-123, and R-134a are displacing CFC refrigerants, including R-11, R-12, R-113, R-114, and R-500 (a blend of R-12 and R-152a), to protect the stratospheric ozone layer. Another contender is direct-fired absorption equipment. All of these options offer good means to reduce or, for R-134a and absorption equipment, eliminate ozone depletion entirely. As environmental focus shifts to global warming, comparison of the commercially available options, including products anticipated in 1995, shows that electric vapor-compression chillers using R-22, R-123, and R-134a offer the best means to minimize the net global warming impact. Regional analyses to examine the consequences of different fuel mixes for electricity generation indicate that the absorption option is much less favorable even in the regions with the highest dependence on coal. Two mechanisms—reduction of refrigerant emissions and use of high-efficiency equipment—are shown to have far greater benefit in reducing global warming than selection among the three alternative refrigerants. Finally, the new information presented reaffirms the finding of prior studies that regulation of refrigerants based on their global warming potential, without regard to the commercially attainable efficiency of alternatives, would increase rather than decrease environmental harm. Ω

References

1) Calm, J. M., "Alternative Refrigerants: Challenges and Opportunities," *Heating/Piping/Air Conditioning,* May 1992, pp. 38-49.

2) Houghton, J. T., G. J. Jenkins, J. J. Ephraums, *Climate Change, The IPCC Scientific Assessment,* Intergovernmental Panel on Climate Change, University Press, Cambridge, U.K., 1990.

3) Houghton, J. T., P. A. Callander, S. K. Varney, *Climate Change 1992, Supplementary Report to the IPCC Scientific Assessment,* Intergovernmental Panel on Climate Change, University Press, Cambridge, U.K., 1992.

4) Lashof, D. A., and D. R. Ahuja, "Relative Contributions of Greenhouse Gas Emissions to Global Warming," *Nature,* Vol. 34, April 1990, pp. 529-531.

5) *Hydrochlorofluorocarbons (HCFCs) and Hydrofluorocarbons (HFCs) Address Global Warming: A Perspective,* E. I. du Pont de Nemours and Co., Wilmington, Del., October 1990.

6) Fischer, S. K., P. J. Hughes, P. D. Fairchild, C. L. Kusik, J. T. Dieckmann, E. M. McMahon, and N. Hobday, *Energy and Global Warming Impacts of CFC Alternative Technologies,* Alternative Fluorocarbons Environmental Acceptability Study, Washington, D.C., December 1991.

7) Calm, J. M., *Characteristic Efficiencies and Costs for Air-Conditioning Equipment with Selected Refrigerant Alternatives,* Report JMC/ ARI-9104A, Air-Conditioning and Refrigeration Institute, Arlington, Va., April 1991 (republished as Appendix F of Reference 6).

8) Calm, J. M., *Refrigerant Charge in Air-Conditioning Equipment with Selected Refrigerant Alternatives,* Report JMC/AFEAS-9106C, Alternative Fluorocarbons Environmental Acceptability Study, Washington, D.C., June 1991.

9) Calm, J. M., *Comparative Global Warming Impacts of Electric Vapor-Compression and Direct-Fired Absorption Equipment,* draft report, Electric Power Research Institute, Palo Alto, Calif., December 1991.

10) *EPRI Technical Assessment Guide,* Electric Power Research Institute, Palo Alto, Calif., September 1989.

11) *"Near Zero" Emissions Centrifugal Chiller,* The Trane Co., La Crosse, Wis., September 1992.

12) *Reducing Emission of Fully Halogenated Chlorofluorocarbon (CFC) Refrigerants in Refrigeration and Air-Conditioning Equipment and Applications,* Guideline 3-1990 and Addendum 3a-1992, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, Ga., 1990 and 1992.