GLOBAL WARMING AND END-USE EFFICIENCY IMPLICATIONS OF REPLACING CFCs*

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Abstract

The direct contribution of CFCs to calculated global warming has been recognized for some time. As a result of the international agreement to phase out CFCs due to stratospheric ozone and the ensuing search for suitable alternatives, there has recently been increased attention on the DIRECT global warming potential (GWP) of the fluorocarbon alternatives as greenhouse gases. However, to date there has been little focus on the INDIRECT global warming effect arising from end-use efficiency changes and associated CO₂ emissions. A study being conducted at Oak Ridge National Laboratory (ORNL) addresses this combined or total global warming impact of viable options to replace CFCs in their major energy-related applications. This paper reviews selected results for air-conditioning, refrigeration, and heat pump applications. The analysis indicates that the CFC user industries have made substantial progress in approaching near-equal energy efficiency with the HCFC/HFC alternative refrigerants. The findings also bring into question the relative importance of the DIRECT (chemical-related) effect in many applications. Replacing CFCs is an important step in reducing the total global warming impact, and at present the HCFC and HFCs appear to offer the best efficiency and lowest total impact of options available in the relatively short time period required for the transition away from CFCs.

Introduction

- "CFCs: The Challenge of Doing Without"
- "In Search of a National Energy Strategy"
 - "The Science of Global Warming"
 - "Promoting End-Use Efficiency"

What do these topics have in common? First, these were all cover stories in the EPRI Journal over the last two years. These topics certainly address some of the major energy and environmental issues of our time — issues that have direct implication for the future of the electric utility industry. Secondly, understanding how these issues are interrelated is critical to making sound decisions about alternatives to meet societal needs for refrigeration, air-conditioning, and heating, as we make the transition away from CFCs (see Fig. 1). Today, I want to focus on the global warming issue and its linkage to CFC alternative technologies and end-use energy efficiency.

Several years ago, before the Montreal Protocol agreement was signed, ORNL undertook a study for DOE looking at the potential national energy-use impacts of a CFC phaseout, focusing on CFC-11 and CFC-12 applications [Fischer, 1988]. At that time, much less was known about the toxicity, energy efficiency, lubricants and materials compatibility of the potential fluorocarbon replacements. The study was intended to help guide R&D planning and therefore considered a wide range of hypothesized scenarios to estimate the limits of energy impacts.

The lowest energy-penalty scenario assumed that the leading HCFC (hydrochlorofluorocarbon) and HFC (hydrofluorocarbon) substitutes are accepted, produced commercially, and applied successfully. These included HCFC-123 and HCF-141b as replacements in CFC-11 applications and HFC-134a as the replacement in CFC-12 applications, for example. In the "worst case" scenario, the use of HCFCs as CFC substitutes was banned, the use of fiberglass was assumed instead of finding an acceptable foam insulation alternative, and ammonia and propane became the principal refrigerants used. The findings suggested that the national energy impacts could range from a penalty of as little as 0.2 quad/year to as much as 2.2 quads/year. Figure 2, which represents a mid-case scenario (1.0 quad/year energy penalty), illustrates the major application sectors in which these energy penalties would occur. The single largest impact in each scenario was found to be for household refrigerators and freezers, due in part to the number in use and the fact that they operate 24-hours per day, plus the fact the CFCs are used both in the cabinet insulation (blowing agent, CFC-11) and as the refrigeration working fluid (refrigerant, CFC-12). Looking just at the electric end-use equipment applications, the effects of the different CFC phaseout/replacement scenarios ranged from an increase of 13 billion kWh/yr under the near-term drop-in substitute scenario, to over 94 billion kWh/yr for the worst-case. (Fifty-six (56) billion kWh/yr increase estimated for mid-case scenario. Annual U.S. electricity consumption in 1988 estimated at 2450 billion kWh/yr) [EPRI, 1989].

It should be emphasized that these estimated impacts do not take into account current uses of HCFC-22, which is not (currently) included in the scheduled phaseout of CFCs under the Montreal Protocol because of its relatively low ozone-depletion potential (ODP) of 0.05. HCFC-22 is the most widely used refrigerant in the U.S. for air-conditioning and heat pump equipment, and constraints on its use could have much worse electric energy and economic impacts and more severe societal consequences than the phaseout of CFC-11 and 12.

Since the time of that initial ORNL study, there has been an unprecedented research effort by the chemical manufacturers and the CFC-user industries to develop suitable alternatives and modified/new system designs adapted to use of these alternatives (such as HCFC-123 or HFC-134a). This has also been a period of unparalleled collaboration and information sharing in the U.S. between industry, government, universities, and EPRI and, internationally, with technical colleagues and organizations in many other countries.

It was this kind of collaboration that made possible a 1991 study that is nearing completion, which I plan to highlight for you today.

This study was cosponsored by DOE and the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS). AFEAS is a consortium of the world's leading chemical companies, many of whom also support the Program for Alternative Fluorocarbon Toxicity Testing (PAFT) consortium activities which you may be familiar with. This past year, under this DOE/AFEAS project, we revisited the CFC alternatives versus energy use issue with a different focus — a focus on the potential global warming implications of the various options to replace CFCs.

Basis for Systems Approach to Global Warming Assessment

To date, most of the atmospheric scientist and environmental policymakers' attention has been placed on the DIRECT contribution to global warming of CFCs and their fluorocarbon alternatives, HCFCs and HFCs, as greenhouse gases. This DIRECT effect is characterized by a so-called GWP (global warming potential) value for the particular compound. However, this value alone does not account for the total potential global warming impact, since it excludes the INDIRECT CO₂ greenhouse gas emissions effect due to the energy consumption of the system in which the CFC is used (to meet some societal need).

For convenience in combining these effects in this study, the DIRECT (chemical emission) effect is expressed as equivalent carbon dioxide, consistent with the Global Warming Potential (GWP) indexing approach of Intergovernment Panel on Climate Change [IPCC, 1990]. This equivalent CO₂ DIRECT effect can readily be combined with the INDIRECT (energy-related) CO₂ emissions. The combined or total effect is termed the Total Equivalent Warming Impact or TEWI.

This concept is illustrated in Fig. 3 for replacement of CFCs in a household refrigerator/freezer. The pie chart on the left represents the TEWI for a 20 ft³ automatic defrost refrigerator/freezer using CFC-11 blown polyurethane insulation and CFC-12 as the refrigerant. Eighty percent of the TEWI is a consequence of CO₂ emissions from generating electricity to operate the refrigerator for the assumed 15 year useful life. The balance of the impact on global warming comes from emissions of the blowing agent and the refrigerant. The pie chart on the right represents the calculated TEWI for a refrigerator/freezer using HCFC-123 and HFC-134a using actual foam insulation thermal conductivities and measured refrigerator performance. In this example, the total equivalent warming impact (TEWI), represented by the comparative area of the two "pies," is reduced by about 18% in the transition from CFCs to the HCFC and HFC alternatives. This improvement is due to the reduction in DIRECT impact (from 20% to 2%) combined with no change in INDIRECT (energy-related) impact. An evaluation of this combined impact for the various alternatives to CFCs in a number of specific end-use applications was undertaken in this study.

For electric systems, end-use energy is referenced back to the power plant for purposes of estimating CO₂ emissions, as illustrated in Fig. 4.

Selected Results of Study

Figure 5 shows the TEWI results for representative chillers with various HCFC/HFC alternative refrigerants compared to reference CFC chiller cases. The heavily shaded area at the bottom of each column represents the INDIRECT (energy-related) component of TEWI. The top cross-hatched area represents the DIRECT (chemical-emission) component. The differences in total column height therefore represent the differences in TEWI or total global warming impact. The INDIRECT, DIRECT, and TEWI values are expressed as kg (x10³) of equivalent CO₂ per refrigeration ton (RT) over the 30-year service life of the chiller. It is readily apparent that for this CFC end-use application, the INDIRECT effect dominates over the DIRECT effect, and that once HCFC/HFCs replace CFCs, the differences in chiller TEWI due to the refrigerant are small. The reason is that differences in performance factors between the refrigerant options are relatively minor.

Figure 6 shows the contrasting TEWI results for the retail refrigeration application. In this case, the DIRECT effect dominates, and replacement of CFCs with HCFC/HFC alternatives yields a dramatic

reduction in the DIRECT effect and the TEWI. Although it is significantly reduced, the DIRECT effect is still a large percentage of the TEWI because of the traditionally high refrigerant leakage rates. In this commercial refrigeration application, the value of the refrigerated product inventory, whether it is fresh seafood or top-of-the-line ice cream, usually outweighs the expense of replenishing refrigerant. And, in the past, that expense has not been a sufficient incentive to prompt store owners to adopt systematic or rigorous preventive maintenance programs. The systems are usually designed for the convenience of quick servicing on the sales floor, which is not conducive to low leakage, and the use of remote compressors and condensing units with extensive refrigerant piping necessitates that they have a very large refrigerant charge. The average 40,000 ft² (3700m²) supermarket has a refrigerant inventory of 4000 lbs (1800 kg) and typical loss rates have been quoted as high as one-third of the charge each year [Ares, 1991]. The figure illustrates results for both the CFC-12 high temperature (fresh produce) and medium temperature (meats and dairy) display cases typical of older stores and the HCFC-22 high and medium temperature cases more typical of newer stores. The figure also shows that HCFC-22 is presently the refrigerant option of choice to replace R-502 in low temperature cases (frozen foods and ice cream), and two-stage compression of HCFC-22 is already starting to replace R-502 in some regions. The "HCFC-22 (reduced)" case illustrates the impact that improved service schedules and maintenance practices could have if they reduced the annual loss to only 10% of the charge. These potential future reductions in refrigerant losses could be applied to the other system/refrigerant options as well.

This study, unlike the energy impact study conducted earlier, also included present HCFC-22 applications in unitary air-conditioning and heat pump equipment. Results indicate that converting from HCFC-22 to HFC-134a in unitary equipment could result in a significant increase in calculated TEWI, particularly for heat pumps. This point is illustrated as well as the dominance of the INDIRECT over the DIRECT effect for several different refrigerant loss scenarios, in Figure 7.

The common-basis equipment performance values used in the energy and CO₂ analyses are generally based on equivalent manufacturing costs. The collaborative effort of the Air-Conditioning and Refrigeration Institute (ARI) and their member companies that made this approach possible is gratefully acknowledged [Calm, 1991]. Manufacturing cost was used because it could be directly related to the optimized chiller and unitary equipment designs for each alternative refrigerant.

Preliminary Findings and Observations

Figure 8 provides a summary of the results across a range of representative refrigeration and air-conditioning applications. It shows the change in TEWI of various alternatives relative to the baseline CFC technology (i.e., as a % of the TEWI for the existing CFC use). It illustrates some of the preliminary findings of the study, which include:

- Replacement of CFCs with suitable HCFCs or HFCs can yield a dramatic benefit in reducing the TEWI for all CFC end-use applications considered; reductions range from 10% to over 80% (refrigerants).
- There is a wide variation among applications with regard to the relative importance of the INDIRECT and the DIRECT effect of the HCFC/HFC alternatives.
- Energy efficiency/energy use differences are small between CFC baseline refrigerants and HCFC or HFC alternatives.

- Early published test data indicated some efficiency penalties for substitutes, but recent industry data show near equal refrigerant performance as achievable, especially in CFC-12 applications,
 - with new lubricants
 - with optimized engineering design

Figure 9 includes only the fluorocarbon (HCFC and HFC) alternatives and focuses on the relative importance of their INDIRECT and DIRECT effects. It should be recognized that most of the alternative technologies are still being optimized and, thus, the currently available data are not likely to represent the lowest cost effective energy consumption or the lowest losses/emissions achievable. Accordingly, this perspective can help identify opportunities for further future reductions in the TEWI.

- For applications dominated by INDIRECT effects (i.e., chillers, household refrigerators, unitary space conditioning), a change of only 2-5% in efficiency would have a greater impact on TEWI than completely eliminating the DIRECT (chemical emission) effect.
- Applications in which DIRECT effects of alternatives are a substantial proportion of the TEWI (e.g., automotive air conditioning and retail refrigeration) represent important target opportunities for improved containment and "not-in-kind" technology options,
 - though energy efficiency can play a major role in future TEWI reductions in these applications also.

The potential importance of non-fluorocarbon or "not-in-kind" (NIK) technology options in the longer-term is acknowledged. The DOE/AFEAS study also looked at CFC solvent cleaning applications, and aqueous and semi-aqueous cleaning technologies are examples of NIK alternatives already in widespread use which exhibit a substantial reduction in TEWI relative to CFC-113 solvent systems (for electronics and metal cleaning). However, in the refrigeration and air-conditioning applications, those NIK options evaluated (e.g., absorption systems, ammonia vapor compression, and Stirling cycle) do not yet offer the performance, costs, or lack of perceived risks needed to substantially displace fluorocarbon vapor-compression technology in such a relatively short time period as the CFC phaseout requires.

Concluding Remarks

Recent progress in improving energy efficiency with the HCFC and HFC alternatives represents an encouraging and important trend. Results of the earlier CFC phaseout assessment indicated the potential for more serious energy consequences. However, the energy-intensive user industries have responded strongly to this challenge in the past 2-3 years.

The replacement of CFCs is probably the most important single near-term step that can be taken toward reducing the total global warming impact. The contribution of CFCs to global warming in the last decade, estimated at 24% of the total by the IPCC, is second only to CO₂ (at 55% of the total). And simply replacing CFCs with HCFC and HFC alternatives (in the refrigerant, insulation blowing agent, and solvent cleaning applications studied) would result in a nominal 90% reduction in that DIRECT global warming impact. Reducing CO₂ and other greenhouse gases is likely to be much

more difficult to achieve due to the world's dependence on fossil fuels as its primary energy source and the difficulties in changing that significantly in the next 20-30 years [OTA, 1991].

As demonstrated in this study, a continuing emphasis on energy efficiency during the CFC transition will be important in limiting future CO₂ emissions.

Finally, as this study makes clear, it is important to understand how these different CFC transition issues are interrelated and to consider an integrated approach to assure that a decision or policy has the intended effect. HCFC and HFC alternatives each have their own specific advantages in specific applications. Further constraints on these fluorocarbon alternatives could be counterproductive to efficiency and global warming in many applications.

Also, global warming is not the only issue. We face a complex set of issue trade-offs and compromises. The information developed in this analysis complements ongoing studies to assess other environmental effects, safety, toxicology, and costs. It is intended to assist environmental and energy policymakers, industry, utilities, and the R&D community as we try to shape our future course to respond to the realities of the CFC transition.

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Fig. 1. Global warming and end-use energy efficiency linked to CFC alternative choices.

NATIONAL ENERGY IMPACT

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NOTE:
1987-88 estimates for
median penalty scenario

Fig. 2. Breakdown by application of potential energy use impacts

Refrigerator/Freezer Shows Impact of CFC Alternatives

The following two examples are based upon an identical energy efficiency of systems compared.

Fig. 3. Example of Total Equivalent Warming Impact from replacing CFCs with alternative fluorocarbons.

Electricity end-use energy is referenced back to the power plant for purposes of estimating CO₂ generation

1.14 kg CO ₂ (2.5 lb) if coal	}	0.67 kg CO ₂ (1.48 lb) per kWh of electricity (kWh _e) for U.S. "mix"
0.96 kg CO ₂ (2.1 lb) if oil		
0.58 kg CO ₂ (1.3 lb) if natural gas		
0 kg CO ₂ if hydro or nuclear

Thermal Equivalent assuming 33% plant efficiency

Fig. 4. Conceptual illustration of CO₂ emissions from electric end-uses of energy.

Fig. 5. Equivalent lifetime CO_2 emissions of electric-driven water-cooled chillers.

Fig. 6. Total equivalent warming impact for retail refrigeration display cases.

Fig. 7. Equivalent lifetime CO₂ emissions of unitary air-conditioners and heat pumps.

Fig. 8. Changes in TEWI relative to baseline CFC technology for selected refrigeration and air-conditioning applications.

Fig. 9. DIRECT/INDIRECT effects as proportion of TEWI for HCFC and HFC refrigerant alternatives.