Total equivalent warming impact: a measure of the global warming impact of CFC alternatives in refrigerating equipment

Steven K. Fischer
Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA
Received 8 September 1992; revised 4 January 1993

Chlorofluorocarbons (CFCs) are important components of refrigeration equipment, plastic for insulation for buildings and appliances, and solvent cleaning processes. The Montreal Protocol to Protect Stratospheric Ozone Layer and recent revisions to the protocol require a rapid phase-out of the production and use of CFCs and a transition to alternative materials and technologies. It is important that the alternative technologies selected do not exacerbate the global warming problem while attempting to preserve stratospheric ozone. A study was conducted to evaluate the total global warming impact of proposed alternatives to CFCs and this paper focuses on the aspects of that study relevant to refrigeration and air-conditioning. The concept of total equivalent warming impact (TEWI) is developed as a measure of the combined global warming impacts of the refrigerant losses to the atmosphere and the CO_2 emissions from fossil fuels to generate power to run the refrigeration and air-conditioning systems. Equipment using alternatives to CFCs has lower TEWIs than current systems in almost all cases, with dramatic reductions possible in some applications.
(Keywords: substitute; greenhouse effect; measurement)

Le concept de l'impact sur le réchauffement total équivalent: mesure du réchauffement de la terre provoqué par les substituts des CFC utilisés dans les équipements frigorifiques

Les chlorofluorocarbures (CFC) sont largement utilisés dans les équipements frigorifiques, dans les matières plastiques pour l'isolation des bâtiments et des matériaux, et dans les procédés de nettoyage par solvants. Le Protocole de Montréal, qui vise à protéger la couche d'ozone stratosphérique, et ses révisions récentes prévoient un arrêt imminent de la production et de l'utilisation des CFC et l'adoption de substances et technologies de substitution. Or il est important que les technologies de substitution choisies, tout en essayant de préserver l'ozone stratosphérique, ne favorisent pas l'effet de serre. On a effectué une étude pour évaluer l'effet global de certains substituts des CFC sur le réchauffement de la terre, et l'article concerne plus particulièrement les domaines du froid et du conditionnement d'air. Le "concept de l'impact sur le réchauffement total équivalent" (TEWI) est utilisé pour mesurer les effets combinés des émissions de frigorigènes dans l'atmosphère et des émissions de CO_2 dues aux combustibles fossiles utilisés pour le fonctionnement des installations frigorifiques et de conditionnement d'air. Les équipements utilisant des substituts des CFC présentent un potentiel de réchauffement inférieur à celui des équipements actuels dans presque tous les cas, et d'importantes réductions sont envisageables dans certaines applications.
(Mots clés: substitut; effet de serre; mesure)

The Montreal Protocol of 1987, along with the 1989 and 1991 revisions, is an international framework for the orderly phase-out of production and use of chlorofluorocarbons (CFCs) as refrigerants, foam blowing agents, cleaning solvents, aerosol propellants and medical sterilants. The ambitious schedule for replacing CFCs frequently requires manufacturers and users to make decisions on working fluids and begin a transition away from CFCs before sufficient information is available on alternatives. It is extremely important that companies and regulatory agencies do not select chemicals or technologies that exacerbate one environmental problem as they seek to solve another. Poor choices will inevitably result in requiring a second costly transition.

Besides contributing to the destruction of stratospheric ozone, the Antarctic ozone hole and significant ozone reductions in the Arctic, CFCs have also been implicated as a major anthropogenic cause of global warming[1]. As refrigerants are lost through leaks, equipment maintenance and retirement, they disperse throughout the atmosphere and act as greenhouse gases and contribute to global warming. CFCs are particularly effective greenhouse gases because of their very long atmospheric lifetimes and because they block the escape of infrared radiation in a range of the spectrum where 80% of it would otherwise be lost from the earth/atmosphere system[2]. The selection of alternative chemical compounds to replace CFCs must not result in the use of compounds that are worse than CFCs from a global warming perspective.

Besides the accumulation of CFCs in the atmosphere, there is an additional factor that needs to be taken into consideration when assessing the global warming impacts of CFCs and their replacements in energy-consuming systems and processes. Not only do these applications use CFCs, they also either consume or conserve large quantities of energy during their operating lifetimes. Almost all of this energy (with the exceptions of electricity generated by hydro-electric dams or nuclear power plants) results from the combustion of fossil fuels and creates emissions of CO_2. Carbon dioxide is the largest contributor to global warming. The goal to keep in mind when trying to evaluate the impacts of CFC replacements, then, is not just the direct effect of the refrigerants, blowing agents or solvents on global warming, but the total impact of the gases released to the atmosphere, including the lifetime CO_2 emissions from energy use.

The Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), a consortium of fluorocarbon manufacturers, and the US Department of Energy sponsored a project at Oak Ridge National Laboratory (ORNL) to evaluate the impacts of CFC replacements on global warming. This study developed the concept of total equivalent warming impact (TEWI) as a measure of the combined direct effects and indirect energy related effects for systems using CFCs in order to make comparisons of alternative chemicals and technologies. This paper focuses on the aspects of that study which concern refrigeration and air-conditioning.

Methodology

Several indices have been defined and tabulated as measures of the greenhouse warming potentials (GWPs) of trace gases that are similar in concept to the ozone depleting potentials, ODPs, used in the Montreal Protocol. Fisher *et al.*[3] proposed a halocarbon global warming potential (HGWP) for CFCs, hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) that related the impact of each gas to an equivalent mass of CFC11. Similar tables of global warming potentials have been printed and used in which the reference gas is CFC12. Although each of these definitions has the advantage that each compound has a unique GWP value depending on the reference gas chosen, neither allows a system evaluation that also takes into account CO_2 emissions associated with energy use. The Intergovernmental Panel on Climate Change (IPCC) settled on a definition of GWPs which is useful in evaluating a system impact because it uses CO_2 as the reference gas; the GWP of a compound is defined to be 'time integrated commitment to climate forcing from the instantaneous release of 1 kg of a trace gas expressed relative to that from 1 kg of carbon dioxide'.[4]

$$\mathrm{GWP} = \frac{\int_0^n a_i \cdot c_i \, dt}{\int_0^n a_{CO_2} \cdot c_{CO_2} \, dt} \qquad (1)$$

As defined by the IPCC, in Equation (1) 'a_i is the instantaneous radiative forcing due to a unit increase in the concentration of trace gas i, c_i is the concentration of the trace gas i remaining at time t after its release and n is the number of years over which the calculation is performed. The corresponding values for carbon dioxide are in the denominator.'[5] *Table 1* contains a list of compounds and their GWPs using CO_2 as the reference gas with the upper limits of integration, or integration time horizons, set to 100 and 500 years.

Table 1 Global warming potentials (GWPs)
Tableau 1 *Potentiels de réchauffement de la terre*

Compound	100 years	500 years
CO_2	1	1
CFC11	3400	1400
CFC12	7100	4100
CFC113	4200	2100
CFC114	7000	5800
CFC115	700	8500
HCFC22	1600	540
HCFC123	90	30
HCFC124	440	150
HCFC141b	580	200
HCFC142b	1600	540
HFC134a	1200	400
HFC152a	150	49

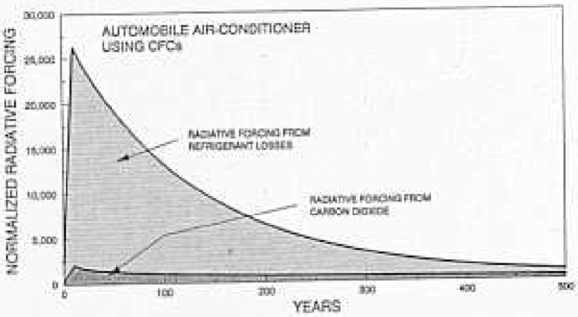

Figure 1 Normalized radiative forcing due to refrigerant losses and fuel combustion to power and transport an automobile air-conditioner
Figure 1 *Moyenne du rayonnement terrestre stoppé par les émissions de frigorigènes et de combustibles utilisés pour le fonctionnement et le transport d'un conditionneur d'air d'automobile*

The definition in Equation (1) can be extended to cover energy-consuming systems by including the time release of refrigerants and CO_2 emissions from annual energy use in the numerator of the equation while leaving the denominator as the area under a curve for the instantaneous release of CO_2. *Figure 1* contains an illustration of the two contributions to radiative forcing for an automobile air-conditioner (normalized by the impact of a release of 1 kg of CO_2) from the CFC12 lost to the atmosphere from leakage and maintenance and also the carbon dioxide from burning gasoline to power the compressor and blower and also just to transport the weight of the system components. Radiative forcing from both the CO_2 (darkly shaded portion) and the refrigerant (lightly shaded portion) increases during the relatively short useful lifetime of the equipment, peaking at an impact equivalent to releasing over 25 000 kg of CO_2, and then they gradually decay in time. For a system then, the numerator of Equation (1) is the area under the two curves from the initial time 0 to some agreed-upon 'integration time horizon', n. The denominator is then the area under a similar curve for the release of a single kilogram of CO_2 from time 0 to n.

Although the integrals in Equation (1) for systems can be calculated in closed form, they are difficult to set up correctly when both the refrigerant emissions and energy use are occurring over time. This is not a large problem when looking at one or two working fluids for a single application, but it was not used in the DOE/AFEAS study because of the hundreds of evaluations performed for the different applications and alternative chemicals and technologies. Equation (2) was used to define the TEWI, where X is the mass of refrigerant emitted to the atmosphere, $GWP_{x,n}$ is the CO_2-based global warming potential of compound X for time horizon n, α is a conversion factor to change energy use from basic units (e.g. kWh $year^{-1}$, ly^{-1} for gasoline) to CO_2 emissions, L is the operating lifetime of the system and E is the annual fuel use. The TEWI has been shown to be a very good approximation of the total impact using the integrals when the time horizon is large relative to the lifetime of the system[6].

$$\text{TEWI} = X \cdot GWP_{x,n} + \alpha_{CO_2} \cdot L \cdot E \qquad (2)$$

Automobile air-conditioning

It may be easier to understand the results presented later if a couple of sample comparisons are made to show how the calculations are performed. Consider first a representative automobile air conditioner for a US-made car with CFC12 as the refrigerant, and then consider a hypothetical comparable system using HFC134a. The car with an air-conditioner using CFC12:

1. contains 1.2 kg of refrigerant and loses approximately 400 g of refrigerant annually through leaks and maintenance (and all the remaining refrigerant is recovered when the car is scrapped);
2. has a useful lifetime of 11 years;
3. weighs 15 kg;
4. is driven 16 400 km per year;
5. has a system coefficient of performance (COP) of 1.90 which is a combination of the cycle COP at 66°C condensing, 4°C evaporating, 54°C liquid, and 18°C return gas with the power supply to the air-conditioning blower, the condensing fan and the power transmission loss in the mechanical drive.

Two estimates from industry sources are used to convert the information listed above to annual fuel use: (1) 47 l of fuel are required per 10 000 km driven to power an automobile air-conditioner using CFC12, and (2) the fuel use for incremental weight changes is 57 l 100 kg^{-1} per 10 000 km/driven[7]. Both of these estimates are fleet-wide averages for new cars and the fuel use for air conditioning is an 'annualized' value that includes the miles driven when the system is idle as well as the on-time when the compressor and fans are operating. A factor of 2.32 kg CO_2 l^{-1} of gasoline is used to convert from annual fuel use to carbon dioxide emissions. A few calculations show that:

1. 91 l per year of fuel are required to power and transport the air conditioner:

$$\frac{47\ \text{l}}{10\,000\ \text{km}} \times 16\,400\ \text{km year}^{-1} + \frac{57\ \text{l}}{100\ \text{kg} \times 10\,000\ \text{km}} \times 15\ \text{kg} \times 16\,400\ \text{km year}^{-1}$$

2. 2300 kg of CO_2 are emitted during the lifetime of the air-conditioning unit:

$$\frac{2.32\ \text{kg CO}_2}{1\ \text{l of fuel}} \times 91\ \text{l of fuel year}^{-1} \times 11\ \text{years}$$

3. 31 000 kg equivalent of CO_2 are released from refrigerant losses using the 100 year GWP value in Table 1, 18 000 kg equivalent with the 500 year GWP value:

$$\frac{0.4\ \text{kg CFC12}}{\text{year}} \times 11\ \text{years} \times \frac{7300\ \text{kg CO}_2\ \text{equivalent}}{\text{kg CFC12}}$$

or

$$\frac{0.4\ \text{kg CFC12}}{\text{year}} \times 11\ \text{years} \times \frac{4500\ \text{CO}_2\ \text{equivalent}}{\text{kg CFC12}}$$

The TEWI is then 33 000 with the 100 year GWP (31 000+2300) or 20 000 with the 500 year value (18 000 + 2300).

The automobile industry has already begun changing over from using CFC12 to HFC134a in new cars. Although basically the same, there are some differences in the two systems. An automobile air-conditioner using HFC134a:

1. contains an estimated 1.1 kg of refrigerant and will lose approximately 367 g $year^{-1}$;
2. weighs 15 kg;
3. has a system COP of 2.04.

Keeping the other assumptions the same as they are for the CFC-based air-conditioner, and decreasing the air-conditioning energy use by the ratio of system COPs yields:

1. 86 l fuel $year^{-1}$:

$$\frac{47\ \text{l}}{10\,000\ \text{km}} \times \frac{1.90}{2.04} \times 16\,400\ \text{km year}^{-1} + \frac{57\ \text{l}}{100\ \text{kg} \times 10\,000\ \text{km}} \times 15\ \text{kg} \times 16\,400\ \text{km year}^{-1}$$

2. 2200 kg of CO_2 emitted:

$$86\ \text{l year}^{-1} \times 2.32\ \text{kg CO}_2\ \text{l}^{-1} \times 11\ \text{years}$$

3. 4800 kg equivalent of CO_2 with the 100 year GWP or 1600 kg equivalent with the 500 year value:

$$\frac{0.367\ \text{kg HFC134a}}{\text{year}} \times 11\ \text{years} \times \frac{1200\ \text{kg CO}_2\ \text{equivalent}}{\text{kg HFC134a}}$$

or

$$\frac{0.367\ \text{kg HFC134a}}{\text{year}} \times 11\ \text{years} \times \frac{400\ \text{kg CO}_2\ \text{equivalent}}{\text{kg HFC134a}}$$

The TEWIs for the alternative air-conditioning system are thus 7000 and 3800 for the 100 year and 500 year time frames, respectively. Both of these TEWIs are dramatic reductions from the values for the CFC-12 air-conditioner.

Retail refrigeration

Similar calculations can be performed for a supermarket refrigeration system using two racks of compressors (meats, dairy products and produce refrigeration using CFC12 and low-temperature freezers using R-502), remote condensing units and refrigerated cases distributed on the sales floor. An alternative system could perform the same functions using HCFC22 for all three applications. The key assumptions for the baseline CFC system are:

1. initial charges of 1120 kg of CFC12 and 400 kg of R-502;
2. one-third of the refrigerant is lost annually through leaks and servicing;
3. 396 000 kWh yr^{-1} for the refrigeration system using CFC12 and 223 000 kWh yr^{-1} for the low-temperature R-502 systems;
4. a useful lifetime of 20 years for the refrigeration systems.

Manufacturers have been able to design and install refrigeration systems using HCFC22 that achieve virtually the same efficiencies as those using CFC12 and R502, so the only significant changes in the assumptions are reflected in the refrigerant charge and leakage. The conversion to HCFC22 is assumed to require a charge of 1022 kg HCFC22 for the meat, dairy and produce system and 390 kg for the freezers. The leakage rate is assumed to be the same.

In North America, the average CO_2 emissions from power generation are 0.67 kg kWh^{-1} delivered (0.58 in Japan and 0.51 in Europe because of the smaller use of coal and greater dependence on nuclear and hydroelectric power). The 500 year TEWIs for commercial refrigeration in North America are:

1. 52 800 800 kg CO_2 equivalent for the CFC12/R502 systems:

$$\frac{374\text{ kg CFC12}}{\text{year}} \times \frac{4500\text{ kg CO}_2}{\text{kg CFC12}} \times 20\text{ years} + \frac{133\text{ kg R-502}}{\text{year}} \times \frac{4080\text{ kg CO}_2}{\text{kg R-502}} \times 20\text{ years} + \frac{619\,000}{\text{year}} \times 20\text{ years} \times \frac{0.67\text{ kg CO}_2}{\text{kWh}}$$

2. 12 900 000 for HCFC22:

$$\frac{470\text{ kg HCFC22}}{\text{year}} \times 20\text{ years} \times \frac{510\text{ kg CO}_2}{\text{kg HCFC22}} + \frac{619\,000\text{ kWh}}{\text{year}} \times 20\text{ years} \times \frac{0.67\text{ kg CO}_2}{\text{kWh}}$$

The replacement of CFC12/R502 refrigeration systems with systems using HCFC22 thus represents a 76% reduction in TEWI in the 500 year time frame.

Results

Worldwide uses of CFCs were surveyed to identify the major energy-related applications in refrigeration and air-conditioning, building and appliance insulation, and solvent cleaning. Household, or domestic, refrigeration, centrifugal chillers, unitary heat pumps and air conditioners, automobile air-conditioning and retail refrigeration were found to be the most significant applications in refrigeration because of the large number of units in operation, large volumes of refrigerant used, or amounts of energy involved. Other applications (e.g., refrigerated transport, ice makers, dehumidifiers), while important, were considered much less significant on a global scale in this analysis. It was also determined that the major geographical regions using CFCs are Europe, North America and Japan.

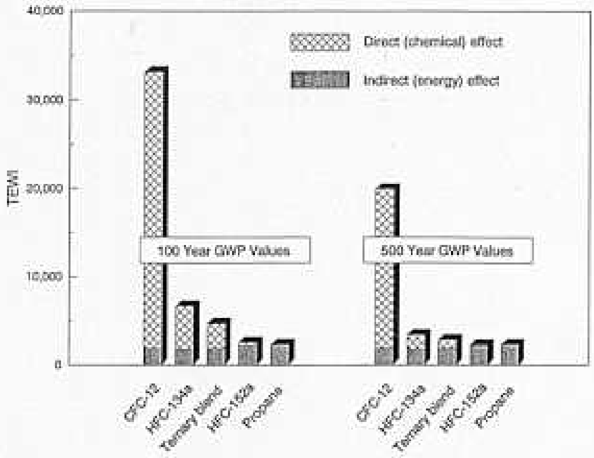

Figure 2 Total equivalent warming impact of CFC–12 and alternative refrigerants in an automobile air-conditioner

Figure 2 *Impact sur le réchauffement total équivalent du CFC12 et des frigorigènes de substitution utilisés dans un conditionneur d'air d'automobile*

Information was gathered from both corporate and government research laboratories, universities, industry trade groups and public interest organizations to identify the most promising replacements for CFCs that could be incorporated in new equipment during the period of CFC phaseout, the 1990s. Because of the limitations of the time frame, this list of alternatives consisted primarily of alternative chemical compounds that could be used in equipment very similar to current products based on CFCs. Very little quantitative information was found on revolutionary technology developments that could be incorporated into near-term consumer products, though there are promising ideas that merit further development. Data were also gathered for use in the TEWI calculations on the operating efficiencies of equipment using CFC substitutes; emphasis was placed on actual measured or relative system performance wherever possible rather than theoretical cycle calculations.

Results can be presented in two different ways; first as bar charts showing the direct chemical emissions effect and indirect energy effect of CO_2 emissions for several CFC substitutes for a single application, and then as relative changes in TEWI for several applications where the TEWI for each type of equipment has been normalized by the TEWI of the baseline CFC system for that application.

Figure 2 shows the TEWI for automobile air conditions, both the 100 and 500 year values, for the baseline CFC12 system and several proposed alternatives, including (1) HFC134a, (2) a blend of 30 wt% HCFC22, 23

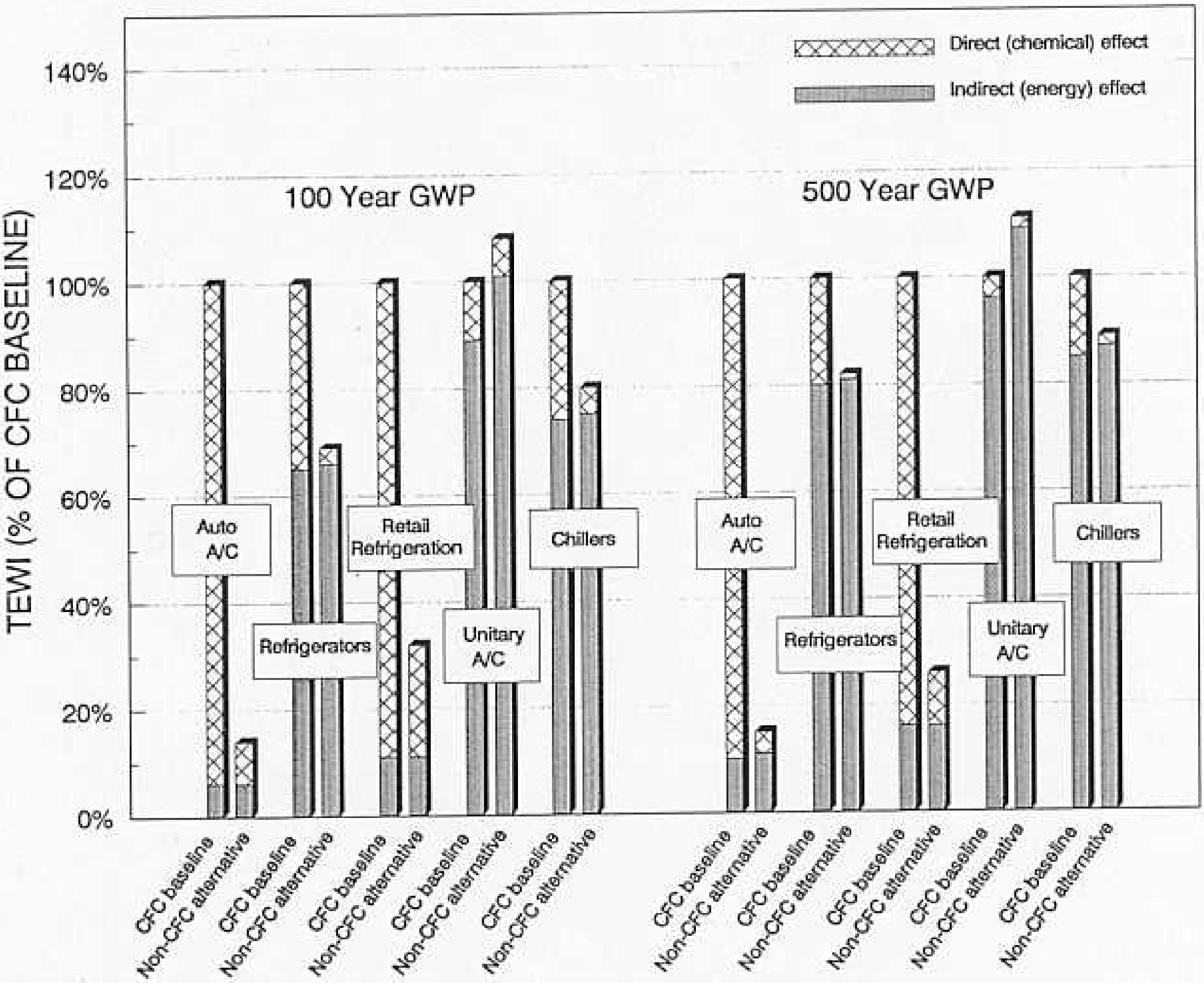

Figure 3 Normalized TEWI for refrigeration applications for CFC baseline equipment and averaged values for proposed non-CFC alternatives
Figure 3 *Moyenne de l'impact sur le réchauffement total équivalent des équipements frigorifiques utilisant des CFC et valeurs moyennes des substituts sans CFC proposés*

wt% HFC152a and 47 wt% HCFC124, (3) HFC152a and (4) propane. Both sets of bars indicate dramatic decreases in the TEWI because of the extremely high impacts of the direct effects from refrigerant losses. There is little or no discernible difference in the energy-related effects of most of the possible alternatives. The 100 year values in particular continue to show significant direct effects for some of the proposed alternatives, indicating a need for reduced refrigerant losses or alternatives with lower GWPs. The auto industry is working hard to improve equipment and maintenance procedures to reduce refrigerant emissions, with both CFC12 and the alternatives proposed for the future, by as much as two-thirds.

Figure 3 shows changes in the normalized TEWI for automobile air-conditioners, refrigerator/freezers, retail refrigeration, residential-sized unitary air conditioners and centrifugal chillers, again using both the 100 and 500 year GWPs. In this case the graph has been simplified by presenting just the TEWI for the CFC baseline for each application and an average of the TEWIs for several non-CFC alternatives. The high-loss applications, retail refrigeration and automobile air-conditioning, show dramatic reductions in TEWI in both the 100 and 500 year results, while household refrigeration and chillers show decreases in TEWI and little or no change in energy use. At the time this project was conducted the only alternative being considered to HCFC22 in unitary equipment was HFC134a. Industry projections at that time were that there would be significant efficiency losses by using HFC134a instead of HCFC22 assuming a fixed equipment and installation cost. The resulting increase in energy use is shown by the longer shaded portions of the bars for the non-CFC alternatives for unitary air conditioners in *Figure 3*.

Conclusions

Several conclusions can be drawn from the information plotted in *Figure 3*. First, for low-loss applications like refrigerator/freezers, unitary air-conditioners and centrifugal chillers (also residential heat pumps, although this is not shown), the direct contribution of the CFC alternative is only a small fraction of the TEWI. This is true using either the 100 year or 500 year GWP values to compute the TEWI. In these applications there is little benefit to be gained from using refrigerants with lower GWPs or technologies that do not use greenhouse gases. Second, the greatest reductions of TEWI can be made by using CFC alternatives in the applications that have relatively high losses, retail refrigeration and automobile air-conditioning (it should be noted that this applies to large centralized supermarket refrigeration systems; self-contained display cases have TEWI similar to refrigerator/freezers). In these cases the direct effect is still a large fraction of the TEWI and it may be possible to reduce TEWI even further by innovative or next-generation technologies.

Finally, recent findings are throwing some doubt on whether or not CFCs actually have a warming or cooling effect on the atmosphere[8]. When these new questions are finally resolved, the net result is that the GWPs of the CFCs and HCFCs listed in *Table 1* are likely to be reduced. The consequence on this work is that the energy-use contributions to TEWI will be even more dominant than they are now, which only emphasizes the fact that the most effective way to reduce contributions to global warming in the future will be to improve system efficiencies and reduce energy use.

References

1 **Houghton, J. T., Jenkins, G. J., Ephraums, J. J.** (Eds) *World Meteorological Organization/United Nations Environment Programme Intergovernmental Panel on Climate Change* Cambridge University Press, Cambridge, England (1990) p xx

2 **Ramanathan, V.** The greenhouse theory of climate change: a test by an inadvertent global experiment *Science* (April 1988) **240** 293–299

3 **Fisher, D. A., Hales, C. H. Wang, W. Ko, M. K. W., and Sze, N. D.** Model calculations of the relative effects of CFCs and their replacements on global warming *Nature* (5 April 1990) **344** 513–516

4 **Houghton, J. T., Jenkins, G. J., Ephraums, J. J.** (Eds) *World Meteorological Organization/United Nations Environment Programme Intergovernmental Panel on Climate Change* Cambridge University Press, Cambridge, England (1990) pp 58

5 *Ibid.*

6 **Fischer, S. K., Hughes, P. J., Fairchild, P. D., Kusic, C. L., Dieckmann, J. T., McMahon, E. M. and Hobday, N.** Energy and global warming impacts of CFC alternative technologies *ORNL/M-1869*, Oak Ridge National Laboratory

7 **Fischer, S. K.** *et al.* Energy and global warming impacts of CFC alternative technologies *ORNL/M-1869*, Oak Ridge National Laboratory, p 8.3

8 *Executive Summary: Scientific Assessment of Stratospheric Ozone, 1991*, WMO/UNEP (October 22, 1991)