Alternatives to CFCs and Global Warming: A Systems Approach to Evaluating Net Contributions

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Introduction

CFCs proved to be one of the more useful classes of compounds ever developed because of their many desirable properties. They promote worker and consumer safety because they are nonflammable, noncorrosive, and very low in toxicity. They are used in a wide variety of applications, such as refrigerants, foam blowing agents, and cleaning solvents, because of their desirable physical properties that enhance energy efficiency and product reliability.

However, some of the properties that make CFCs desirable from a worker and consumer safety and applications standpoint have led to global environmental concerns. Because of their chemical stability, CFCs have long environmental residence times, and emissions lead to accumulation in the lower atmosphere. CFCs slowly mix into the upper atmosphere where they dissociate, releasing chlorine atoms that can catalyze destruction of ozone. Recent scientific findings have clearly linked chlorine from CFCs and other man-made compounds and bromine from man-made and natural sources to the seasonal ozone losses over Antarctica, the Antarctic ozone hole, and have indicated that these compounds are probably causing ozone losses over populated areas of both the northern and southern hemispheres as well.[1] Since ozone provides a screen against solar ultraviolet radiation (UV-B) and excess UV-B has a potential to contribute to health and environmental concerns,[2] significant reductions in ozone should be avoided. This information provides a sound basis for the Montreal Protocol, an international agreement amended in 1990 requiring a total phaseout of CFC production and consumption by 2000.[3]

The phaseout of CFCs has implications to the global warming issue as well. Because of their long atmospheric lifetimes and their infrared absorption properties, CFC emissions contribute to future global warming. Over the decade of 1980 to 1990, they contributed about 24% of the total increase in global warming forcing.[4] Global warming forcing is the warming due to greenhouse gases, which is but one factor in the more complex global climate change equation.

Two classes of compounds under evaluation as replacements for CFCs, hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), also have the potential to contribute to global warming because of their infrared absorption properties. However, because their atmospheric lifetimes are about one-tenth those of the CFCs, these alternatives have about one-tenth the global warming potentials of the CFCs. Thus, replacement of CFCs with HCFCs with HFCs will yield a significant reduction in direct contributions to global warming.

However, there is a less recognized, but equally important role of CFCs and their replacements with respect to global warming. CFCs have been used in many refrigerant, air conditioning, and insulation applications because they contribute to energy efficiency. Since, in most cases, carbon dioxide (the major contributor to future global warming) is a by-product of energy conversion, improved energy efficiency reduces contributions to global warming. Thus, it is important to evaluate both the direct and indirect contributions of CFC alternatives to global warming.

Such an evaluation of the impacts of using CFCs or their alternatives in refrigeration equipment and thermal insulation requires examination of both the masses of greenhouse gases that escape to the atmosphere from the system and also the lifetime energy use of the system. The concept of global warming potential (GWP) has been developed as a measure of how an emission of one trace gas affects future global warming relative to an emission of an equal mass of a reference gas. Carbon dioxide is commonly used as the reference gas.

The concept is complicated by the need to relate the GWP to a period of time since the gases are removed from the atmosphere by different processes and at different rates. (See Table I for chemical names and formulas.) For example, the 100-year GWP of CFC-12 is 7300 which means that the instantaneous release of a single kilogram of CFC-12 would have the same effect on radiative forcing over the subsequent 100 years as the instantaneous release of 7300 kilograms of carbon dioxide. The 500-year GWP of CFC-12 is 4500; less than the 100-year GWP because CFC-12 is removed from the atmosphere more rap-

Table I: Chemical Names and Formulas for Common CFCs/HCFCs/HFCs.

Common Name	Chemical Name	Chemical Formula
CFC-11	Trichlorofluoromethane	CCl_3F
CFC-12	Dichlorodifluoromethane	CCl_2F_2
HCFC-22	Chlorodifluoromethane	$CHClF_2$
HCFC-123	Dichlorotrifluoroethane	$CCHCl_2CF_3$
HCFC-124	Chlorotetrafluoroethane	$CHClFCF_3$
HCFC-141b	Dichlorofluoroethane	CH_3CCl_2F
HFC-134a	Tetrafluoroethane	CH_2FCF_3
HFC-152a	Difluoroethane	CH_3CHF_2

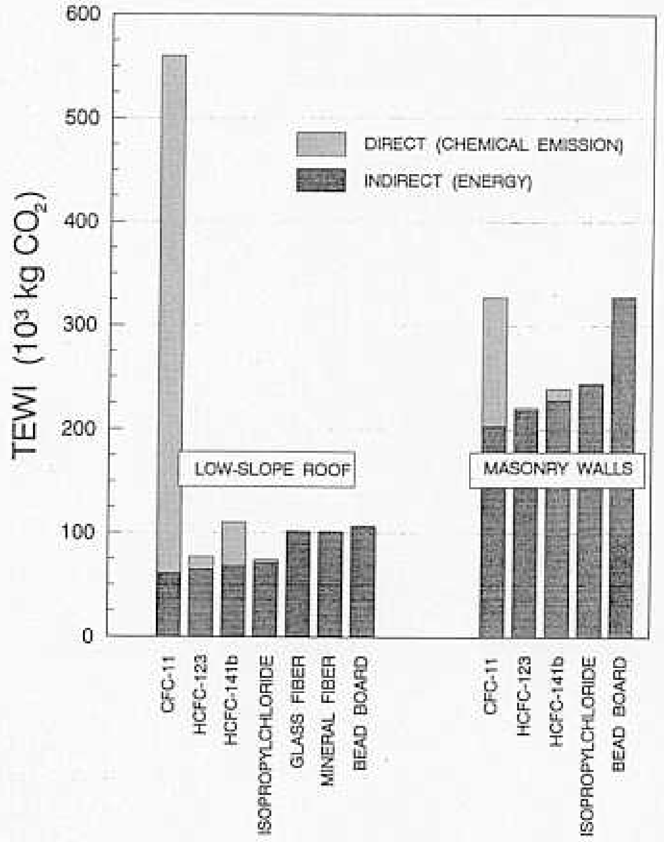

Figure 1. TEWI for commercial building roof and wall insulation for CFC-11 and alternative foam blowing agents (labeled across the bottom).

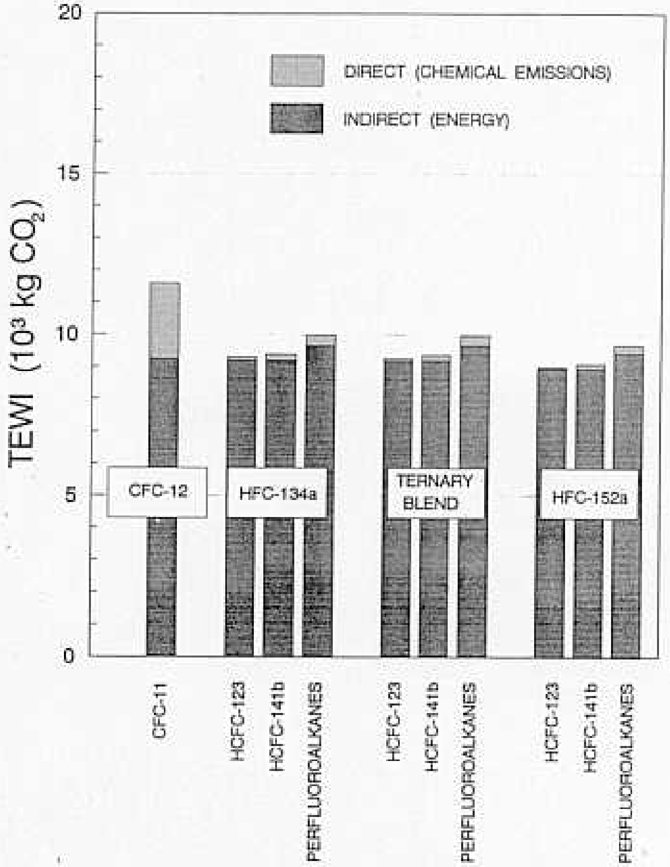

Figure 2. TEWI for alternative refrigerants (labeled across bars) and foam blowing agents (labeled across bottom) in household refrigerators (perfluoroalkanes refers to a mixture where perfluoroalkane is used as a surfactant).

idly than is carbon dioxide. Examples presented in this paper use the 500-year GWPs but the significant conclusions would be unchanged if 100-year GWPs were used instead.

The use of carbon dioxide as the reference gas is particularly convenient when evaluating the total impact of systems requiring energy for their manufacture or use. The lifetime fuel use for the system can be estimated with a reasonable degree of accuracy, and there are known emissions of carbon dioxide corresponding to the use of fossil fuels and the generation of electricity. The indirect effects from carbon dioxide emissions from lifetime energy use plus the direct effects from the release of greenhouse gases (GWP times the mass released) yields an index for the total equivalent warming impact (TEWI) of the system. A study sponsored by the Alternative Fluorocarbons Environmental Acceptability Study and the U.S. Department of Energy was conducted by the Efficiency and Renewables Research Section of Oak Ridge National Laboratory to assess the TEWI for major energy related applications of CFCs.[5] Eleven different applications of CFCs were evaluated, two of which are highlighted in this paper. The assessment involved six steps:

- Development of appropriate engineering parameters to characterize the baseline technology and algorithms for calculating energy use in each application.
- Identification of alternatives under development to replace CFCs in each application.
- Collection and compilation of user industry data on comparative engineering parameters and physical properties to characterize the technology option(s).
- Calculation of lifetime energy use and estimated carbon dioxide emissions (indirect effect) from unit lifetime estimates and regional fuel utilization or electric power generation mix.
- Calculation of equivalent carbon dioxide emission of greenhouse gas content or loss (direct effect), if applicable, for each option using the GWP of the gas.
- Combination of the indirect and direct global warming effects to yield TEWI and comparison of TEWI among technology options.

Recently released information[1] indicates that observed stratospheric ozone losses could be decreasing global warming by an amount that at least partially offsets that caused by the increased infrared trapping of CFCs. Although this information may in effect decrease the GWPs of CFCs (because CFCs are probably contributing to those ozone losses), it does not change the main conclusions of the analysis summarized below. If anything, it emphasizes the need for a systems approach and the importance of considering energy efficiency since the role of carbon dioxide in global warming forcing is enhanced by the recent information.

Examples

Building Insulation

Polyisocyanurate foam boards formed with CFC-11 are frequently used as insulation in the low-slope roofs on commercial buildings as well as in the air gap between the exterior brick veneer and concrete block inner wall of these buildings. CFC-11 is particularly amenable to the manufacturing processes for foam insulation because of its solvency in the plastics feed stocks, its specific heat (it acts as a heat sink in the foaming process), and its vapor pressure in the temperature range of use. The resulting foams are well suited to insulation applications because of their higher thermal resistances, or R-values. CFC-11 has a very low thermal conductivity and contributes to the high R-values of the foam. It is entrapped in the bubbles or cells as the foam hardens and remains an integral part of the product.

Each of the proposed alternatives has a higher thermal conductivity than CFC-11, and so the gas entrapped in the foams is less effective in blocking heat transfer. Efforts to reduce cell size, alter the orientation of the cells, and reduce the cell wall thickness are expected to be successful in reducing the conductive and radiative heat transfer through the cell walls. These modifications should compensate for the higher gas thermal conductivity so that the overall R-value of the alternative foams are the same as that of current CFC blown foams.

TEWIs were calculated for a retail store in a shopping mall in Chicago, Illinois with roof and walls insulated using polyisocyanurate foam insulation and alternative materials. Results are shown in Figure 1 for CFC-11 blown foam, alternative fluorocarbons blown foam, and some alternative (non-foam) materials. TEWI calculations are based on two assumptions; roof insulation is replaced every 15 years and wall insulation remains effective over a 50-year useful building life. The bars on the left side of the graph should not be compared with those on the right side because of this difference in assumed lifetimes of the insulating surfaces.

The overall height of the bars in Figure 1 corresponds to the TEWI for each insulating material with the darkly shaded portion representing the indirect effects of carbon dioxide emissions from energy use and the cross-hatched portion the direct effects from emission of chemical blowing agents. Each of the alternatives, blown foams or fibrous materials, shows a dramatically lower direct effect on global warming from chemical emissions compared to the CFC-11 blown foam. In some cases there is an increase in the indirect emissions from energy use due to losses in insulating properties that partially offsets the reductions in direct effect. These differences are not significant for the alternative fluorocarbon blown insulations, and further improvements in alternative foam technology will very likely lead to identical or lower indirect effects.

Refrigerator/Freezers

Refrigerator/freezers use CFCs both as the working fluid in the refrigeration system and as blowing agents in plastic foam insulation. CFC-12 is well suited as a refrigerant for the operating conditions of a refrigerator/freezer because it is low in toxicity, nonflammable, highly efficient, compatible with copper heat exchanger tubing and compressor motor windings, and works well with inexpensive mineral oil lubricants. CFC-11 is an excellent foam blowing agent because of the low thermal conductivities of the insulation it produces. Another important factor is that modern refrigerators rely heavily on the CFC-11 blown foam insulation to provide rigidity to the cabinets.

Several candidates are under evaluation as possible replacements for the CFC refrigerant and foam blowing agent in refrigerator/freezers. Some of the refrigerant alternatives are:

- HFC-134a,
- a blend of HCFC-22, HFC-152a, and HCFC-124, and
- HFC-152a.

HFC-134a has similar thermodynamic properties to CFC-12 and has attracted the most attention as a substitute refrigerant for CFC-12. One major drawback is that it is not miscible with the mineral oils that have been used in the past, and the system energy requirements are strongly dependent on the lubricant used. Extensive effort has gone into identifying the best oils for use with HFC-134a to enhance compressor reliability and system energy efficiency. The components and composition of the ternary blend have been carefully selected in order to approximate the thermal properties of CFC-12. Only small and relatively inexpensive design changes would be needed to incorporate the blend into refrigerator/freezers originally designed for use with CFC-12. HFC-152a has been proposed because its theoretical vapor compression efficiency is better than CFC-12 or HFC-134a and it has a very low GWP. However, compensating factors including operating temperature, heat capacity, and thermal conductivity may allow HFC-134a system efficiencies comparable to those that can be achieved with HFC-152a. Also, because HFC-152a is flammable some people have raised concerns over its use in an application where a nonflammable refrigerant has been the standard. The plus side of each of these alternative refrigerants is that lubricants have finally been identified and compressors and heat exchangers can be redesigned so that systems using any of these refrigerants could be as efficient, or even slightly more efficient, than current refrigerators using CFC-12.

Several different foam agents have also been investigated as substitutes for CFC-11, principal among these have been HCFC-123 and HCFC-141b, each of which contain chlorine and has some ozone depleting potential. Perfluoropentane and perfluorohexane have also been considered chlorine free, and hence zero ozone depletion potential foam blowing alternatives. The perfluoroalkane (PFA) compounds have been evaluated both as the sole blowing agent, in which case relatively large quantities of them are used (a disadvantage because of the large GWPs of PFAs), and as surfactants to improve the cell structure and reduce the thermal conductivity of carbon dioxide blown foam insulation. In this latter case only two to three weight percent of the PFA is used. Refinements of foam formulations with HCFC-123 and HCFC-141b are reaching the point where these alternatives can achieve the same thermal properties and similar mechanical properties as foam blown with current CFC-11 technology. Sample foams blown with the PFAs as surfactants have not yet achieved the low thermal conductivities of CFC-11 blown polyurethane.

Results for the TEWI of combinations of these refrigerants and blowing agents are shown in Figure 2 for the typical 15-year appliance lifetime; the PFAs are shown when used as surfactants only. The TEWI for the baseline refrigerator is shown on the left of the figure. A series of three bars are shown for equivalent refrigerators using HFC-134a as the refrigerant and either HCFC-123, HCFC-141b, or PFAs as the blowing agents (labeled across the bottom). The most recent engineering data for each alternative have been used to estimate the energy use for these combinations. Similar sets of results are shown for systems using the ternary blend and HFC-152a as the refrigerants.

The direct impact on global warming from chemical emissions have been reduced to just 1 to 2% of the total by switching from the CFCs to any of the three refrigerants and either HCFC-123 or HCFC-141b. The PFAs have a noticeable direct impact (even when they are used only as surfactants as shown here) and there is also an increase in the energy related indirect effect. HFC-152a appears to provide a slight improvement in energy efficiency, though it must be stressed that the results shown in Figure 2 do not take into account any efficiency losses that may be encountered when using a flammable refrigerant safely in a household appliance. Also, optimization of the systems to take advantage of the heat capacity and thermal conductivity of HFC-134a may result in comparable efficiencies for HFC-134a and HFC-152a systems.

Conclusions

Two major conclusions can be drawn from this information. First and foremost, incorrect decisions can be made if entire systems are not considered carefully in evaluating impacts of alternative technologies. Expanded polystyrene bead board and resinated mineral fiber boards are alternative insulating materials that could be used in place of CFC blown foam insulation in commercial buildings. Neither of these materials employ greenhouse gases so, on the surface they may appear preferable to foam insulation. However, neither of them is as effective in blocking heat transfer as HCFC blown foams and their total equivalent warming impact is higher than that of some insulating materials that do use greenhouse gases. This is illustrated clearly in Figure 1. A second conclusion that can be drawn is that in some cases there are no significant differences between alternative technologies, even when the entire system is considered. Figure 2 shows that there are very minor differences between the TEWIs for HCFC-123 and HCFC-141b as foam blowing agents in refrigerators using either HFC-134a, HFC-152a, or the ternary blend as refrigerants. There is not a strong basis for preferring any of these compounds as refrigerants or blowing agents on this criteria. Again, however, one would reach a very different conclusion based solely on comparisons of the GWPs of these compounds.

Acknowledgments

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