Global warming implications of replacing CFCs

Both energy efficiency and fluorocarbon emission effects must be considered when selecting alternative refrigerants

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The late 1980s were a challenging time for the HVAC&R industries because of the demands being made for increased energy efficiency, the development of alternative refrigerants that do not destroy stratospheric ozone, and the intense pressures of international competition. The 1990s will not be any less demanding, with further requirements to improve efficiency and changing understandings of environmental acceptability.

Global warming has emerged as a controversial environmental issue. Some believe it will never be more than an issue. Others consider controlling the emissions of gases that contribute to increased global warming to be one of the greatest challenges in the immediate future, both for the energy-related industries and for the scientific and technical communities.

Dealing with the global warming issue creates further difficulties in adapting the refrigeration and insulation technologies for future needs as chlorofluorocarbons (CFCs) are phased out of production and use in accordance with the Montreal Protocol.

The study reported in this article was conducted to help industry, government and international policymakers reach sound decisions during the change-over from CFCs to alternative compounds and technologies.[1,2,3] Information developed in this effort complements ongoing studies to assess safety, toxicology, cost and other factors influencing these decisions.

In addition to destroying stratospheric ozone, CFCs have been recognized as contributing to increases in global warming resulting from human activity. It has been estimated that, during the 1980s, CFCs released to the atmosphere (the direct effect of CFCs) were responsible for 24% of the human-caused increase in the radiative forcing responsible for future global warming.[4] This contribution is second only to the 55% share from carbon dioxide (CO_2) emissions during that period.

The direct effect of CFCs on global warming has been quantified in a set of indices called global warming potentials (GWPs). This is similar to how the damage to stratospheric ozone has been quantified in ozone depletion potentials (ODPs). GWPs are frequently cited that reference the impact of a greenhouse gas to an equal mass of either R-11 or R-12 (both CFCs). But, perhaps the most useful values are the GWPs determined by the Intergovernmental Panel on Climate Change (IPCC).

This set of GWPs is based on CO_2 as the reference gas. Here, the GWP equals the number of pounds (or kilograms) of CO_2 that would need to be released into the atmosphere to cause the same increase in radiative forcing as the instantaneous release of a single pound (or kilogram) of the gas in question.

There is a time dependance of the GWPs defined by the IPCC that can be confusing. Greenhouse gases are removed from the atmosphere by natural processes (though not at the same rates), and the differing rates of decay must be considered in assigning GWPs.

For example, one pound of R-11 would have the same impact on global warming as 4,500 lb of CO_2 during the first 20 years after it escapes into the atmosphere. However, its impact would be comparable to only 3,500 lb of CO_2 over 100 years or 1,500 lb over 500 years. (One kilogram of R-11 would have the same impact as 4,500 kg of CO_2 during the first 20 years, 3,500 kg over 100 years, and 1,500 kg over 500 years).

This integration time horizon is an important factor in discussing the direct effects (emission-related effects) of greenhouse

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gases. However, there is not a single value for it that is accepted by everyone. Many of the IPCC values for GWPs of trace gases, refrigerants and plastic foam insulation blowing agents are listed in *Table 1*.

The direct effects of chemical emissions are not the only impacts that CFC end-use applications like refrigeration and space conditioning have on global warming. The energy consumed by these systems can often be traced back to a fossil fuel (coal, natural gas, oil or gasoline) and there are indirect global warming impacts due to the CO_2 formed during the combustion of these fuels.

Carbon dioxide emissions from the generation of electricity are depicted in *Figure 1* where there are losses in the power plant itself and also in transmission and distribution of electricity. The indirect effects of CO_2 emissions continue throughout the entire useful lifetime of the system, whether it is a household refrigerator, automobile air-conditioner or centrifugal chiller. These indirect effects can be of comparable magnitude or even larger than the direct effects of refrigerant losses and the emission of blowing agents from foam insulation.

The choice of alternative chemicals and technologies to replace CFCs as refrigerants and blowing agents must consider the total global warming impact of the alternatives and not just the GWP of the chemicals released into the atmosphere. The concept of the total equivalent warming impact (TEWI) has been developed as a means of combining the direct and indirect impacts on global warming of alternative refrigerants and technologies.

Table 1. Global Warming Potentials of Trace Gases Relative to CO_2

	Global Warming Potential Integration Time Horizon		
Trace Gas	20 years	100 years	500 years
Carbon dioxide	1	1	1
Methane	63	21	9
Nitrous oxide	270	290	190
CFC-11	4500	3500	1500
CFC-12	7100	7300	4500
CFC-113	4500	4200	2100
CFC-114	6000	6900	5500
CFC-115	5500	6900	7400
HCFC-22	4100	1500	510
HCFC-123	310	85	29
HCFC-124	1500	430	150
HCFC-141b	1500	440	150
HCFC-142b	3700	1600	540
HFC-125	4700	2500	860
HFC-134a	3200	1200	420
HFC-143a	4500	2900	1000
HFC-152a	510	140	47

Total global warming impacts

Although there may be differences in interpretation of climate data on whether the earth is warming or cooling or how fast the average temperature is changing, there is a general acceptance that certain gases in the upper atmosphere trap infrared radiation (preventing it from being rejected into space), and that these gases consequently enhance a radiative forcing effect that contributes to future global warming. The earth will be warmer with these gases in the upper atmosphere than it would be without them.

The warming effects of these gases over time depend on measurable quantities such as atmospheric lifetimes and the spectral absorption of the molecules. These quantifiable properties can be used to calculate the theoretical radiative forcing of a gas in the atmosphere as a function of time. Graphs of the radiative forcing (frequently normalized to the forcing of one kilogram of CO_2) can be used to illustrate the total contributions to global warming from energy consuming systems that use CFCs, such as refrigerator/freezers.

Figure 2a shows the effects of gases in the atmosphere resulting from the operation and eventual disposal of a common

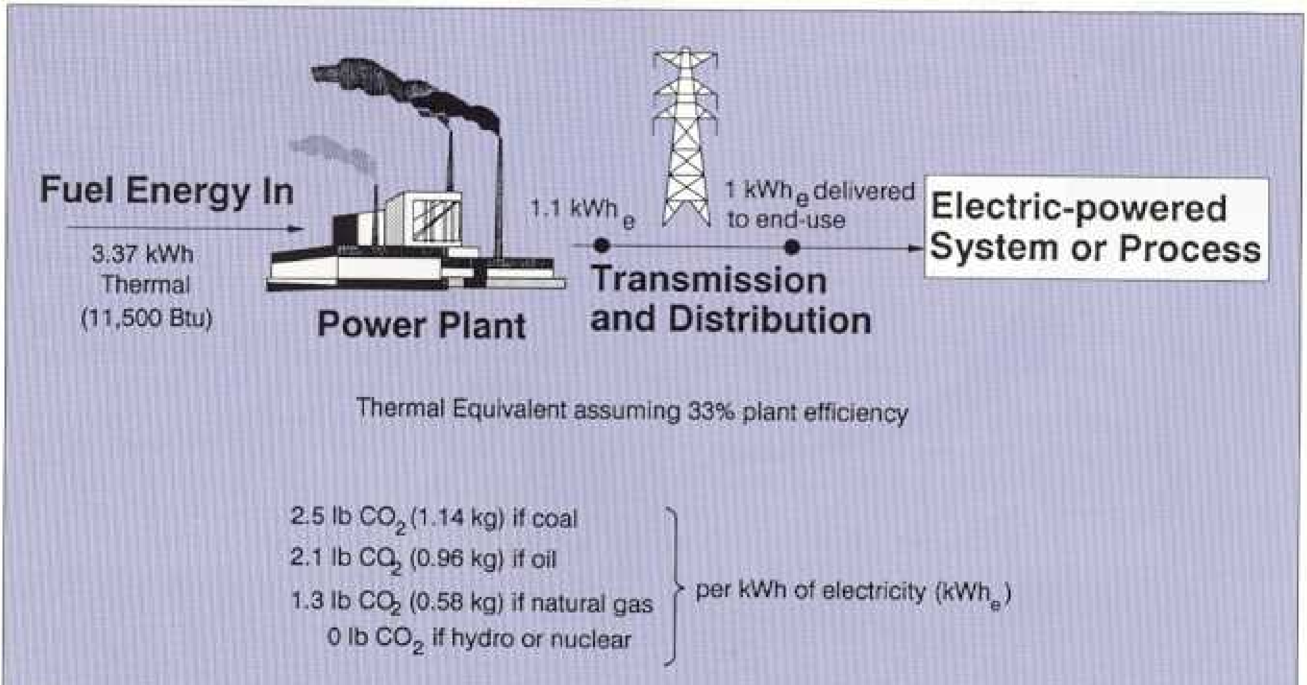

Figure 1. Conceptual illustration of CO_2 emissions from electric end-uses of energy.

household refrigerator. (The vertical axis is dimensionless and represents the radiative forcing normalized to the forcing of CO_2.) Carbon dioxide from operating the refrigerator builds up in the atmosphere because of power consumption during the appliance's useful lifetime (the simultaneous decay does not show because it is so much smaller than the annual increment). Then, when the refrigerator is disposed of, the R-11 from the foam insulation and the R-12 refrigerant are assumed to be released instantaneously. All three gases (CO_2, R-11 and R-12) are gradually removed from the atmosphere by natural processes (photodecomposition and interaction with oceans).

The refrigerator's cumulative warming impact is proportional to the area under the top curve in *Figure 2a*. The impact from energy use is the unshaded region under the lower-most curve, the impact from the blowing agent is the lightly shaded region, and the impact from the refrigerant is the darkly shaded region. The warming impact relative to CO_2 would be the area under the curve in *Figure 2a* divided by the area under a similar curve for the release of 2.2 lb (1.0 kg) of CO_2. *Figure 2b* is similar to *Figure 2a* except it shows the impacts from a CFC-free refrigerator that uses R-134a (an HFC) as the refrigerant and R-123 (an HCFC) as the blowing agent.

Appliance manufacturers have been adapting equipment to use CFC alternatives. At this time, CFC-free refrigerators are anticipated to have virtually the same energy use as current models. The contributions from the refrigerant and blowing agent are significantly lower for the HFC/HCFC refrigerator than the conventional refrigerator used for *Figure 2a*. These direct contributions are a much smaller fraction of the total area under the curve regardless of whether the upper limit is set at 100 years, 300 years or 500 years.

Methodology

The computations required to estimate warming impacts using the radiative forcing curves (as in *Figure 2*) can be difficult, especially for applications where there are continuous low-level chemical emissions from non-hermetic systems such as automotive air-conditioners and retail refrigeration systems.

The concept of a total equivalent warming impact (TEWI) was developed as a simplified substitution for the normalized integrated radiative forcing in *Figure 2*. In general, TEWIs are within 1% to 3% of the theoretical cumulative impacts; this is within the round-off error of the GWPs used in the calculations. (TEWIs vary from the theoretical values by up to 10% for some applications and integration time horizons where the lifetime of the equipment is nearly the same as the time horizon.)

TEWIs for each application can be computed by estimating the amounts of refrigerant and blowing agent released to the atmosphere, the annual energy use of the equipment being considered, and the typical useful lifetime of the product. These factors can then be combined to obtain the TEWI:

$$\text{TEWI} = \text{MASS}_{\text{refrigerant}} \times \text{GWP}_{\text{refrigerant}} + \text{MASS}_{\text{blowing agent}} \times \text{GWP}_{\text{blowing agent}} + \alpha \times \text{E}_{\text{annual}} \times \text{L}_{\text{years}}$$

The factor α is used to convert from whatever units are used for annual fuel use, E_{annual}, to the corresponding CO_2 emissions. L_{years} is the assumed useful lifetime of the product. The factor α for changing electricity consumption to CO_2 is 1.5 lb CO_2/kWh (0.67 kg CO_2/kWh) of electricity, using an average of values for coal-, gas- and oil-fired power plants and nuclear plants and hydroelectric power based on the installed generating capacities in North America. The factor is 19.5 lb CO_2/gallon of gasoline or diesel fuel (2.32 kg/L) for automobile air-conditioning and refrigerated transport.

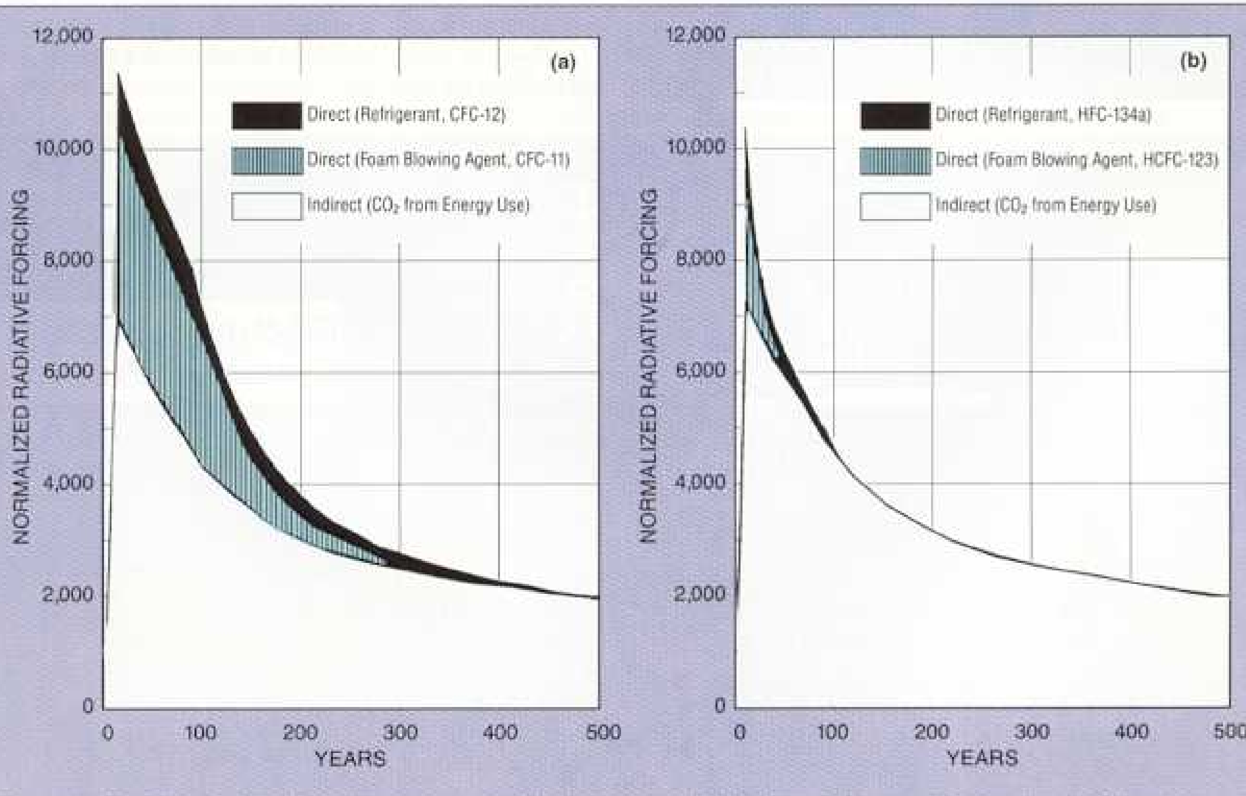

Figure 2. Radiative forcing of global temperature resulting from a household refrigerator/freezer: (a) conventional refrigerator; (b) CFC-free refrigerator.

Global warming

As an example, consider a fairly typical 20 ft^3 (570 L) frost-free refrigerator/freezer that uses 2.53 kWh per day. This unit would use about 6 oz (170 g) of R-12 as the refrigerant and approximately 2.3 lb (1,060 g) of R-11 in the foam insulation. The TEWI for this system (using the 100 year GWP values) would then be:

$$TEWI_{100} = 0.170 \times 7300 + 1.06 \times 3500 + 0.67 \times (2.53 \text{ kWh/day}) \times (365 \text{ days}) \times (15 \text{ years})$$

or 31,000 lb (14,200 kg) of CO_2. This assumes the refrigerator is used for 15 years and that no refrigerant is recovered when the unit is scrapped. It also assumes that refrigerant leakage during use is virtually zero.

The TEWI for the 500-year GWPs for R-11 and R-12 would be 25,500 lb (11,600 kg) of CO_2. Of these totals, 20,400 lb (9,280 kg) of CO_2 is from energy consumption, so 65% of the 100-year TEWI and 80% of the 500-year TEWI are from the indirect effect of energy use. The same capacity refrigerator designed to be CFC-free could use 5.5 oz (155 g) of R-134a and 2.26 lb (1,030 g) of R-123 instead of R-12 and R-11. This would correspond to TEWIs of 20,600 to 21,100 lb (9,380 to 9,600 kg) of CO_2 (500-year and 100-year GWPs) for a refrigerator having the same energy efficiency, of which 97% to 99% is from CO_2 emissions for power generation.

This simplified comparison is illustrated in *Figure 3* for the 500-year GWP values. The reduction in TEWI between the CFC and the CFC-free refrigerators is shown by the decrease in area between the two pies. The figure also shows the relative proportions of the direct (chemical emission) and indirect (energy use) effects.

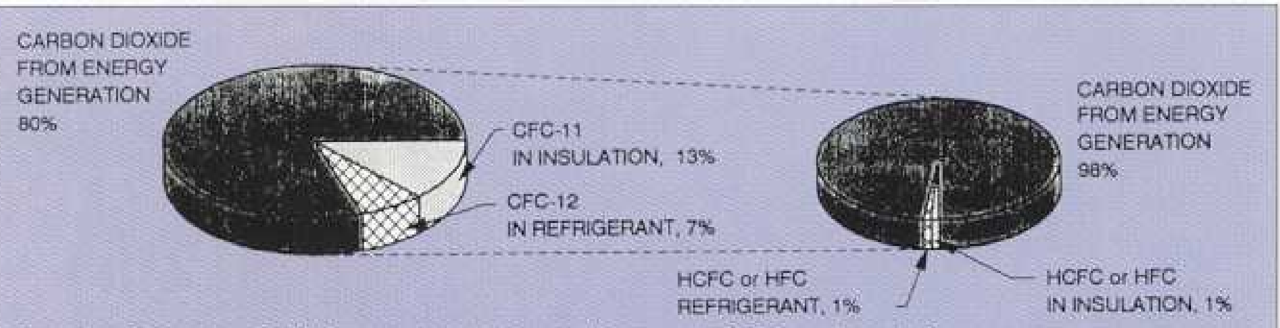

Figure 3. Comparison of TEWI for conventional refrigerator/freezer and a CFC-free refrigerator/freezer.

Applications affected

CFCs have proven to be useful in hundreds, if not thousands, of different applications. What is interesting in this study are the applications that consume energy and are also in widespread use around the world. These restrictions narrow the list to the areas of refrigeration, air conditioning and plastic foam insulation. The principal uses in these areas include:

- Household refrigerators and freezers,
- Retail and commercial refrigeration,
- Automobile air-conditioning,
- Centrifugal, reciprocating, screw and scroll water chillers,
- Unitary air-conditioners and heat pumps,
- Wall sheathing in residential buildings,
- Built-up roofs in commercial buildings,
- Wall insulation in commercial buildings, and
- Appliance insulation.

Results

Table 2 shows some of the study results and presents TEWIs for both the baseline current technologies in several applications and for alternative refrigerants and blowing agents. The HCFC/HFC alternatives listed in this table are averages of the results for the most frequently discussed substitutes for each application.

For example, R-123 and R-141b (both HCFCs) are considered as substitutes for R-11 in polyurethane and polyisocyanurate insulation. Similarly, HFC-134a, HFC-152a and blends of HCFC-22, HFC-152a and HCFC-124 are considered as substitutes for refrigeration and air-conditioning.

Not too surprisingly, the greatest reductions in TEWI would occur for replacements in retail refrigeration, automobile air-conditioning and roofs of commercial buildings. Retail refrigeration and automobile air-conditioning are both non-hermetic systems that have traditionally had refrigerant loss rates of 25% to 30% of the total charge per year. A large proportion of the TEWI is because of the direct effect. Substituting an HCFC or HFC with lower GWP than the CFC it replaces causes a large drop in the TEWI in these cases.

The roofs of commercial buildings are the third application where there would be very large reductions in TEWI. Large volumes of foam insulation are used in this application, so the amount of blowing agent needed is very high relative to the indirect energy-related CO_2 emissions that can be attributed to low-slope roofs. Consequently, substituting either R-123 or R-141b would give a much lower TEWI than the use of foam blown with R-11.

The last two columns of *Table 2* provide a breakdown of the TEWI for the HCFC/HFC alternatives for each application between the portions that are from the emission of refrigerants and blowing agents into the atmosphere and the portion due to CO_2 from energy consumption. The same three rows (or applications) stand out in these columns as are discussed in the preceding paragraphs.

In these cases, 32% to 37% of the TEWI comes from chemical emissions to the atmosphere. There is an opportunity to further reduce the TEWI by cutting down the chemical loss rates or finding chemicals with GWPs even lower than those of the HCFC/HFCs currently considered.

It is interesting to observe what little opportunity exists to reduce the TEWI in the remaining applications by focusing on just the chemicals. In these cases, 96% to 99% of the TEWI is from the CO_2 from energy consumption. The primary avenue for reducing TEWI here would be in reducing energy use through improved efficiency.

Conclusions

It was judged most important in this initial assessment to focus on current generation technology options and to use assumptions that reflect the thinking and planning of the mainstream of the user industries. The impacts of their preferred options represent the most likely outcome for the immediate CFC transition in the 1990s.

The analysis and findings of this study highlight those applications in which the opportunities for not-in-kind (NIK) technology options may be the greatest, that is, in applications for which substantial HCFC/HFC direct (emissions-related) effects remain. In the other applications in which the indirect (energy-related) effects dominate, the NIK technologies would essentially have no significant TEWI advantage over fluorocarbon technologies unless they also offered lower energy use.

A change of only 2% to 5% in efficiency would have a greater impact on TEWI than completely eliminating the direct (fluorocarbon emissions-related) effect. Therefore, NIK technologies would have to be developed that are equal (or better) in energy efficiency and comparable in cost to the HCFC/ HFC options to offer a TEWI reduction benefit in these applications.

The recent progress in improving energy efficiency with HCFC and HFC alternatives represents an encouraging and important trend. It also suggests that further energy-related reductions are likely. Results of previous CFC phase-out assessments indicated the potential for more serious energy consequences.[5,6] However, the energy-intensive user industries have responded strongly to the challenge in the past two to three years. It now appears that the CFC transition may be implemented with little or no effect on longer-term energy conservation efforts.

Table 2. TEWI for Major Refrigeration and Insulation Applications Based on 500-year GWPs

Application	Total Equivalent Warming Impact (lb CO_2)		HCFC/HFC Alternative Breakdown of TEWI	
	CFC Baseline	HCFC/HFC Alternative	Chemical Emission (%)	Energy Use (%)
Refrigeration				
Refrigerator/freezer	56,000	44,000	1	99
Retail refrigeration	$255{,}000 \times 10^3$	$62{,}000 \times 10^3$	37	63
Automotive air-conditioning	108,000	17,000	32	68
300 ton centrifugal chiller	$42{,}000 \times 10^3$	$33{,}000 \times 10^3$	0.5	99.5
2.5 ton unitary air-conditioner	183,000	205,000	2	98
2.5 ton heat pump	812,000	1,045,000	0.5	99.5
Insulation				
Residential	231,000	147,000	4	96
Commercial roofs	$5{,}100 \times 10^3$	730×10^3	35	65
Commercial walls	$2{,}900 \times 10^3$	$1{,}500 \times 10^3$	6	94
Refrigerator/freezer	56,000	44,000	1	99

HCFC alternatives and HFC alternatives each have their own advantages in specific applications. The fluorocarbon options for refrigeration, air conditioning and long-life insulating foam applications offer lower or comparable TEWI over their service lifetimes than any available or near-term alternative products. Further constraints on the HCFC and HFC alternatives could be counterproductive from a global warming point of view. It is important to consider a systems approach (as was done here) to make certain that an action or policy has the intended effect.

The potential importance of the NIK options in the longer-term is acknowledged. This study has included some examples, although many more are under development. These options should be considered more fully, but information and verifiable data on many of these options are fragmented and difficult to interpret and compile.

It is also difficult to assure comparability of available data on developmental technology with commercial or near-commercial technology. Misleading or speculative conclusions could be reached, perhaps to the detriment of the new or unconventional technology. At a later stage, when these technologies reach a more mature state of development, further analysis should be attempted.

Finally, it is well recognized that the needs of the developing countries must be considered. The industrialized nations must be sensitive to the applicability, adaptability and appropriateness of technological solutions in those regions where, for example, refrigeration needs are increasing dramatically.

Global environmental issues such as ozone depletion and global warming require almost complete participation worldwide if the solutions are to be effective. These challenges will not be met if the needs of the developing countries are not also satisfied. The energy and CFC replacement technology choices made by the developing nations will be crucial in determining how well we do overall on the environmental scorecard.

It should be noted that new scientific data[7] indicate that observed stratospheric ozone losses could be decreasing the global warming forcing by an amount that at least partially offsets that caused by the increased infrared trapping of CFCs. Although this second-order effect may decrease the GWPs of CFCs, it does not change the main conclusions of this study. Rather, the new information increases the importance of a systems analysis and the need to account for carbon dioxide emissions resulting from the energy requirements of a system. ■

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