ENERGY AND GLOBAL WARMING IMPACTS OF CFC ALTERNATIVE TECHNOLOGIES

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ABSTRACT

Chlorofluorocarbons (CFCs) are used in a number of applications and volumes of CFCs used grew at a tremendous pace during the 1960s and 1970s. However, in the mid-1980s, it was confirmed that these extremely useful chemicals contribute to the destruction of stratospheric ozone. These chemicals are being phased out of use rapidly to protect the ozone layer and it is very important that the replacements for CFCs do not result in a net increase in global warming by introducing less efficient processes that lead to higher energy use and increased carbon dioxide emissions. A study was conducted to identify those alternative chemicals and technologies that could replace CFCs in energy related applications before the year 2000, and to assess the total potential impact of these alternatives on global warming. The analysis for this project included an estimate of the direct effects from the release of blowing agents, refrigerants, and solvents into the atmosphere and the indirect effects in the form of carbon dioxide emissions resulting from energy use for commercial and residential heating and cooling, household and commercial refrigeration, building and automobile air-conditioning, and general metal and electronics solvent cleaning. The discussion in this paper focuses on those aspects of the study relevant to refrigeration and air-conditioning. In general the use of hydrofluorocarbon (HFC) and hydrochlorofluorocarbon (HCFC) alternatives for CFCs lead to large and sometimes dramatic reductions in total equivalent warming impact (TEWI), lifetime equivalent CO_2 emissions. Most of the reductions result from decreased direct effects without significant changes in energy use.

1. INTRODUCTION

Chlorofluorocarbons (CFCs) have been used as blowing agents in foam insulation, as working fluids in cooling and refrigeration equipment, and as solvents in general and precision cleaning applications since their introduction in the 1930s. The number of applications and volumes of CFCs used grew at a tremendous pace during the 1960s and 1970s, but in the mid-1980s it was confirmed that these extremely useful chemicals contribute to the destruction of stratospheric ozone and are the primary cause of the Antarctic ozone hole. The Montreal Protocol was drafted as an international agreement to phase-out the use of CFCs in an effort to reduce future ozone losses and to permit stratospheric ozone levels to be restored to pre-1986 levels. CFCs have also been found to be second only to carbon dioxide as a factor causing increased greenhouse warming. It is very important that the compounds and technologies developed as replacements for CFCs do not result in a net increase in global warming by introducing less efficient processes that lead to higher energy use and increased carbon dioxide emissions. A study was conducted to identify those alternative chemicals and technologies that could replace CFCs in energy related applications before the year 2000, and to assess the total potential warming impact of these alternatives on global warming /1/, /2/. The analysi includes an estimate of the direct effects from the release of blowing agents, refrigerants, and solvent into the atmosphere and the indirect effects of carbon dioxide emissions resulting from increase energy use for heating and cooling commercial and residential building using non-CFC insulations household and commercial refrigeration, building and automobile air-conditioning, and general meta and electronics solvent cleaning. The main emphasis of this paper is on the alternatives to CFC-11 and CFC-12 in refrigeration and air-conditioning.

2. TOTAL EQUIVALENT WARMING IMPACT

The impacts that greenhouse gases have on global warming are frequently quantified and compared with each other by using their global warming potentials (GWPs). Tables of these values are often presented expressing the contributions of a trace gas to global warming relative to the impact of either CFC-11 or CFC-12; one of the most useful sets of values for GWPs are those compiled by the Intergovernmental Panel on Climate Change (IPCC) and the World Meteorological Organization (WMO). These data express the impact of a single pound or kilogram release of a greenhouse gas relative to the impact of an instantaneous release of the same mass of carbon dioxide, CO_2. In this context the GWP of a gas is equal to the mass of CO_2 that would have the same net impact on global warming as the release of a single unit (pound or kilogram) of the gas in question. The IPCC/WMO GWP values for some common gases are listed in Table I.

The columns in Table I are labeled with different time frames, or integration time horizons. The concept of the "integration time horizon" for the GWP values is an important idea that needs to be explained in order to understand the numbers in Table I and some of the results from this study. The time horizon arises because the GWPs are related to CO_2, and the atmospheric lifetimes of the different greenhouse gases are not the same as that of CO_2 (in fact the atmospheric lifetime of CO_2 is not known). The GWPs represent a cumulative impact on global warming over a specified period of time relative to the cumulative impact of an equal mass of CO_2 over the same period of time. If that gas is removed from the atmosphere more rapidly than is CO_2, then its GWP will decrease as the time horizon under consideration increases. An examination of CFC-11 shows that over a 20 year period, an instantaneous release of one kilogram of CFC-11 has the same impact on global warming as the release of 4500 kg of CO_2. Over a 100 year period, the impact is equivalent to the release of 3500 kg of CO_2, and over a 500 year period it has the impact of 1500 kg of CO_2. This decrease is a result of the fact that CFC-11 has a shorter atmospheric lifetime than CO_2. No single time horizon is clearly the "right" one and the choice is often controversial.

A drawback of the GWPs is that they cannot take into account changing system efficiencies when one of these gases replaces another in an application that uses energy. If a set of GWPs is used that is based on CO_2, however, a "composite" value or total equivalent warming impact (TEWI) can be computed for systems that both use a greenhouse gas as a working fluid and also indirectly cause emissions of carbon dioxide due to energy use. For example, consider a 230 l (8.1 ft^3) refrigerator/freezer that uses CFC-12 as the refrigerant and reduced CFC-11 (partially water-blown) foam insulation. A representative refrigerator of this size in Europe would contain about 200 g (7 ozs) of CFC-11 in the foam, use 140 g (4.9 ozs) of CFC-12 as the refrigerant, and consume 500 kWh_e per year.

Table I. Global Warming Potentials Relative to CO_2

Greenhouse Gas	Integration Time Horizon		
	20 years	100 years	500 years
Carbon Dioxide	1	1	1
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

The CFC-11, CFC-12, and CO_2 from energy use all contribute to the radiative forcing in the atmosphere that can result in increases in average surface temperature. The combination of the three contributions to global warming are illustrated in Fig. 1a where it has been assumed that the refrigerant and the blowing agent trapped in the foam escape when the refrigerator is scrapped after 15 years. The unshaded portion below the curves corresponds to the effects on temperature change resulting from the CO_2 emissions from energy use during the fifteen years of operation, and the shaded portion represents the effects of the refrigerant and blowing agent when they are released to the atmosphere. Both contributions decay very slowly over time, but it can still be seen that the impacts of the CFCs in this case are significant whether the cumulative effect is considered over 50, 100, 300, or 500 years. Figure 1b has a similar set of curves using the corresponding assumptions for a hypothetical refrigerator using HFC-134a as the refrigerant and HCFC-123 blown insulation. The difference in energy use between the two cases is insignificant to the point it is indiscernible. The impact of the CFC substitutes is much smaller than in Fig. 1a and it is an insignificant portion of the cumulative effect over almost any time horizon. The total effect, corresponding to the area beneath both curves in Fig. 1b, is less than the total effect with the CFCs in Fig. 1a.

The computation of the areas under the curves is an unnecessarily tedious calculation. The Total Equivalent Warming Impact (TEWI) can be calculated from the total mass of the gas released to the atmosphere, its GWP, the lifetime of the system, and the annual energy use and emissions of CO_2. The TEWI is proportional to the areas under the curves in Fig. 1 and it is a very good approximation of the total impact on global warming for energy using systems (within a few

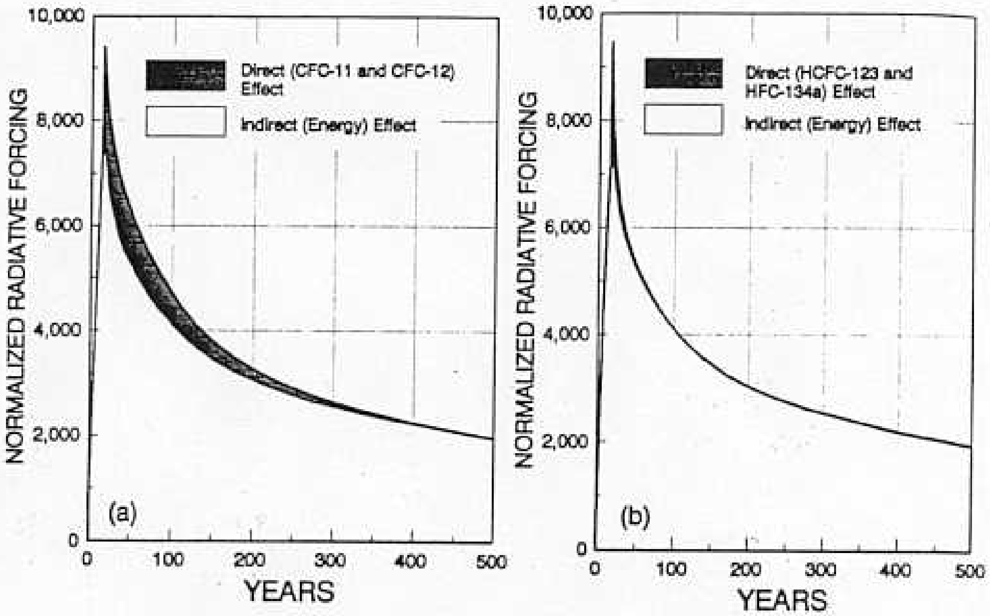

Fig. 1. Potential radiative forcing from gasses associated with household refrigeration: (a) baseline case using CFC-11 and CFC-12 and (b) alternative case using HFC-134a and HCFC-123.

percentage points of the area under the curves except when the lifetime of emissions is of the same order of magnitude as the time horizon for the GWP used). The TEWI is defined as the mass of a greenhouse gas released into the atmosphere times its GWP plus the lifetime of the system (refrigerator in this case) times its annual emissions of CO_2 from energy use. Naturally the TEWI is going to depend on the GWP and the integration time horizon chosen. For the two cases pictured in Fig. 1, the 100 year TEWI for the refrigerator using CFCs is 5600 kg equivalent of CO_2, while that for the refrigerator using HFCs and HCFCs is 4000. The 500 year TEWIs are 4800 and 3900 respectively.

3. BASELINE EQUIPMENT

The study was comprehensive and included every major energy consuming refrigeration and air-conditioning application of CFCs worldwide. Household refrigeration, unitary air-conditioning, centrifugal chillers, retail refrigeration, and automobile air-conditioning were identified as the applications with the greatest impacts because of the large volumes of refrigerants used and amounts of energy consumed. Each of these areas was evaluated for typical or representative equipment in

Europe, North America, and Japan taking into account differences in lifestyles and customs, equipment designs, and source energy in each region.

Figure 2 is a bar chart showing the proportion of the 500 year TEWI due to the direct

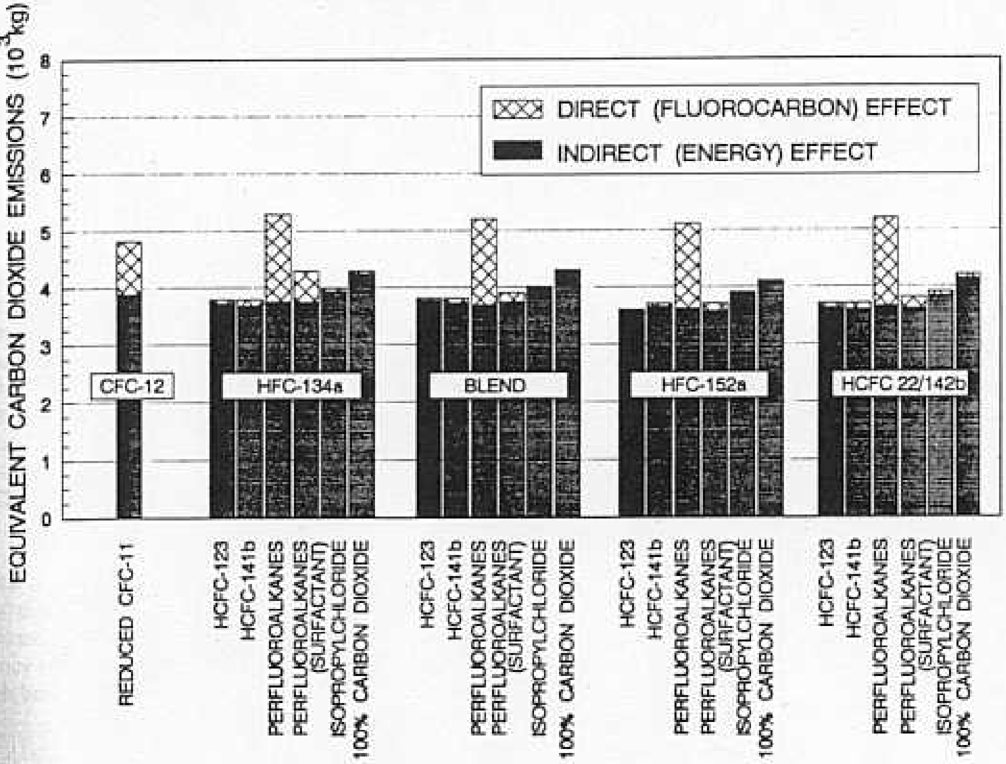

Fig. 2 Comparison of TEWI for refrigerator/freezers using CFC alternatives (500 year GWP values).

emissions of refrigerant and blowing agent for refrigerators using CFCs and possible combinations of CFC replacements. The cross-hatched portions represent the contributions from refrigerants and blowing agents while the darkly shaded sections correspond to the contribution from energy use. Each group of bars is labeled with the refrigerant used (e.g., CFC-12; HFC-134a; a blend of HCFC-22, HFC-152a, and HCFC-124; HFC-152a, and a blend of HCFC-22 and HCFC-142b) and each bar is labeled at the bottom with the foam blowing agent. There are no significant differences in energy use between any of the combinations except for the cases using 100% CO_2 blown foam insulation or isopropylchloride. Several perfluoroalkane compounds have been proposed as blowing agents, and two different assumptions were used for the results in Fig. 2; first as the sole blowing agent and second at a very low weight percentage of perfluoroalkane as a surfactant in CO_2 blown foam. Each of these cases show higher TEWI than the cases using either HCFC-123 or HCFC-141b as the blowing agent. The important results to note are that the use of HCFC-123 or HCFC-141b with any of the refrigerants considered results in a lower TEWI than the base case using CFC-12 and reduced levels of CFC-11 and that the direct effect of the CFC substitutes is insignificant in these cases.

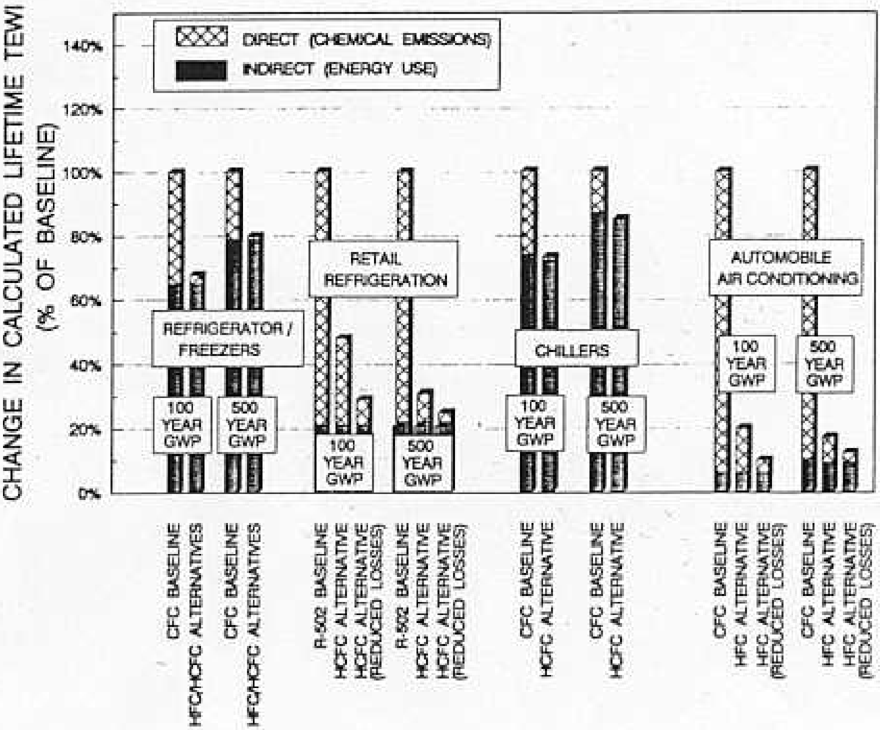

Fig. 3 Comparison of TEWI for CFC alternatives with baseline technologies for four refrigeration applications.

Results for four different applications are illustrated in Fig. 3 using both the 100 and 500 year GWP values. In this figure the TEWI for each application (and time horizon, e.g., 100 or 500 years) have been normalized by the TEWI for the corresponding baseline CFC case. The bars for refrigerator/freezers represent "composite" values that average the results for Europe, North America, and Japan and the bars for the CFC alternatives are averages of the leading candidates (e.g., HCFC-123 and HCFC-141b for blowing agents, HFC-134a and HFC-152a as refrigerants). The sets of bars for retail refrigeration (supermarket display cases) assume a large refrigeration system with a remote condenser and compressor machine room. The very large direct contributions to TEWI from the high refrigerant loss rates in supermarkets show up clearly in Fig. 3, both for the CFC baseline (CFC-12 and R-502) and for the HCFC-22 alternative. A third bar is included for this application that shows the results for the HCFC alternative assuming that refrigerant losses can be reduced from almost a third of the refrigerant charge per year (which is representative of current experience in

North America) to only 10% of the charge per year. The third set of bars shows composite results for centrifugal chillers with the estimated current refrigerant loss rates. In this case the direct effect of the non-CFC alternatives (HCFC-123 and HFC-134a) is virtually indiscernable on the graph. The final set of bars is for automobile air-conditioning. Once again results are shown for the past experience in refrigerant loss and also with industry targets for reducing losses from one-third of the charge per year to around 10% of the charge through improved service practices and mandatory refrigerant recovery during servicing and when the unit is retired from use. It is interesting to note that even with improved maintenance practices to reduce losses and the recovery of all the refrigerant when the car is scrapped, the direct effect is a major part of the total contribution to global warming — the alternative does yield more than an 80% reduction in TEWI relative to the CFC-12 baseline.

4. CONCLUSIONS

Several conclusions can be drawn from the information plotted in Fig. 3. First, for low-loss applications like refrigerator/freezers, unitary air-conditioners and heat pumps (not shown), and centrifugal chillers, the direct contribution of the CFC alternative is only an insignificant fraction of the TEWI. This is true using either the 100 year or 500 year GWP values to compute the TEWI. 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, however, the direct effect of the escaping refrigerant is still a large fraction of the total global warming impact 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 net warming affect on the atmosphere /3/. When these new questions are finally resolved, the net affect is that the GWPs of the CFCs and HCFCs listed in Table I are likely to be reduced. The consequence on this work is that the energy 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.

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