

Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant, and Fire Protection Applications

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**Final Report to the Alliance for
Responsible Atmospheric
Policy**

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Executive Summary

In the Kyoto Protocol, HFCs were included in the comprehensive “basket” of greenhouse gases along with carbon dioxide, methane, nitrous oxide, PFCs and SF₆. The protocol requires developed countries to first eliminate any growth in their greenhouse gas emissions that took place over the two decades (since 1990) and then collectively to further reduce their emissions 5.2% (or about 5%) below 1990 levels on average over the 2008 to 2012 time period. In the Montreal Protocol, parties have discussed the viability of HFCs as a substitute for ozone-depleting CFCs.

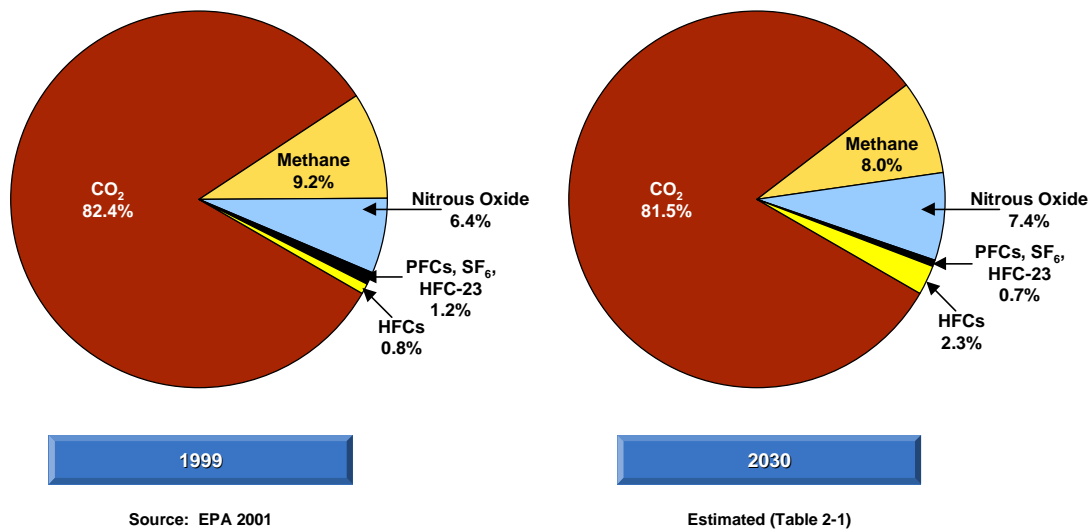
This report is an update of the report first published in August, 1999. It provides an objective analysis of the key aspects of HFCs in comparison with alternative fluids and technologies in the major applications involving HFCs. This study is intended to provide input to the Secretariat of the Climate Change Convention in connection with the issue of coordinating the HFC policy objectives of the Montreal Protocol (not to interfere with the smooth phase-out of ozone depleting substances through adequate availability of substitutes) and the Framework Convention on Climate Change (examining what real and cost effective opportunities might exist to reduce greenhouse gases).

Objective

The objective of this study is to document the overall performance of specific HFCs compared to other fluids and technologies in the key applications where HFCs have emerged as replacements for CFCs and HCFCs. The application areas include automobile air conditioning, residential and commercial refrigeration, unitary air conditioning, HVAC chillers, foam insulation, solvent cleaning, aerosols, and fire protection. The overall performance attributes that have been addressed include energy efficiency and global climate impact, safety, and economics.

Key Findings

- Figure E-1 provides a breakdown of the warming impact of greenhouse gas (GHG) emissions in the United States in 1999 and a projection for 2030. In 1999, PFC, HFC, and SF₆ emissions together were 2.0% of the total warming impact. Nonprocess related HFC emissions were 0.8% of the total warming impact of U.S. GHG emissions
- The remaining 1.2% of total U.S. GHG emissions within the PFC, HFC, SF₆ category are primarily process emissions (from manufacturing aluminum and magnesium, fugitive emissions of HFC-23 from HCFC-22 production). Fluorochemical manufacturers have committed to reduce this source of HFC-23 emissions. With the phase-out of HCFC-22 production under the Montreal Protocol, which will be largely completed by 2010 and fully completed by 2020, this major source of HFC emissions may be reduced substantially (not completely eliminated, due to continued production of HCFC-22 as a feedstock for polytetrafluoroethylene – PTFE – production).



Source: EPA 2001

Estimated (Table 2-1)

Figure E-1: Breakdown of Greenhouse Gas Emissions in the United States

- The production of various HFCs is increasing, as the phase-out of CFCs and HCFCs proceeds. However, the quantities of HFCs that are likely to be produced in the future, under present Montreal Protocol and Kyoto Protocol treatment, given inherently higher production costs and end-user prices and tight regulation of system tightness and servicing/venting practices, are significantly less than the peak of quantities of CFCs and HCFCs that were produced in the late 1980s. In Figure E-1 an estimate of the breakdown of U.S. greenhouse gas emissions in 2030 is also included. HFCs are estimated to be 2.3% of a total that assumes a high degree of stabilization of CO₂ emissions.
- Global greenhouse gas emissions are broken down in Figure E-2 and parallel the U.S. breakdown, except that energy related GHG emissions (CO₂) account for a larger part of the total and HFCs account for a smaller part.
- The cumulative effect of these categories of greenhouse gas emissions on radiative forcing has been estimated by the Intergovernmental Panel on Climate Change (IPCC) for the next 50 years and is shown in Figure E-3. In 2050, HFCs will still account for less than 2% of radiative forcing.

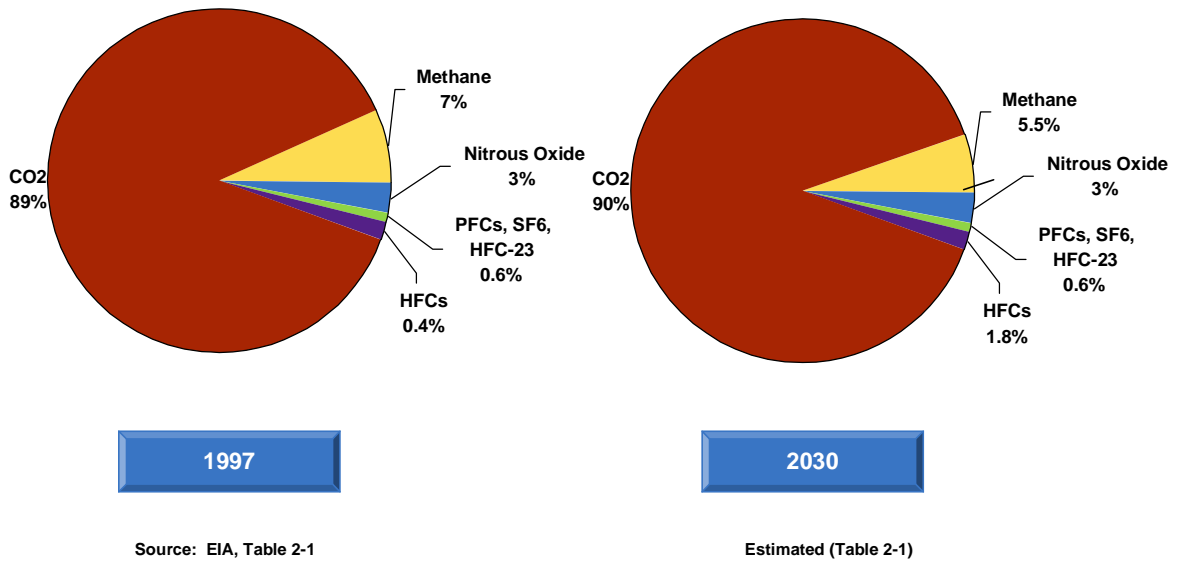
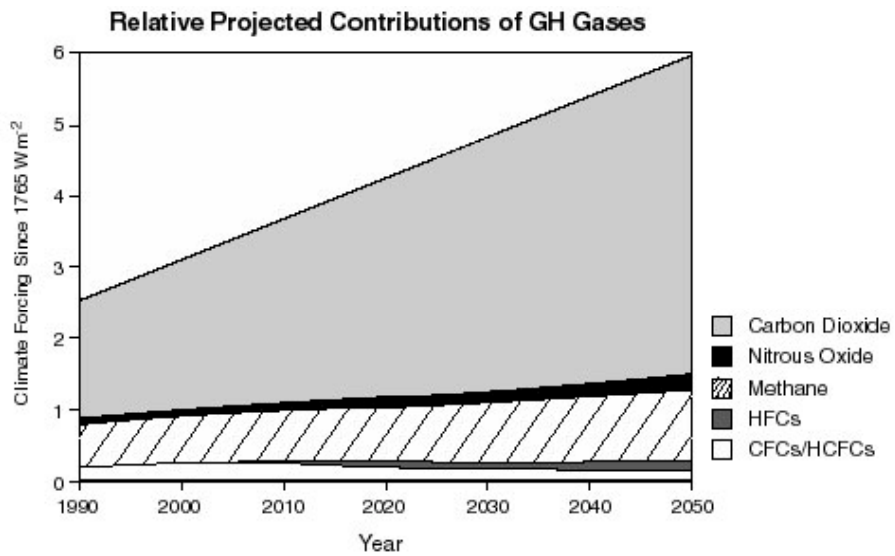


Figure E-2: Breakdown of Global Greenhouse Gas Emissions



Source IPCC: IS92A Scenario

Figure E-3: Relative Projected Contributions of Greenhouse Gases to Radiative Forcing

- The transition from CFCs to HCFCs and HFCs has already significantly reduced the potential warming impact of fluorocarbon production, as shown in Figure E-4.

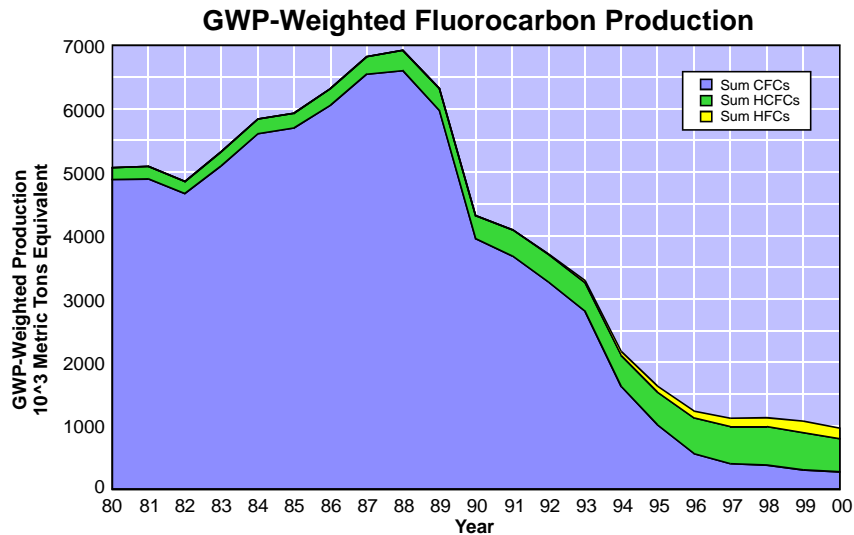


Figure E-4: GWP Weighted Fluorocarbon Production from 1980 – 2000 (Source: AFEAS, WWW.afeas.org/ing/table/gwp.pdf)

- The preceding figures substantially **overstate** the **net** warming impact of HFCs, given the significant contribution to energy savings that the unique properties of HFCs provide in many applications. Only a small amount (about 10%) of HFCs will be used in directly emissive, non-energy consuming applications. In the remaining applications the HFC based technology generally has the lowest net warming impact, as measured by the Life Cycle Climate Performance (LCCP). In other words, the net warming impact of most HFC use is close to zero or provides a net reduction in warming.
- The LCCP is a rigorous method of calculating the cradle-to-grave warming impact of any product, including those that use fluorocarbons. The LCCP accounts for warming impacts due to direct greenhouse gas emissions from the product and to indirect greenhouse gas emissions associated with the energy consumption of the product. In applications such as domestic and commercial refrigeration, stationary and mobile air conditioning, and foam insulation, the lowest LCCP solution uses HFC refrigerants and/or foam blowing agents.
- Absent a rigorous methodology, a rough estimate of the societal cost savings provided by the use of HFCs has been made, as summarized below and presented in detail in Section 3. The annual costs, in the U.S. and worldwide, would be \$17 billion and \$36 billion, respectively and include increased product costs, increased energy costs, and increased costs of safety and accident damage. This is an order of magnitude estimate that clearly could be refined with a much larger analytical and data gathering effort.

Safety Considerations

The HFCs that have emerged as the preferred replacements for the CFCs and HCFCs retain the desirable safety characteristics – low toxicity, non-flammable – that originally lead to the widespread use of CFCs and HCFCs as refrigerants, foam blowing agents, etc. Many of these applications are in mass markets, with hundreds of millions of products in service. Table E-1 summarizes the number of refrigeration and air conditioning systems in service globally, a total on the order of 1 billion units. Over the lifecycle of this large number of units, non-flammable HFC refrigerants make a significant contribution to meeting the societal demand for safe products.

Other than the HFCs, the primary non-ozone depleting alternatives to the CFCs and HCFCs are hydrocarbons, which are highly flammable, carbon dioxide, which is higher in pressure and ammonia, which is toxic and flammable. The measures required to allow the safe use of these alternatives vary with the application, but increase the cost of the application. Given the enormous numbers of products in service, and a typical product lifecycle that includes (in addition to normal use) manufacturing, transportation, field servicing, and end of life disposal, the inherent potential for mishaps cannot be dismissed easily, even when the hazardous characteristics have been taken into account in the design. Determination of acceptable safety levels within the legal and political framework of country is a significant undertaking that is fraught with uncertainty. Similarly, verification that a product meets or exceeds a given safety level is a major undertaking and is also subject to significant uncertainties.

Table E-1: Approximate Quantities of Refrigerators and Air Conditioners in Service Globally

Product Category	Global Production Million Units/Year	Millions of Units in Service Globally
Domestic Refrigerator	60	500
Mobile Air Conditioner	45	400
Unitary Air Conditioner	6-8	100
Room Air Conditioner	10-15	150
Chiller	0.1	2
Supermarket Refrigeration System	0.05	1
Self-Contained Commercial Refrigerator	1	10
Beverage Vending Machine	1	10

Value Provided to Society by HFCs

As the phase out of CFCs and HCFCs proceeds, various HFCs have emerged or are emerging as the preferred refrigerant, blowing agent, solvent, aerosol propellant, or fire extinguishant in a wide variety of applications. Many of the applications, such as domestic and commercial refrigeration and air conditioning are pervasive throughout modern society. Others such as solvent cleaning and fire protection address smaller, but critical niches. Where HFCs are the preferred alternative, the reason usually is that the HFC provides the most cost-effective combination of superior overall performance and safety. The use of HFCs will provide significant cost savings compared to the less cost-

effective and, in many cases, less safe, poorer performing materials or processes that would be used as alternatives to HFCs.

An estimate has been prepared of the aggregate cost savings provided to society by HFCs. As presented in Section 3, the basis of the estimate is a comparison of the costs of the most viable non-HFC option with the most likely HFC option. While the approximate timeframe for this estimate is 2020-2030, when the full impact is felt of the technology choices made to replace CFCs and HCFCs, these costs have been applied to current market levels of sales and installed units, without attempting to project future market growth. This estimate of U.S. and worldwide societal cost savings provided by HFCs is summarized in Tables E-2 and E-3, respectively.

Table E-2: Societal Cost Savings from HFCs in the United States

Application	Societal Cost Savings in the U.S. from HFCs (in Millions U.S. \$)		
	Product Cost	Energy Cost	Total
Domestic Refrigeration	440	400	840
Mobile Air Conditioning	1,500	5,300	6,800
Unitary Air Conditioning	6,600	0	6,600
Chillers	210	715	925
Commercial Refrigeration	240	420	660
Foam Insulation			1,000
Solvents			
Aerosols			
Fire Protection			
Totals			17,000

Table E-3: Societal Cost Savings from HFCs, Worldwide

Application	Societal Cost Savings Worldwide from HFCs (in Millions of U.S. \$)		
	Product Cost	Energy Cost	Total
Domestic Refrigeration	1,580	1,400	3,000
Mobile Air Conditioning	3,500	12,300	15,800
Unitary Air Conditioning	9,000	3,000	12,000
Chillers	400	1,400	1,800
Commercial Refrigeration	500	800	1,300
Foam Insulation			2,000
Solvents			
Aerosols			
Fire Protection			
Totals			36,000

Sufficient data could not be found to attempt an estimate of the cost savings provided by the use of HFCs as solvents, aerosols, or fire extinguishents, but as discussed in Section 3, there are many critical uses of HFCs in these areas that create significant economic value. For example, metered dose inhalers are the mainstay treatment method for asthma

used by several hundred million individuals worldwide. The value, both to these individuals, their families, and to society at large, in terms of quality of life, workplace productivity, and prolonging life is incalculable in monetary terms, but is extremely high.

As discussed in Section 3, these figures are an attempt to estimate the societal cost savings provided by HFCs; none of the figures are beyond dispute. However, the order of magnitude is large – more than \$17 billion annually in the U.S. and \$36 billion globally. The estimate would be higher if market growth were accounted for. This suggests that the issue deserves more in-depth analysis and should be considered carefully in policy decisions.

LCCP Results Summary

The basic contributors to LCCP are carbon dioxide emissions due to energy use and the direct warming impact of emissions. For a range of HFC applications, detailed comparisons of LCCP have been made between HFC based systems and non-HFC based alternative systems/technologies. The results in each application area are summarized briefly below.

Domestic Refrigeration

Domestic refrigerators use both a refrigerant and a foam blowing agent. Options for non-ozone depleting refrigerant and blowing agent are HFC-134a or isobutane, a hydrocarbon, for the refrigerant and HFC-245fa, other HFCs, and blends of the hydrocarbons, cyclopentane and isopentane, for the foam blowing agent. In Section 4, these alternatives are examined across the international context. As shown in Figure E-5, the major warming contribution to the Life Cycle Climate Performance (LCCP) of a domestic refrigerator is the indirect warming effect of the lifetime electric energy consumption of the appliance, regardless of whether HFCs or hydrocarbons are used as refrigerant and foam blowing agent (note that based on recently reported improved insulation performance with HFC-134a blowing agent, the TEWI plot for HFC-134a would fall between the plots for HFC-245fa and for hydrocarbons). Key points are:

- The refrigeration system of a domestic refrigerator is hermetically sealed and few units ever require any service over their lifetime. Consequently, lifetime emissions of refrigerant from domestic refrigerators are very small, less than 10% of the initial refrigerant charge. With HFC-134a refrigerant the warming impact of lifetime refrigerant emissions is negligible (and 85% less than for comparable emissions of CFC-12, which HFC-134a has replaced) and could be offset by a small (approximately 1/4 percent) efficiency increase.
- Even if 100% of the blowing agent is lost to the environment (which research shows is not the case [Kjeldsen, 2002]), the LCCP of the HFC and hydrocarbon blowing agent options are comparable, due to the superior insulating performance of HFC-

245fa blown foam.

- The *reduction* in LCCP that has been achieved since the U. S. industry moved to the efficiency standards levels established in 2001 is much greater than the potential direct warming impacts of refrigerant and blowing agent.
- HFC and HC based designs have similar LCCP and are both environmentally sound, non-ozone-depleting design options.
- Having a diversity of environmentally sound ODS substitution options will allow each region to make ODS substitution decisions that best fit the circumstances of that region.
- Diversity of choice will result in the best solutions, considering all factors, unless confusion leads to a delayed phase-out of ODS in developing countries.

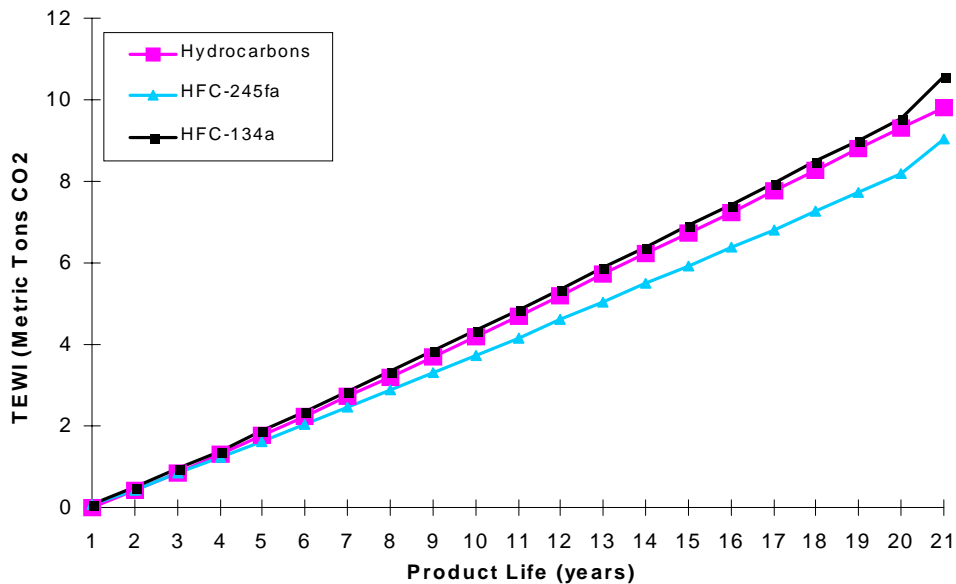
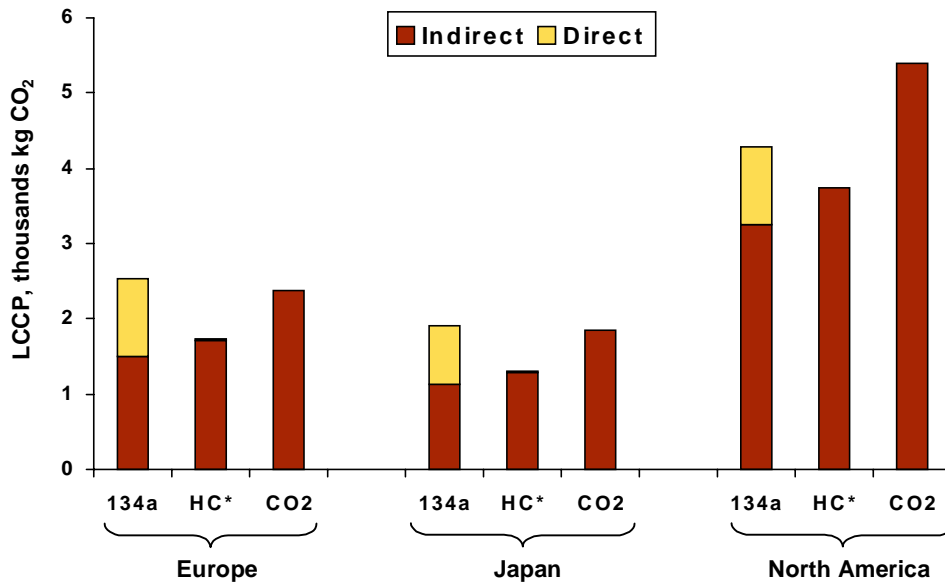


Figure E-5: LCCP for Domestic Refrigerator in the U.S.

Mobile Air Conditioning

The three non-ozone-depleting refrigerant options under consideration for mobile air conditioning are HFC-134a, carbon dioxide in a transcritical vapor cycle, and flammables (propane or HFC-152a). Flammables would be used with a secondary loop on the cold side to keep the flammable refrigerant out of the passenger compartment. The global

automobile industry has invested \$5 billion converting production automobile air conditioning systems from CFC-12 to HFC-134a; flammable refrigerant and CO₂ systems are in the early development stage. Figure E-6 compares the LCCP for these three options, as applied in representative climatic and driving conditions in Europe, Japan, and the U.S., assuming lifetime emissions of approximately 75% of the initial refrigerant charge. The indirect impact is additional CO₂ emissions from the vehicle tailpipe, due to energy consumption of the A/C and the resulting fuel consumption. The direct impact is the warming impact of refrigerant emissions. The results show only moderate differences in LCCP among the alternatives. In North America, where more miles are driven in hotter weather, the superior energy efficiency of HFC-134a based systems results in a lower overall LCCP.



*With a Secondary loop; essentially the same for HFC-152a

Figure E-6: LCCP for Mobile Air Conditioning

Unitary Air Conditioning

The non-ozone-depleting options for residential unitary air conditioning include HFC blends (primarily R407C and R410A) and propane (HC-290). Propane would be used only with a secondary loop on the low side to transport the cooling capacity from an all-outdoor propane based cooling unit to the air handling system indoors. (Note that secondary loops have significant energy penalties) In Figure E-7 the LCCP has been compared for these options and with HCFC-22, which will be used in newly produced units of this class of equipment until the end of 2009. LCCPs have been calculated for a typical application in Atlanta, GA, at three efficiency levels – seasonal energy efficiency ratio (SEER) levels of 10, 12, and 14 Btu/Watt-hr. The 10 SEER level with HCFC-22 is now representative of the majority of the U.S. market. 12 and 14 SEER units are currently produced as well; by 2010, when HCFC-22 has been phased out for new equipment and higher energy efficiency standards are in place, the 12 SEER product with

an HFC blend refrigerant is likely to be representative of a large part of the market for new equipment. The results generally show direct warming impacts due to life cycle refrigerant emissions are less than 5% of the LCCP. The differences in the indirect warming component of LCCP at different efficiency levels is much greater. While propane emissions have a negligible warming impact, the added cost to use propane safely exceeds the difference in cost between 12 and 14 SEER units, which have a much larger LCCP difference than the direct warming from refrigerant emissions.

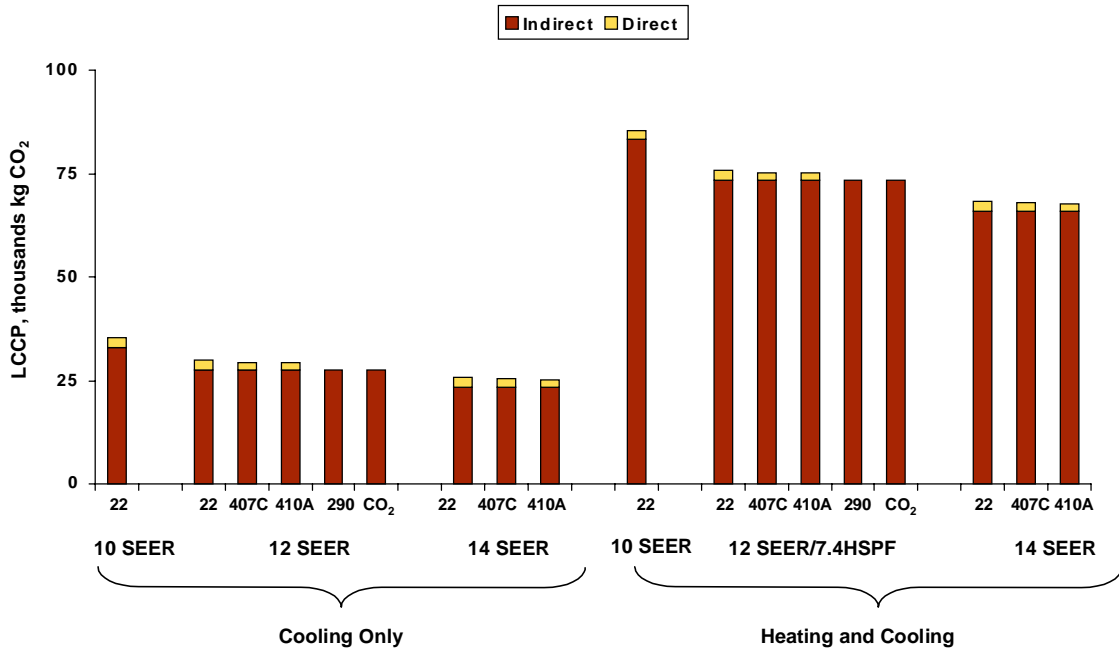


Figure E-7: LCCP for Residential Space Conditioning in Atlanta (3 ton, 2005 Technology)

The LCCP for refrigerant options for a small commercial rooftop air conditioner are compared in Figure E-8 on a similar basis to the comparison for residential equipment, above, with similar results.

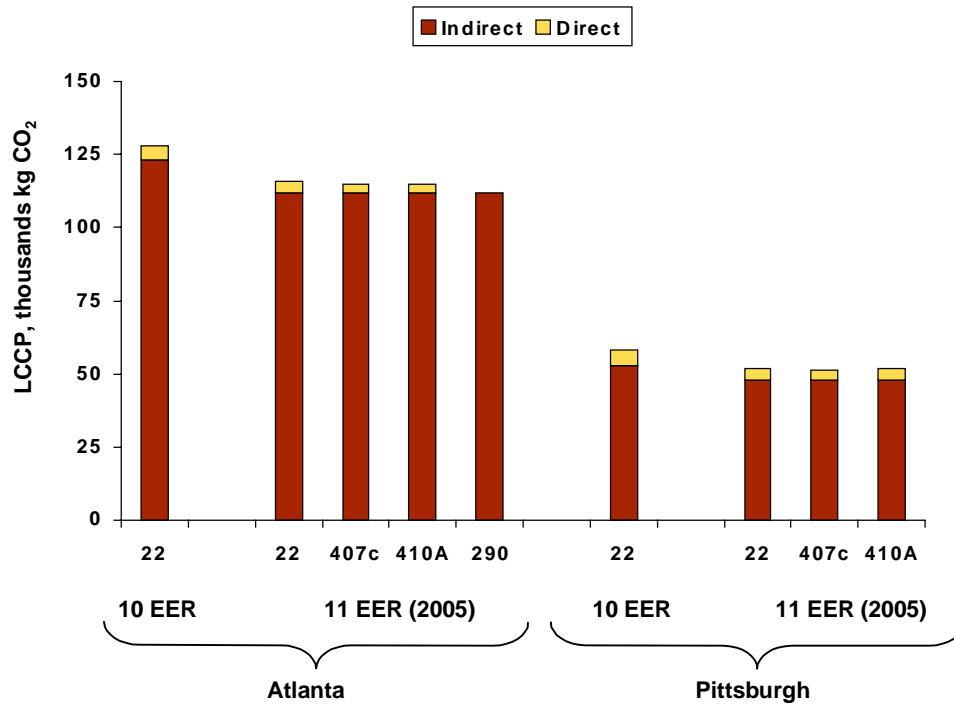


Figure E-8: LCCP for 7.5-Ton Commercial Rooftop Air Conditioner in Atlanta and Pittsburgh

Chillers

Large chillers are produced in capacities between 100 and several thousand tons, and are a highly efficient option for air conditioning large buildings. Screw chillers are commonly used between 100 and 400 tons and centrifugal chillers are commonly used in capacities over 300 tons. Figure E-9 summarizes the LCCP for the chiller technology alternatives (at 350 tons rated capacity), applied to a representative office building in Atlanta. Efficiency levels are representative of best, or nearly best, currently (in 1999) available screw, centrifugal, and direct-fired absorption technology. LCCP values for centrifugal and screw chillers fall within a +/- 5% range and refrigerant emissions account for less than 3% of the LCCP of any of the technology options.

Hydrocarbons, such as propane, have not been considered to be a viable option, due to the large charge size that would be used. Ammonia (R717) has been included as a technical option, but local codes may preclude its use.

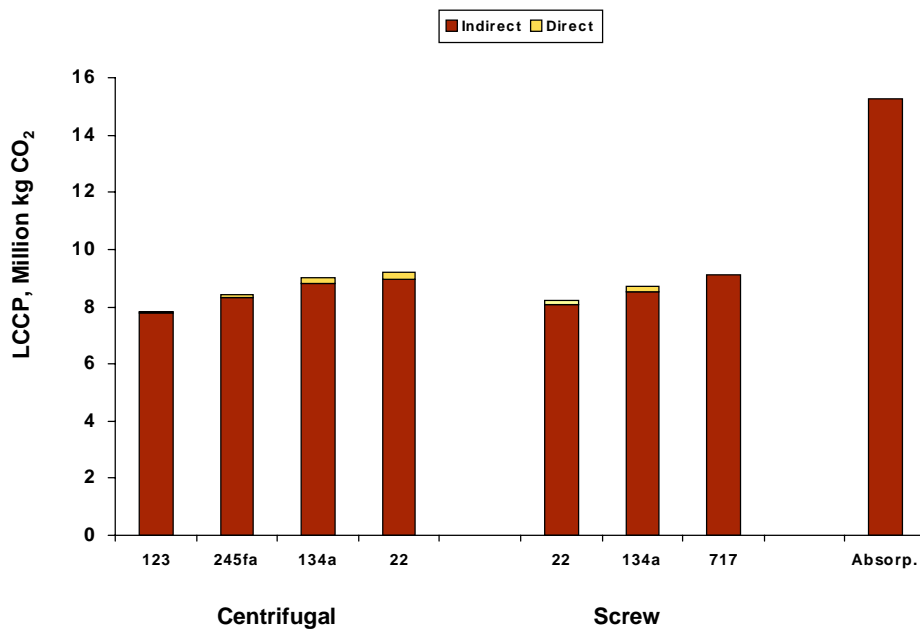


Figure E-9: LCCP for Chillers – Best Current Technology, Atlanta Office Building

The LCCP of a typical direct-fired, double-effect Lithium Bromide -Water absorption chiller is about 65% higher than the average LCCP for the vapor compression cycle chillers. However, in practice a large portion of these machines are operated to meet peak loads only, as a means of reducing electric demand charges, and, as a result, operate for considerably fewer equivalent full load hours per year.

Commercial Refrigeration

Non-ozone depleting alternatives for supermarket refrigeration systems include the similar HFC blends R-404A and R-507, in either traditional direct expansion systems with centrally located, rack-mounted compressor systems or in a distributed system configuration or a secondary loop configuration. In addition, ammonia could be used as the refrigerant in a secondary loop configuration, assuming proper design of the mechanical equipment room and absence of local code issues. The LCCP for these configurations is compared in Figure E-10.

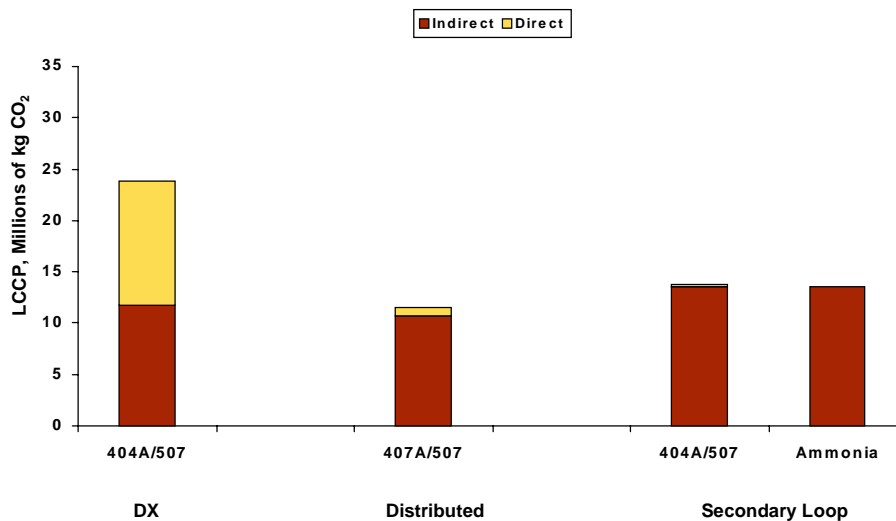


Figure E-10: LCCP Refrigeration in a Typical New Supermarket in the U.S.

Foam Insulation

In typical applications of plastic foam building insulation, the lifetime reduction of carbon dioxide emissions due to reduced consumption of energy for heating and cooling exceeds the direct warming impact of the blowing agent by a factor of 10 to 20. Consequently, plastic foam building insulation makes a major contribution to reducing greenhouse gas emissions.

The choice of blowing agent for building insulation is dictated by a number of factors including cost effectiveness of R-value, processing considerations, U.S. building code regulations, and safety. The much higher cost of some of the HFC blowing agent candidates will lead to their use only in applications where safety considerations dominate and in applications where insulation thicknesses are limited, conferring a premium value to maximizing the foam R-value. In many other applications for plastic foam building insulation, hydrocarbons and carbon dioxide will prove to be the most cost effective blowing agent.

Solvents

Many approaches have been taken to replace CFC-113 in solvent cleaning applications. They included use of HCFC-141b, aqueous cleaning, semi-aqueous cleaning, no clean fluxes and flammable solvents. HCFC-141b was an interim solution since it already has been phased out for most solvent applications. To date, the replacement percentage of CFC-113 by HFC solvents is probably no more than 2 %.

Competing solvents to the HFCs, and not in kind technologies include: HCFC-141b, (CH₃CCl₂F), HCFC-123 (CF₃CHCl₂), HFES, volatile methyl siloxanes, n-propylbromide,

flammable hydrocarbons, alcohols and ketones, aqueous cleaning, semi aqueous cleaning, no clean fluxes, and inert gas soldering.

Since both HFC-43-10 and HFC-365mfc are mild solvents and either high priced or being used in blends with higher priced solvents, based on general market data, they are being utilized only for the cleaning of high value added parts where good solvent compatibility and stability would be an issue. Furthermore, the use of higher end vapor phase degreasers with high freeboards, and secondary cooling systems are required and economically justified in order to minimize the loss of expensive solvent.

The 3M company carried out a batch metal cleaning study to calculate the Total Environmental Warming Impact (TEWI) for HFE-7100, HCFC-141b, and compared the values to an aqueous and a semi-aqueous cleaning process. The vapor phase degreaser used extended freeboard and secondary cooling coils to minimize vapor loss. There was a 1-minute dwell time in the freeboard and a 1-minute dwell time in the vapor zone. The TEWI for HFC-43-10 was estimated based on the similarity of the drag out loss curve for HFC-43-10 compared to HFE-7100 and similarity of the boiling points. The data are plotted in Figure E-11.

The total use of HFC-43-10 has been estimated to be less than 2 million pounds per year which translates to $<3.2 \times 10^{-1}$ million metric tonnes carbon equivalent (MMTCE). The use of HFC-365mfc as a solvent is under development with an industrial –scale plant expected to come on stream at the end of 2002.

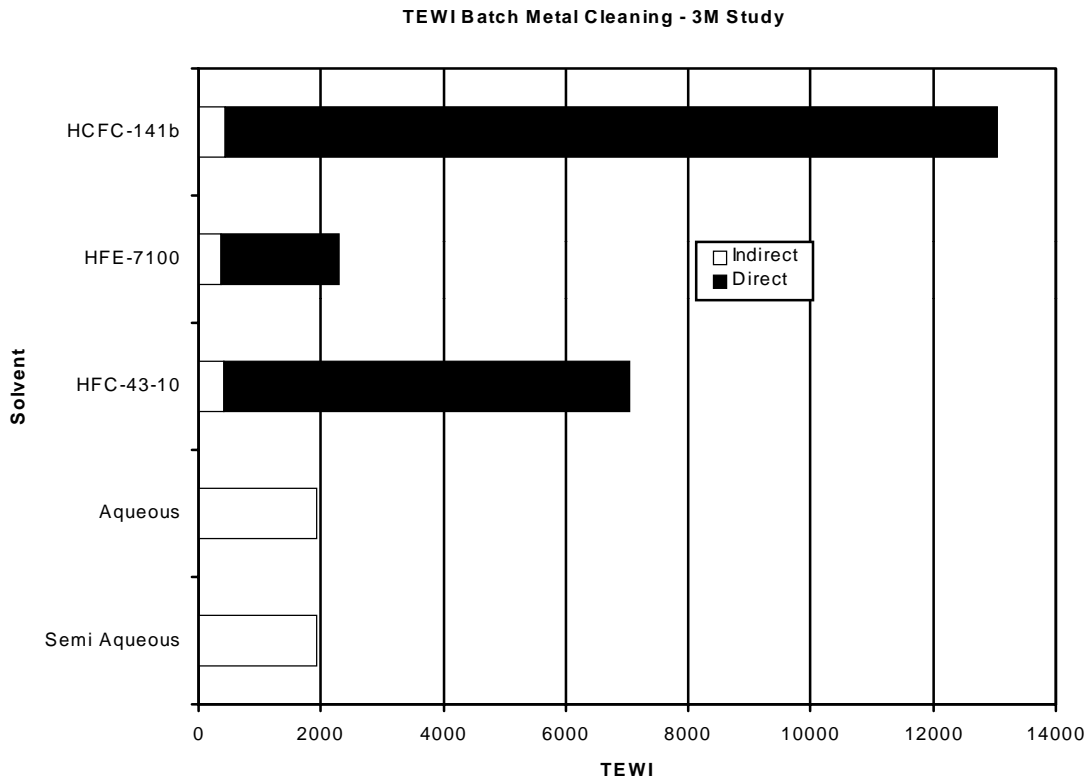


Figure E-11: LCCP for Metal Cleaning Alternatives

Aerosols

Unlike refrigeration, air conditioning, and foam applications, the use of aerosols entails primarily the dispersal of chemicals, and the indirect contributions from this spraying are minimal. Therefore, instead of carrying out LCCP analyses, estimates have been made for the amount of greenhouse gas emitted expressed in units of million metric tons of carbon dioxide equivalent. The estimated embedded energy and GWP of the fugitive emissions associated with manufacturing the aerosol propellant is included in these figures. Note that much of current Metered Dose Inhaler (MDI) production still use CFCs, under a Montreal Protocol essential use exemption. The conversion to HFC-134a or HFC-227ea will occur over the next 5-10 years, as product reformulations are completed and regulatory bodies, such as the U.S. Food and Drug Administration (FDA) approve HFC MDIs for patient use.

The total emissions of HFCs in all aerosol applications is projected to be 4.1 MMTCE by 2010, 5% of overall HFC emissions [EPA, 2001]. The increasing use of HFC-152a in certain specialty aerosols has helped to reduce the business as usual aerosol scenario by almost 2.75 MMTCE since 1999.

Fire Protection

HFCs are important halon substitutes, particularly in occupied areas where space and weight are constrained, or speed of suppression is important. HFC use for fire fighting represents a very small share of total use. About 50% of the previous halon uses have been replaced with not-in-kind, non-ozone depleting alternatives. These include water-based systems, foam, dry powder, and fire-protection engineering approaches involving risk analysis, prevention steps and early detection systems combined with portable extinguishing equipment. About 25% have been replaced with non-halocarbon gaseous agents such as inert gas mixtures or carbon dioxide. Despite the consumption phaseout in developed countries, there remain some critical halon uses in existing and new applications, such as civil and military aircraft, military vehicles, and other specialized high-risk situations. Critical use halon comprises 3 – 4% of the fire fighting market. Only about 20% of the former halon market has been replaced by HFCs.

In contrast to the refrigeration and air conditioning equipment discussed in previous sections of this report, fire suppression systems are essentially non-emissive systems that sit idly while awaiting the mishap against which they are intended to protect. The fire detection system consumes a low level of electrical power, and small amounts of energy are consumed during periodic operating tests.

The systems are material intensive, and can include a significant amount of steel pressure vessels to store the fire suppression agent and steel piping to distribute the fire suppressant. The embodied energy in these materials, as well as the embodied energy in manufacturing the fire suppression material is the most significant energy input over the life cycle.

Emissions of the fire suppressant can be categorized as non-fire and fire emissions, i.e., releases of the fire suppressant to extinguish a fire. Modern fire suppressant systems do not leak and do not require discharge testing. Consequently, current practices hold emissions, both fire and non-fire related, to 1-3% annually of the installed base. Releases to suppress a fire in practice do not occur very frequently and currently are estimated to be approximately 1.5% of the installed bank. Over the 10 to 25 year typical system useful life, most of these systems are never called upon to suppress a fire. At the end of the useful life of a system, the fire suppressant can be recovered for recycling or reclaimed for transformation into non-GWP substances. The warming impact of HFC emissions from fire fighting is approximately 0.006% of the warming impact of all GHG emissions.

1. Introduction

This report is an update of the report having the same title that was first published in August, 1999. During the 2 ½ years since August, 1999, new technology alternatives have emerged and new information has been developed that is incorporated in this volume.

1.1 Background

In the Kyoto Protocol, HFCs were included in the comprehensive set of greenhouse gases along with carbon dioxide, methane, nitrous oxide, and other trace gases whose emissions from developed countries are to be collectively reduced 5.2% (or about 5%) below 1990 levels. At the November, 1998 meeting of the parties to the Montreal Protocol, the issue was raised of the viability of HFCs as a long-term substitute for CFCs and HCFCs, if their use is to be restricted in any way under the terms of the FCCC/Kyoto Protocol.

This report provides an objective analysis of the key aspects of HFCs in comparison with alternative fluids and technologies in the major applications involving HFCs. This study is intended to provide input to the Secretariat of the Climate Change Convention in connection with the issue of coordinating the HFC policy approaches of the Montreal Protocol and the Framework Convention on Climate Change.

Due to the short time that was available for its preparation and the breadth, depth, and quality of the relevant published work that precedes this effort, this document assembles a coherent review of the technical issues – energy, environmental impact, safety, and economics – surrounding the use of hydrofluorocarbons (HFCs) as refrigerants, solvents, foam blowing agents, aerosol propellants, fire extinguishents, etc. This study relies heavily on previously published sources for estimates of energy impact and warming impacts and for safety assessments.

The range of products that use, or potentially use, HFCs includes many that are inextricably associated with the high standard of living of the developed world and that are basic to increasing the standard of living of the less developed countries. Therefore, the economic impact – the basic impact on the cost to consumers to buy and operate the wide range of products that rely on HFCs or alternate fluids or technologies – is a major factor.

Objective

The objective of this study is to document the overall performance of specific HFCs compared to other fluids and technologies in the key applications where HFCs have emerged as replacements for CFCs and HCFCs. The application areas include unitary air conditioning, HVAC chillers, automobile air conditioning, residential and commercial refrigeration, foam insulation, solvent cleaning, aerosols, and fire

protection. The overall performance attributes that have been addressed include energy efficiency and global climate impact, safety, and economics.

1.2 Methodology

An inherent challenge of a study of this nature is to simplify the vast complexities of and differences between the real world applications while retaining and addressing the essence of the comparative aspects of HFCs with alternative fluids and technologies. The basic approach that we have followed is to define a prototypical application (as summarized in Table 1-1) to represent each application area and to develop an internally consistent comparison of the HFC based equipment with the alternatives. The approach is similar to, and draws heavily upon, the approach followed in the Alternative Fluorocarbon Environmental Acceptability Study/Department of Energy (AFEAS/DOE) sponsored TEWI 1, 2, and 3 studies. Consequently, the choice of the prototypical application has been aligned with the examples in the TEWI-3, where appropriate. The assessment has been broadened to encompass safety and economic issues as well. The treatment of each application includes an introductory discussion describing the range of products used and the prototypical system that was selected to represent the category. The discussion qualitatively addresses the key and/or unique performance requirements in the application, the economic drivers, and safety aspects. Alternative technologies are described. An analysis of energy consumption (where relevant) and life-cycle direct/indirect global warming impacts has been conducted, expressed in terms of LCCP. The extent to which energy efficiency standards tend to drive all alternatives to a common energy impact will be discussed, along with economic implications. Safety has been assessed primarily in terms of toxicity and fire risk. Where available, published risk analyses have been cited to provide additional perspective. Economic factors have been discussed in terms of both consumer cost impact and manufacturer investment impacts. A detailed analysis of these cost impacts is outside of the scope of this work, but relevant literature is cited and, as appropriate, rough estimates have been prepared.

The TEWI/LCCP analysis methodology is rigorous and consistent with the methodology established in the AFEAS/DOE sponsored TEWI studies (in which Arthur D. Little was one of the two contractors responsible for developing the methodology and performing the analysis).

Table 1-1: Prototypical Applications for HFC Study

Application Area	Prototypical System(s)
Domestic Refrigeration-USA	22 cubic foot, side-by-side with R134a refrigerant, HFC-245fa foam insulation, meeting July 1, 2001 energy efficiency standards
Domestic refrigeration-elsewhere	230 liter refrigerator with cold wall, rollbond evaporator w/manual defrost
Automobile Air Conditioning	Typical R134a based systems for a mid-sized car
Unitary Air Conditioning	An air-to-air split system residential central air conditioner at 12 SEER, using either R410A or R407C
Centrifugal Chiller	A large tonnage (350 ton and 1000 ton) centrifugal chiller using R134a or HFC-245fa refrigerant
Commercial Refrigeration Supermarket Systems	Typical uneven parallel, rack mounted compressor based system using R507/R404A for low temperature and for medium temperature
Commercial Refrigeration – Self-Contained	30 cubic foot reach in refrigerator or beverage merchandiser with R134a refrigerant and HFC-245fa insulation
Foam Insulation	Foam PIR boardstock with HFC-245fa blowing agent (use in appliances addressed above)
	Foam XPS boardstock with HFC-134a, CO ₂ , or blends thereof blowing agent, or others yet to be discovered
	Spray plastic foam (SPF) roof insulation
Solvents	Printed circuit board cleaning
	Precision metal parts cleaning
Aerosols	Metered dose inhalers, tire inflators, electronics cleaning sprays, dusters, mold release sprays, formulated consumer products
Fire Extinguishing	A typical computer room fire protection using HFC-227ea

1.3 Trace Greenhouse Gases and Energy – The TEWI and LCCP Concepts

The basic concept of both the Total Equivalent Warming Impact (TEWI) and the Life Cycle Climate Performance (LCCP) is, for a given product or activity, to rigorously identify all of the warming impacts due to the use of the product through its lifetime. The TEWI methodology explicitly seeks to identify both the “direct” effect of greenhouse emissions from the product and the “indirect” effect of carbon dioxide emissions related to the energy consumption of the product.

The LCCP concept corrects a few specific oversights that have typically occurred in the practice of TEWI analysis:

- Failure to include the embodied energy and trace greenhouse gas emissions associated with fluorocarbon production in the total warming estimate
- Inappropriate use of a 100 year integration time horizon (ITH) in conjunction with certain long-lived greenhouse gases
- An LCCP analysis accounts for end of product life loss/emission of working fluids. Most of the major TEWI studies that have been published have explicitly addressed end of life disposition of the fluorocarbon inventory.

Not all published TEWI studies have been guilty of these oversights, but the LCCP measure can be taken as a more rigorous measure of warming impact due to its explicit identification of these issues.

In the context of this study, the 100-year ITH is an appropriate, if conservative choice of integration time frame. The atmospheric lifetime of CO₂ exceeds 100 years. In order to properly account for its environmental impact, an ITH of at least 100 years is needed. None of the HFCs of practical interest have atmospheric lifetimes greater than 50 years, and a longer ITH would yield a lower value for the GWP.

Table 1-2 summarizes the GWP values (Climate Change 95) of the HFCs of interest and includes an estimate of the embodied energy and prorata share of the GWP of fugitive emissions based on data summarized in Appendix A. As discussed in Appendix A, data was available for HFC-134a, but not the other HFCs. Values for the other HFCs have been extrapolated from HFC-134a. The impact on the effective warming is small, well within the +/-35% accuracy of the GWP values.

Table 1-2: Global Warming Properties of HFCs

HFC	Atm. Life ¹	GWP ¹ (Climate Change 1995)	Embodied & Fugitive in Terms of 100 year GWP ²
		100 year ITH	
134a	14.6	1300	13
152a	1.5	140	10
32	5.6	650	11
125	32.6	2800	17
143a	48.3	3800	20
245fa	7.3	820	12
227ea	36.5	2900	17

1. Source: Climate Change 1995

2. Source: See Appendix A

2. General Policy Considerations

In this section, the broader policy considerations cutting across all HFC applications are discussed. General topics addressed include the overall greenhouse gas (GHG) emission picture and the part played by HFCs in this picture, a brief summary of the Montreal Protocol CFC and HCFC phase-out schedules, economic constraints on wasteful use of HFCs in the future, and general safety considerations.

2.1 HFCs and Global Climate Change--The Overall Greenhouse Gas Picture

The purpose of this section is to provide some overall perspective on the global climate change issue and the impact of current levels of HFC production and the likely impact of future levels of HFC production on overall global climate change.

Figure 2-1 is a pie chart that allocates the global warming impact among U.S. emissions of the major greenhouse gases in 1999 and among projected U.S. GHG emissions in 2030. The breakdown of current (1999) emissions is based on the annual U.S. Environmental Protection Agency (EPA) figures [EPA, 2001], and the projected breakdown of greenhouse gases in the U.S. in 2030 is explained in 2.1.1. Currently carbon dioxide emissions due to the combustion of fossil fuels is by far the largest contributor at 82%. The remaining warming impacts are caused by methane, nitrous oxide (together 16% of the total), and HFC/PFC/SF₆ emissions, accounting for 2.0% of the overall total. HFCs used for specific end-uses – refrigerant, foam blowing, solvent, aerosol, and fire protection applications – are only 0.8% of the warming impact of total GHG emissions. The projected breakdown in 2030 is similar, with HFCs used for specific end-uses rising to 2.4% of the warming impact of total GHG emissions, as the process of substitution of HFCs for CFCs, HCFCs, and other ODS is completed.

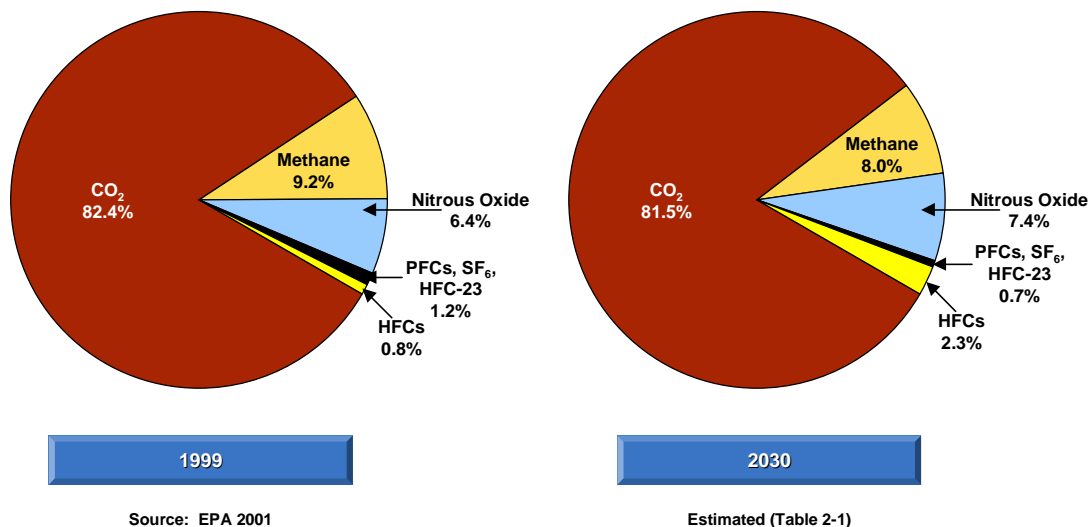


Figure 2-1: Breakdown of Greenhouse Gas Emissions in the United States

Globally, the breakdown of the warming impact of GHG emissions is shown in Figure 2-2. In 1997, carbon dioxide emissions were 89% of the total while PFCs, SF₆, and HFCs were only 1%, only half of which is HFCs for refrigerant, foam blowing, etc. applications. The projected share in 2030 of the warming impact of emissions from HFC end-uses rises to approximately 2%, as the process of substitution of HFCs for ODS is completed.

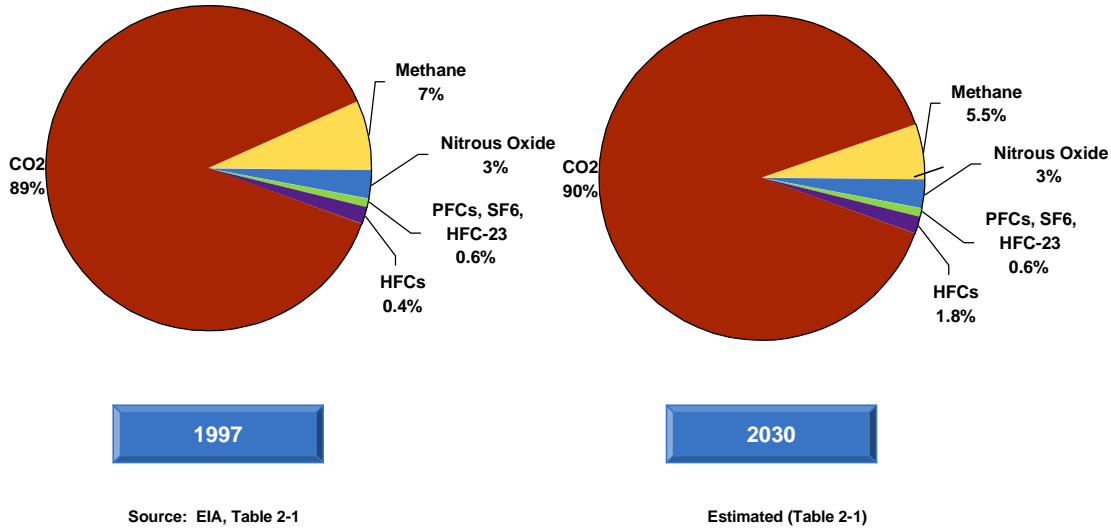


Figure 2-2: Breakdown of Global Greenhouse Gas Emissions

Figures 2-1 and 2-2 include *gross* HFC emissions. As discussed throughout this report, in most applications HFC technology provides the least warming impact as measured by LCCP. This means that the reduced lifetime energy consumption of the HFC technology **reduces** lifetime CO₂ emissions and the associated warming impact by **more** than the warming impact of the lifetime HFC emissions for that application.

2.1.1 Greenhouse Gas Emission Data

Table 2-1 summarizes the greenhouse gas emissions in the U.S. and globally, for 1990 (based on reported data) for 1999 (based on EPA estimates for the U.S. and other estimates) and for 2030 (based on the assumptions discussed below). For each time period, GHGs are broken down into the major categories, with HFCs produced for specific end-uses broken out as a separate category.

Note that the units are Tg CO₂ equivalent, instead of million metric tonnes of carbon equivalent (MMTCE) reflecting the change in units used by the EPA to report U.S. greenhouse gas emissions.

Table 2-1: Summary Breakdown of Greenhouse Gas emissions in the U.S. and Global, at Several Points in Time

Year	Greenhouse Gas Category	Emission, Tg CO ₂ Equivalent	
		USA	Global
1990	Carbon Dioxide	4,913 ¹	16,500 ⁴
	Methane	645 ¹	
	N ₂ O	397 ¹	
	PFCs, SF ₆ , HFC-23	83,0 ¹	
	HFCs Subst. For ODS	0.9 ¹	
	Total	6,038 ¹	18,700
	CFCs and HCFCs		4,820 ³
1999	Carbon Dioxide	5,558 ¹	20,900 ⁴
	Methane	620 ¹	
	N ₂ O	433 ¹	
	PFCs, SF ₆ , HFC-23	79.0 ¹	
	HFCs Subst. for ODS	56.7 ¹	
	Total	6,746 ¹	23,400
	CFCs and HCFCs		2,160 ³
2030	Carbon Dioxide	5,600 ²	29,000 ⁵
	Methane	550 ²	
	N ₂ O	505 ²	
	PFCs, SF ₆ , HFC-23	50 ²	
	HFCs Subst. for ODS	165 ²	
	Total	6,870 ³²	32,500
	CFCs and HCFCs		< 400

1 Source: EPA, 2001

2 See discussion in 2.1.1

3 Source: AFEAS, Production, Sales, and Atmospheric Release of Fluorocarbons through 1996

4 Source: U.S. Energy Information Administration

5 Source: U.S. Energy Information Administration, extrapolated from 2015 to 2030 at half the growth rate from 2005-2015

6 Source: UNEP, 1999 – 1998 Report of the Technical and Economic Assessment Panel

In Table 2-1, the figures for the U.S. are based on EPA figures [EPA, 2001]. The projection for the U.S. in 2030 is based on assuming:

- Stabilization of carbon dioxide emissions at 1999 levels
- Extrapolated growth (-0.4%/yr) of methane emissions 1990-1999
- Growth of N₂O extrapolated at half the 1990- 1999 growth rate (1/2 of 1%/yr), in line with assuming stabilization of energy consumption
- No net change in PFC, SF₆ from 1999 levels
- Improved control of fugitive emissions of HFC-23 from HCFC-22 production

The global figures for CO₂ are based on the Energy Information Administration (EIA) projection through 2015. Growth in CO₂ emissions was extrapolated to 2030, based on a 1% annual growth rate, half the growth rate projected by the EIA between 2005 – 2015.

Global values for methane, N₂O, and for PFCs, HFC-23, and SF₆ were assumed to be, in the aggregate, approximately double the U.S. values for these substances. Global HFC emissions were based on the 1998 Report of the TEAP, assuming that HFC emissions are approximately 2/3 of HFC consumption. HFC consumption in 2030 was projected by extrapolating the TEAP figures forward from 2015, probably overstating likely consumption in the process, because much of the substitution for ODS will already have occurred by 2015. Carbon equivalent emissions of ODS (CFCs 11, 12, 113, 114, 115, and HCFCs 22, 142b, and 141b) for 1990 and 1997 were based on AFEAS data, which covered about 90% of global production in 1990 and virtually all developed country production in 1997. It is noteworthy that in the seven years between 1990 and 1997, when the CFC phaseout took effect in the developed countries, the warming impact of ODS emissions fell by more than 50%. The transition from CFCs to HFCs will provide substantial benefits. [AFEAS, 2002] shows the extent to which the warming impact of fluorochemical production already has been reduced. By 2030, ODS releases to the atmosphere globally should be down to negligible proportions. The warming impact of projected HFC emissions in 2030 is only 12% of the warming impact of CFC emissions in 1990 (one of the peak years for CFC emissions).

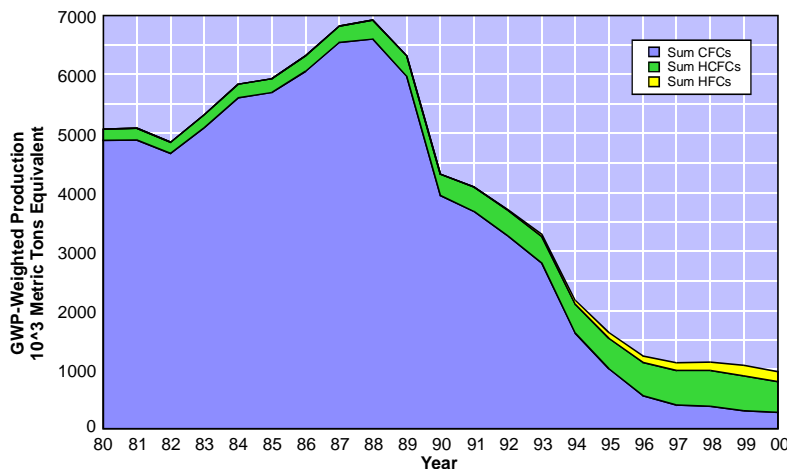


Figure 2-3: GWP Weighted Fluorocarbon Production from 1980 – 2000 (source: AFEAS www.afeas.org/ing/table/gwp.pdf)

2.2 The Montreal Protocol CFC and HCFC Phase-Out Schedules for Developed Countries

This subsection is included as background information on stratospheric ozone depletion and global climate.

2.2.1 The Montreal Protocol and the CFC Phase-Out

For a recent historical perspective, the evolution of the CFC phase-out is depicted graphically in Figure 2-4. With limited exceptions, the production of CFCs in developed countries, including the U.S., ceased at the end of 1995. CFCs will continue to be

available from stocks existing as of January 1, 1996 and from reclamation of CFCs recovered from equipment being serviced or scrapped, albeit in decreasing quantities and at increasing prices, according to generally available market information.

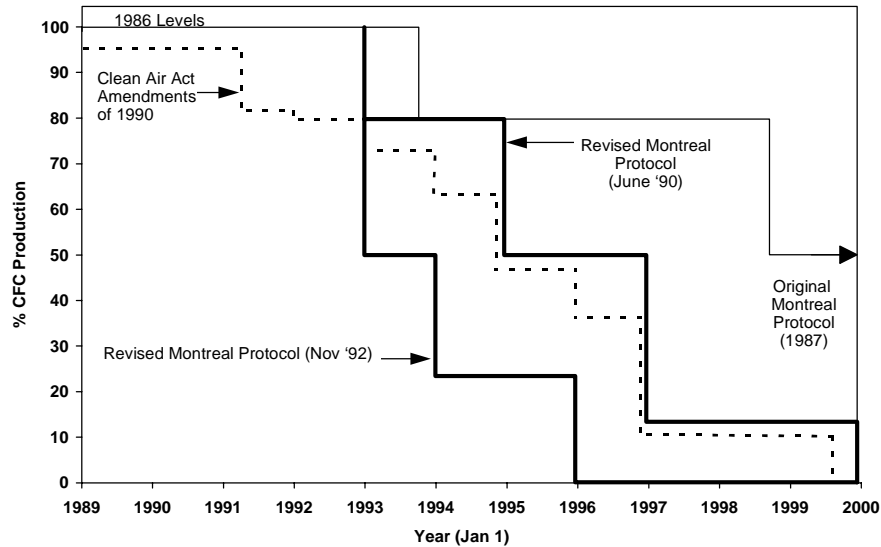


Figure 2-4: Historical Perspective of CFC Phase Out

In addition to the CFCs *per se*, early phase-out times were also established for halons, 1,1,1 trichloroethane (a.k.a. methyl chloroform), and several other chlorinated or brominated compounds.

The EPA developed regulations to comply with the CFC phase-out in the U.S. The basic approach, which is detailed in Federal Register publications, has been to allocate production and consumption quotas to existing fluorochemical manufacturers and importers, based on pre-phase-out market shares.

2.2.2 The CFC Excise Tax

Simultaneous with the CFC phase-out, an excise tax was imposed on CFCs. The first year of the tax was 1990, at \$1.37/ODP-lb (\$3.00/ODP-kg). The tax automatically increased each year by \$0.45/ODP-lb (\$1.00/ODP-kg) and in 2002 reached \$8.50/ODP-lb (\$18.80/ODP-kg). Stocks held over from one calendar year into the next (so-called floor stocks) are also subject to the tax increase, if being held for further sale or manufacture.

2.2.3 The Montreal Protocol and the HCFC Phase-Out – Developed Countries

The Copenhagen Amendments to the Montreal Protocol in November, 1992 established an HCFC phase-out timetable, as shown in graphical form in Figure 2-5. The basic approach is to establish a “Cap” based on combined CFC and HCFC usage, and then periodically to phase down consumption as a percentage of the Cap. The Cap is expressed in terms of ODP weighted consumption (units: ODP-kg) and was established as 3.1% of ODP weighted CFC consumption plus ODP weighted HCFC consumption in 1989. As shown in Figure 2-5, consumption is limited to the Cap beginning in 1996, and

stepped reductions from the Cap occur in 2004, 2010, 2015, and 2020, with a final phase-out in 2030.

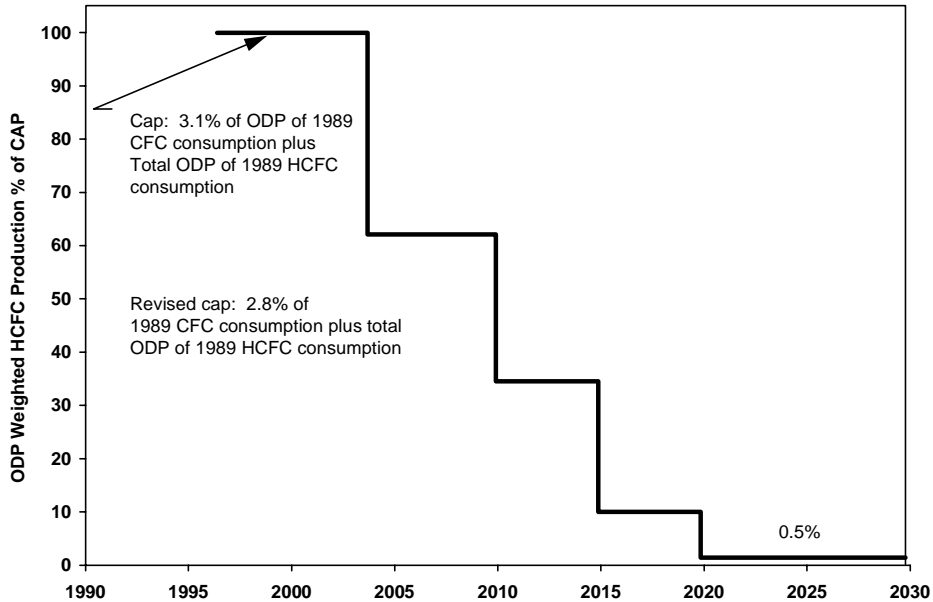


Figure 2-5: The Montreal Protocol HCFC Phase-out Timetable for Developed Countries

In December, 1995, at the Seventh Meeting of the Parties, an adjustment was adopted reducing the cap by approximately 5% overall -- the new formula being 2.8% of ODP weighted CFC consumption plus ODP weighted HCFC consumption. In addition, HCFC consumption from 2020 to 2030 is restricted to servicing existing air conditioning and refrigeration equipment.

The Montreal Protocol HCFC phase-out schedule seems to have stabilized in terms of both the timing of phase-out steps and the associated consumption limits (i.e., the formula for determining the Cap).

2.2.3.1 Developing Countries

Developing countries (as listed in Article V (1) of the Montreal Protocol) must stop producing CFCs by 2010. HCFC production and consumption will continue until 2040.

2.2.4 The EPA Regulation of HCFC Consumption

The U.S. EPA published a final rule establishing an HCFC phase-out to comply with the Montreal Protocol phase-out. As shown in Table 2-2, the approach has been to phase-out specific HCFCs on specific dates. The key features of this approach are:

- HCFC-141b, which is being used primarily as a foam blowing agent (replacing CFC-11), will be phased-out at the beginning of 2003 to meet the first Montreal Protocol HCFC phase down step

- HCFC-22 will continue to be produced for use in new equipment until the end of 2009, when the next Montreal Protocol phase-down step occurs. HCFC-22 will continue to be produced for servicing existing equipment through 2019, when allowable HCFC consumption under the Montreal Protocol is reduced to 0.5% of the Cap
- HCFC-123 and 124 can be produced for sale for use in new equipment through 2019 and can be produced for sale to service existing equipment through 2029, subject to a maximum use of 0.5% of the Cap.

Table 2-2: U.S. EPA Rule Phasing out HCFCs

HCFC	Phase-Out Date (January 1 of)	
	New Equipment	Production
141b	2003	2003
22/142b	2010	2020
All other HCFCs (123, 124, etc.)	2020	2030

2.2.5 The Clean Air Act Amendments of 1990

Specific provisions relating to stratospheric ozone depletion in the Clean Air Act Amendments of 1990 established a ban on intentional venting of refrigerants. The EPA has promulgated extensive regulations in this area, addressing refrigerant recovery system certification, technician certification, and requirements to find and repair leaks. As of late 1995, intentional venting of CFCs, HCFCs, and HFCs is prohibited and the EPA has assessed some rather onerous fines on a number of violators.

A system of CFC warning labels was set up requiring products containing CFCs and/or processed with CFCs to be labeled as such.

The Significant New Alternatives Policy (SNAP) Program was established, under which all substitutes for CFCs and HCFCs are subject to a broad EPA safety (including “environmental safety”) review, on an application-by-application basis. The practical impact in terms of limitations on HCFC and HFC usage have been limited. Specific areas impacted are:

- The use of HCFC-141b as a cleaning solvent (replacing CFC-113 and methyl chloroform) was prohibited, with some limited exceptions for a short time period.
- The use of perfluorocarbons as large-scale replacements for either CFCs or HCFCs was restricted.
- While the EPA has been generally supportive of “natural” refrigerants, including hydrocarbons, highly flammable refrigerants have not been approved for automobile air conditioning.

2.3 Allowing Market Forces to Operate to Limit Wasteful Use of HFCs

Policy makers should recognize that another significant restraint on the careless use of HFCs is the inherently higher cost of these materials compared to CFCs and HCFCs. The shift out of chlorinated halocarbons to ones using only fluorine has perforce resulted in a shift from the relatively simple methane based compounds to more complex ethane and propane based compounds, and to larger percentages of high cost fluorine (compared to chlorine) in these compounds. Table 2-3 compares the bulk quantity costs of HC1 and HF and shows that the cost of fluorine is approximately 4 times the cost of chlorine. The impact of the need to synthesize more complex molecules, with specific isomeric arrangements, causes a significant increase in both capital costs and in raw material and other operating costs. According to generally available market data, the useful HFCs as a group cost considerably more than either the CFCs or HCFCs as a group. A couple of generally available example comparisons of wholesale prices to the refrigeration and air conditioning trades are:

- CFC-12 refrigerant at 1.00/lb. wholesale vs. HFC-134a @ \$4.00
- HCFC-22 refrigerant at \$2.00/lb. wholesale vs. HFC-410A at \$8.00

Table 2-3: Fluorochemical Raw Material Prices

Raw Material	Price \$/lb.	\$/kg
CC1 ₄	0.36 - 0.40	0.80 – 0.90
HC1	0.15 – 0.17	0.33 – 0.37
HF	0.50 - 0.70	1.10 – 1.55

Source: Chemical Market Reporter, June 14, 1999

During the first half of the 1990s, CFC-12 was phased-out on an aggressive timetable (Figure 2-4) and a steeply increasing excise tax was also imposed (Section 2.2.2). At the time, there was intense concern whether the phasedown steps that were imposed could be met. In fact, CFC-12 consumption fell farther than the phasedown steps due to the simple disincentive to waste the material that the rapidly increasing excise tax caused, and in spite of an inventory build-up that occurred as the January, 1996 production phase-out date approached.

2.4 Existing Regulations That Prevent Wasteful Use of HFCs.

In the United States and other countries, stringent regimes of “no-vent” regulation have been in place since the early part of this decade. The regulations apply not only to ODS, but also to HFCs. In the U.S., these regulations have been enforced with draconian fines. Specific provisions include:

- Prohibition of deliberately venting refrigerant from a system or from a refrigerant container. As a minimum, recovery of all but a minimal level of residual vapor is

required, and recycling or reclamation are encouraged.

- Operators of some categories of equipment are required to maintain leakage rates below permissible levels
- When automobile air conditioning systems are serviced, the leak tight integrity of the system must be verified prior to recharging the system
- End of life recovery of the refrigerant charge is mandated for most product categories.

2.5 HFC Responsible Use Principles

The US Environmental Protection Agency and the Alliance for Responsible Atmospheric Policy, an industry coalition, announced the following HFC Responsible Use Principles in February 2002. They will establish a worldwide partnership of industry and government that endorse the following principles:

- Select HFCs for applications where they provide health, safety, or environmental, technical or economic advantages, or unique societal benefits
- Minimize HFC emissions to the lowest practical level during manufacture of the chemical, and during use and disposal of equipment using cost-effective technology
- Design and operate HFC-producing plants with the goal of achieving zero HFC emissions
- Engineer, operate and maintain HFC-using systems to minimize emissions and maximize energy efficiency
- Recover, recycle, reclaim and/or destroy used HFCs where technically and economically feasible
- Promote comprehensive technician training in HFC handling to assure compliance with regulations and stewardship practices
- Meet all appropriate regulatory standards governing HFC equipment installation and maintenance, HFC transport and storage, and where applicable exceed such standards with voluntary initiatives
- Accurately report HFC production and promote models, that accurately estimate emissions

2.6 Safety

The comparative (not absolute) safety with which the CFCs could be handled accounts in large part for their rapid acceptance following their introduction in the 1930s and for accelerated market development and public acceptance of a wide range of refrigeration and air conditioning products. The safe handling characteristics are also a major reason for the emergence of CFC applications ranging from solvents to foam blowing agents to aerosol propellants to fire extinguishers.

To a large degree, the major HFCs retain the fire safety and low toxicity features of the CFCs. In fact, the Program for Alternative Fluorocarbon Toxicity (PAFT) toxicity studies have subjected the HFC alternatives to a far more rigorous toxicity evaluation than the earlier CFCs were ever subjected to. In a number of applications, flammable alternatives have been considered, and in some instances, adopted (most prominently German refrigerators with isobutane refrigerant and cyclopentane foam blowing agent). It is clear that flammable substances, generally fuels, can be and are handled with “acceptable safety” throughout a modern industrial economy. Safety standards exist to guide the widespread industrial use, processing, handling, and transportation of flammable liquids and gases. Consumers purchase and handle propane on a large scale for use in soldering torches, backyard barbecues, and camping stoves and lanterns. A high degree of flammability is an *inherent* characteristic of a fuel, but it is *not an inherent characteristic of a refrigerant*. In most cases the associated risks and responsibilities (and benefits) of handling flammable fuels are assumed voluntarily.

In the preceding paragraph, “acceptable safety” was placed in quotation marks to draw attention to the fact that a precise definition of this term is not as obvious as one might think. A basic problem lies with the difference between risks that are accepted voluntarily by individuals and those that individuals are subjected to involuntarily. This difference plays out in the essentially political determination of the “acceptable safety” for a particular activity, in the nature of the safety and performance standards and regulations that apply, and in the likelihood that injuries that result will result in expensive litigation.

The basic point of this is that “safety” and “acceptable safety” are terms that do not have clear-cut definitions and, in essence, is a (perhaps technically informed) political determination. When a comparatively safe material, such as an HFC refrigerant, is replaced with a material having inherent hazards, such as a hydrocarbon refrigerant, the task of providing a comparable safety level is complex and expensive, involving:

- Theoretical risk assessment, design modification, and safety testing
- Working with applicable safety standard setting bodies and regulators for both design guidance and product approval
- Corporate risk management

Even when a manufacturer has made and documented a competent, good faith effort to achieve comparable safety and comply with standards, accidents and resulting injuries can result in costly product recalls and litigation and tort losses whether or not the accident was caused by the use of the more hazardous material. In the product cradle-to-grave spirit of assessing the impacts of HFCs and alternatives, other potential safety issues involved in manufacturing, transporting, installing, field servicing, and disposal need to be recognized.

When an inherently safe HFC is replaced by an inherently hazardous substance, the process of redesigning for safety, any resulting cost increase of the product itself or its manufacturing environment, other cradle-to-grave safety costs, and the exposure to tort losses are all costs that must be borne by the individuals buying and using the product and, in the aggregate, by society as a whole.

A detailed, application area by application area examination of the cradle-to-grave safety issues associated with alternatives to HFCs is well beyond the scope of this study. Where credible estimates of risks and cost are available from other sources, they have been cited and used as part of the estimate of the cost savings provided to society by HFCs, otherwise, the safety issues are identified and discussed qualitatively.

2.7 Environmental and Economic Cost of Managing the Safety Risk

Hydrocarbons and ammonia can be used safely but not in all applications and not in all circumstances. The risks to be managed generally increase with increasing quantity (charge) and proximity to people. The cost of safety required for highly flammable or toxic refrigerants, which may involve system redesign, might be more effectively invested in improved HFC systems.

- Safety remains a fundamental issue when considering the use of alternatives in comparison to HFCs. Using hydrocarbons or ammonia requires additional risks to be managed.
- For many applications complete system design changes would be necessary if HFCs are not used. These generally add cost - the cost of safety, and can lead to lower efficiency and increased energy consumption.
- Utilizing HFC based refrigeration or air-conditioning systems may allow investment in further energy saving measures rather than investing in the mandatory and expensive safety measures required for toxic or highly flammable refrigerants.

3. Value Provided to Society by HFCs

As the phase out of CFCs and HCFCs proceeds, various HFCs have emerged or are emerging as the preferred refrigerant, blowing agent, solvent, aerosol propellant, or fire extinguishant in a wide variety of applications. Many of the applications, such as domestic and commercial refrigeration and air conditioning are pervasive throughout modern society. Others such as solvent cleaning and fire protection address smaller, but critical niches. In those cases where HFCs are the preferred alternative, the reason is that they provide significant cost savings compared to the less cost-effective and, in some cases, poorer performing and/or less safe materials or processes that would be used as alternatives to HFCs.

An *order of magnitude* estimate of the annual cost savings that will be provided to society by HFCs is presented in the following material. The basic approach is to first identify each application where an HFC is the preferred long term, post-HCFC phase-out choice of refrigerant, solvent, blowing agent, aerosol propellant, or fire suppressant. For each of these applications, the most cost-effective (on a comparable safety basis) alternative technology has been identified. The incremental costs (energy, manufacturing investment, equipment) relative to the HFC baseline are estimated and summed across all applications, in the U.S. and on a global basis. The approximate timeframe for this estimate is 2020-2030, after CFCs and HCFCs have been phased out and the long-term choices among non-ODS technology alternatives have been made and have had their full impact.

As indicated above, this exercise provides only an order of magnitude estimate of the societal cost savings attributable to HFCs. The available data for constructing this estimate are quite limited in many instances, so the estimated costs are subject to refinement in a more in-depth study.

3.1 Domestic Refrigeration

Before the CFC phase-out, domestic refrigerators used CFC-12 as the refrigerant and CFC-11 as the foam-blowing agent. Today the industry has generally adopted two sets of replacements:

- HFC-134a refrigerant, either HCFC-141b or a blend of HCFC –141b and HCFC-22 as the foam blowing agent
- Isobutane refrigerant, a blend of cyclopentane and isopentane as the foam blowing agent, primarily in parts of Asia and most of Europe

As discussed in Section 4, the legal and regulatory ramifications of using the hydrocarbon alternatives differ country by country. HCFC-141b will be phased out in the early part of the next decade (January, 2003 in the U.S.). The most likely substitutes for HCFC-141b in the U.S. are HFC-245fa or HFC-134a (with continued use of HFC-

134a as the refrigerant). As discussed in Section 4, the thermal conductivities of HCFC-141b and HFC-245fa blown foam are equivalent, and between 8-10% better than hydrocarbon blown foam. HFC-134a blown foam falls between HFC-245fa and HC blown foams.

Thus, for the purpose of this estimate, it is assumed that the preferred HFC alternative is HFC-134a for the refrigerant and HFC-245fa for the blowing agent. The alternative to these HFCs is the isobutane/cyclopentane refrigerant/blowing agent combination that would be used instead. The cost differences between the two are:

- Costs of manufacturing facility fire safety measures and VOC compliance measures for handling refrigerant and blowing agent. With HFC-134a and HFC-245fa, there are no costs of this type. As discussed in Section 4, the amortized cost of these safety measures, translated into incremental selling prices to the consumer is approximately \$7/unit in the U.S. and \$4/unit on average elsewhere in the world
- Product manufacturing costs (incremental unit costs in addition to the factory safety and VOC compliance measures indicated above) are estimated to add \$15-30 (for explosion-proof components) to the direct manufacturing cost and \$35-70 to the retail price in the U.S. Elsewhere, the impact is assumed to be one-half of this.
- Energy consumption and operating costs – energy consumption levels for the hydrocarbon option would be 10% higher than the HFC option, due to the lower thermal conductivity of HFC blown foam. The annual energy consumption of the HC refrigerator is 50 kWh/yr greater, adding \$4/year to the annual operating cost. Outside the U.S., the energy cost impact is estimated to be half of the impact in the U.S., or \$2/year, based on the smaller size of the average refrigerator outside the U.S.
- Costs of accidents related to the flammable refrigerant and blowing agent. In this analysis, this cost is assumed to be zero, however, it should be noted that there have been at least two related factory incidents causing damage and harm. (One in an Italian plant refrigerant charging station and one in Indonesia involving foam operating fires). It should also be recognized that the defrost heater in no-frost refrigerators is an issue that does not apply to most refrigerators produced outside of the U.S. and Japan. In addition, U.S. manufactures are concerned that even a small number of accidents could result in large financial claims. Product liability insurance costs could increase significantly. In a recent incident in Australia, the hydrocarbon refrigerant charge of a self-contained commercial refrigerator escaped accidentally while the unit was being serviced. The hydrocarbon vapor subsequently ignited and exploded, severely injuring the two service technicians.

Based on the preceding scenario and assumptions, the estimated annual societal cost savings that will be provided by HFCs for domestic refrigerators are estimated to be:

- In the U.S., 12 million refrigerators and freezers manufactured per year x $(\$7+30)/\text{unit} = \440 million per year.
- Additional annual energy cost in the U.S.: 100 million refrigerators x $\$4/\text{year} = \400 million.
- In the rest of the world, 60 million refrigerators and freezers per year x $(\$4+15)/\text{unit} = \$1,140$ million per year.
- Additional annual energy cost in the rest of the world, 500 million refrigerators x $\$2/\text{year} = \$1,000$ million.

3.2 Automobile Air Conditioning

Having replaced CFC-12 when it was phased out at the beginning of 1996, the HFC-134a vapor compression cycle has already emerged in full, global scale mass production, as the preferred long-term technology for mobile air conditioning. As discussed in Section 5, the most likely alternative to this technology is the transcritical CO_2 vapor cycle. Hydrocarbon vapor cycle still has significant, unresolved fire safety issues. As discussed in Section 5, even with the hydrocarbon refrigerant confined to the engine compartment (with a secondary coolant used to connect the cooling capacity to the interior), the possibility of an unacceptably large number of engine compartment fires cannot be ignored or dismissed. To date, no comprehensive program of design, risk analysis, and collision testing has been carried out to validate a fire-safe hydrocarbon air conditioning system design.

As discussed in Section 5, transcritical CO_2 does not have an LCCP advantage over current HFC-134a based mobile air conditioners. But costs to consumers would be substantially higher. Incremental costs to consumers fall into two basic categories:

- Operating costs
 - Incremental fuel consumption, due to the inherently lower efficiency of transcritical CO_2 . The impact varies with climate, but on average in the U.S. a CO_2 air conditioner would consume $(2325-1401)/11 = 84$ liter/year (see Table 5-3) of additional gasoline. At current gasoline prices of $\$0.30/\text{liter}$ in the U.S., the average additional cost would be $\$25/\text{year}$. In Europe and Japan, the additional fuel use is about half, but the retail price of gasoline is about double, so the

incremental cost to consumers would be about the same.

- CO₂ systems are likely to require more frequent recharges, given the much higher system pressure driving leakage and the smaller CO₂ molecule resisting leakage. The guestimated impact is an average of \$10/year in additional servicing costs.
- Increased vehicle-selling prices due to the higher manufacturing cost of the transcritical CO₂ system. Industry estimates are that a CO₂ system would be 15-20% higher in manufacturing cost translating into an additional \$100 per air-conditioned car at retail.

Table 3-1 summarizes the increased costs on an annual basis.

Table 3-1: Increased Annual Cost to Consumers to Use Transcritical CO₂ Automobile Air Conditioning Instead of HFC-134a Based A/C

	Increased Costs		Quantity Of Cars w/AC		Cost U.S.
	First Cost	Operating	Annual Sales	Total in Service	
U.S.	\$100		15 million		\$1.5 billion
		\$35		150 million	\$5.3 billion
Global (Outside the U.S.)	\$100		20 million		2 billion
		\$35		200 million	7 billion
Total	-	-	-	-	15.8 billion

3.3 Unitary Air Conditioning

HCFC-22 has been the refrigerant used in virtually all-unitary air conditioning equipment. As developed countries implement the Montreal Protocol HCFC phase-out, R-22 will not be produced for use in new equipment in the United States, beginning 2010. Table 3-2 outlines the preferred HFC alternatives and likely non-fluorocarbon fall-back technology, for residential and commercial applications.

Table 3-2: Unitary Technology Alternatives

Unitary Category	HFC Alternative to HCFC-22	Non-fluorochemical fall-back technology
Residential Central	407C/410A	Propane chiller/Indoor fan coil
Small Commercial Rooftop	134a/407C/410A	Propane chiller/AHU
Large Commercial Rooftop	134a/407C/410A	Ammonia chiller/AHU
Ductless Split	407C/410A	Propane chiller/Indoor fan coil
Room A/C (Window)	407C/410A	Propane chiller/Indoor fan coil

The basic assumption is that in the smaller capacity product categories, propane refrigerant with welded-hermetic compressors would be the preferred technology.

These small chillers would be factory assembled and charged. Large commercial unitary would more likely end up using ammonia screw chillers in conjunction with an air handling unit.

The impact on the cost of residential air conditioning is estimated assuming that energy-efficiency standards would dictate equal energy in either case, so that the inherent efficiency disadvantage of a secondary loop would be made up by increased heat exchanger capacity, further adding to the cost. The estimated cost increase is:

- The increased cost of the air conditioning equipment (30%, by industry estimates, TEWI-3) approximately \$600 for every residential central air conditioner sold (currently 6 million units per year) to address safety considerations.
- Increased product cost to achieve equal energy consumption – is comparable to the difference in price between a 14 SEER and a 12 SEER system, approximately \$500.
- No attempt has been made to estimate the impact on maintenance and repair costs.

Table 3-3: Cost Savings Provided by HFCs for Residential Central Air Conditioning in the U.S.

Cost Element	Annual Units	Unit Cost	Cost
Product Cost-Safety	6 million	\$600	\$3.6 billion
Product Cost-Energy	6 million	\$500	\$3.0 billion
Total			\$6.6 billion

3.4 Chillers

The focus is on large chiller applications, primarily centrifugal and screw. If HFCs were banned, open-drive screw chillers with ammonia would be the only practical alternative. The incremental costs associated with this situation would be:

- Costs to address safety issues, primarily special equipment room features – emergency ventilation, vapor monitoring and alarms. The costs of addressing the many local and natural code issues is neglected here, but the issues are real, nonetheless
- Higher chiller equipment cost, balanced somewhat by lower refrigerant cost, an estimated net impact of \$100/ton for 350 ton chillers and \$50/ton for 1000 ton chillers
- Higher energy consumption and costs compared to state of the art screw or centrifugal. Taking chillers in Atlanta as representative, annual electric power

consumption would increase by 40,000 kWh for a 350 ton chiller and by 300,000 kWh for a 1000 ton chiller

Table 3-4 summarizes the cost savings that will result from using HFCs, instead of less cost-effective alternatives, to replace HCFCs in chiller applications (\$0.07/kWh assumed commercial electric rate).

Table 3-4: Costs Savings Provided by HFCs in Large Chillers in the United States

Size Range	Cost Item	Annual Units	Annual Cost/Unit	Cost All Units
350 ton	Equipment	2000	\$35,000	\$70 million
	Safety installation	2000	10,000	20 million
	Energy	30,000	2,800	84 million
1,000 ton	Equipment	2000	50,000	100 million
	Safety installation	2000	10,000	20 million
	Energy	30,000	21,000	630 million
Total				\$925 million

3.5 Commercial Refrigeration

In supermarkets, the common configuration of central, rack-mounted compressors and cold cases with direct expansion evaporators requires a safe - nonflammable, nontoxic - refrigerant. After the CFC and HCFC phaseouts are complete, several HFC refrigerants meet this need will satisfactorily.

- For low temperature, R404A and R507
- For medium temperature, R410A, and the two that are suitable for low temperature (and HFC-134a, though rarely applied due to the high compressor displacements required)

With these HFCs, supermarkets can choose from the direct expansion, distributed system, and secondary loop configurations. The alternative to this range of HFC options would be a secondary loop system with a central ammonia refrigeration system, assuming that the myriad local code restrictions limiting the use of ammonia refrigeration in urban areas were addressed.

Incrementally higher costs would be incurred in several areas:

- Costs of safety in the mechanical equipment room-ammonia vapor detectors, alarms, and emergency ventilation, together adding about \$10,000 to the installed cost of a supermarket refrigeration system. (Not accounting for the potential cost of an operating engineer when codes so require)

- Additional hardware costs of the secondary loop--fluid circulation pumps, fluid reservoirs, the secondary fluid itself, the refrigerant evaporator to chill the secondary fluid. Together, these components will add about \$50,000 to the installed cost of a supermarket system
- Increased energy consumption – based on the energy analysis in Section 8, the annual electric energy consumption of the average supermarket will increase by 200,000 kWh. The increased energy is attributable to the heat transfer temperature difference between the central refrigeration system evaporators and the secondary loops and pumping power in the secondary loops

The total of these costs in the U.S. is calculated in Table 3-5. There are 30,000 supermarkets in the U.S. and a total of 4,000 supermarkets are built or remodeled each year.

Table 3-5: Societal Cost Savings Provided in the U.S. by HFCs for Commercial Refrigeration

Cost Category	No. of Supermarkets Affected Annually	Cost in U.S. \$	
		Per Store	Total
Safety Measures	4,000	10,000	40 million
Secondary Loop	4,000	50,000	200 million
Increased Energy	30,000	14,000	420 million
Total	-	-	660 million

The costs that would be incurred throughout the rest of the developed world would be similar in magnitude.

3.6 Foam Building Insulation

Every year, foam building insulation saves substantial amounts of energy, and the cost of this energy, world wide. As the ozone-depleting blowing agents are phased out, HFC blowing agents (compared to other non-ozone depleting options such as hydrocarbons and CO₂) will contribute to the cost effectiveness of insulating foams in the following ways:

- Higher R-values, providing increased energy savings with a given thickness of foam, particularly important in thickness constrained applications
- In some applications where fire safety considerations are important, e.g., SPF roof insulation, non-flammable HFC blowing agents will be the most cost-effective alternative

A detailed analysis was beyond the scope of this study; annual savings in the 2020-2030 timeframe attributable to HFC blowing agents in foam are estimated to be \$1 billion in the U.S. and \$2 billion worldwide.

3.7 Solvents

The HFC solvents that have emerged – HFC-43-10 mee and HFC-365mfc – are both either expensive or are being used in blends with higher priced solvents, only in applications where the need for the balance of properties provided by these solvents justifies both the high cost of the solvent and the investment in equipment that provides a high degree of containment. The cleaning applications involved are diverse, so it is difficult to quantify the cost savings delivered by this class of solvents to the market. Qualitatively, it can be stated that these HFC solvents that have emerged as replacements for CFC-113 are used to clean parts whose value is many orders of magnitude greater than the cost of the HFC solvents themselves and the critical cleaning and drying achieved through their use is essential to the performance of these components.

3.8 Aerosols

In terms of assessing the value to society of HFCs as aerosol propellants, the range of aerosol applications include applications such as metered dose inhalers where it is difficult to place an adequate value on the health benefit, along with numerous diverse, specialized niche applications where data to quantitatively assess the value is difficult to develop. In section 11 of this report, the social utility of HFC based aerosols is discussed in considerable detail. In summary form, some of the key points are:

Medical Aerosols

Metered dose inhalers (MDIs) require a non-flammable, low toxicity propellant, of which HFCs-134a and 227ea are the only available aerosol propellant alternatives to CFCs, are the mainstay treatment method for asthma and other respiratory illnesses. Millions of patients across the world rely on these lifesaving drug delivery systems. The value, both to these individuals, their families, and to society at large, in terms of quality of life, workplace productivity, and prolonging life is incalculable in monetary terms, but is extremely high.

Other Aerosols

Dusters, freeze sprays, electronic cleaning sprays, and mold release sprays help provide critical product quality and productivity. HFC propellants improve the functional performance and eliminate potential fire hazards, increasing workplace safety for the individuals involved

Tire inflators can significantly reduce both the nature and duration of exposure to roadside danger associated with a flat tire.

3.9 Fire Protection

Insufficient data is available on the diverse installations of HFC based fire protection equipment to generate even an order of magnitude estimate of the economic value of these systems. These systems not only provide for personnel safety, they help to avoid business downtime and to avoid interruption of important emergency and defense services such as air traffic control.

4. Domestic Refrigeration

Household refrigerator/freezers are the most popular major appliance in the world. Because they are located in the kitchen, refrigerators are the most visible major appliance. As a result, many global environmental issues related to refrigerants and energy efficiency are illustrated through examples using household refrigerators.

Putting the global warming and ozone depletion issues into scientific perspective as they relate to refrigerators, however, produces a different relationship than the public may perceive between household appliances and these issues of international concern. The amount of CFC's used by household refrigerators was less than 2% of all CFC's used worldwide before the 1996 phaseout took place. After this phaseout of CFC's in non-article 5 (developed) countries, 75% of all CFC uses were eliminated with not-in-kind technologies. Less than 2% of all global warming gases covered under the Kyoto Protocol are fluorocarbons that replaced CFC's.

The energy consumed by household refrigerators is less than 2% of all energy consumed in the US. In spite of the relatively small impact these household products have on the global environment, appliance manufacturers worldwide are committed to further reducing this impact, both in terms of the ozone depletion of the refrigerants and foams incorporated into designs and the energy consumed to maintain a safe food supply.

4.1 Decision to Replace CFC's

The decision to replace CFC's in all products worldwide was made under the Montreal Protocol and in the United States under the Clean Air Act. In all developed countries, household refrigerators were redesigned to perform without CFC's by the end of 1996. In the US, as in many other countries in the developed world, this redesign was undertaken by assessing the replacements for CFC's in terms of product performance, ozone depletion, global warming, toxicity, flammability, economics, and energy efficiency. These undertakings resulted in several different solutions globally.

Fluorocarbons play two roles in home refrigerators – refrigerant and foam insulation blowing agent. Table 4-1 summarizes the progression that has occurred in the choice of the typical refrigerant and blowing agent, as the phase out of ODS's continues.

Table 4-1: Refrigerant and Foam Blowing Agent Alternatives and Not-in-Kind Technology Alternatives for Home Refrigerators

Function (Timeframe)*	Pre-Montreal Protocol (before 1996)	Transitional (1996-2005)	Non-Ozone Depleting (2003 and beyond)
Refrigerant	CFC-12	HFC-134a Isobutane	HFC-134a Isobutane
Blowing Agent	CFC-11	HCFC-141b Cyclopentane HFC-134a HCFC-22	HFC-134a HFC-245fa Cyclopentane Pentane

*Timeframe in the developed countries

4.1.1 US

The US appliance industry was guided in its effort to replace CFC's by the US Environmental Protection Agency's (EPA) Clean Air Act regulations. The Significant New Alternatives Program (SNAP) approves chemicals and technologies that can be used to replace ozone depleting chemicals. The SNAP regulations were influenced by US Department of Energy (DOE) regulations relating to the impact of the energy efficiency of each CFC replacement. The direct global warming of each replacement chemical was noted as well.

The SNAP list of approved CFC replacements is a result of EPA's analysis of all CFC and HCFC alternatives relative to their ozone depletion, safety (toxicity and flammability), global warming, and energy efficiency, among other factors. The SNAP list includes fluorocarbon, hydrocarbon, and several not-in-kind technologies. Most of the US appliance industry has adopted fluorocarbon replacements for CFC's.

4.1.2 Europe

Efforts to replace CFC's in Europe were most heavily influenced by the direct global warming impact of each replacement chemical. This impact was especially prevalent in Northern Europe. Subsequently, hydrocarbon technologies were the predominant chemical used to replace CFC's in Northern Europe. Companies manufacturing household refrigerators in Southern Europe have adopted a mix of solutions to the problem of CFC replacement. Many companies in this region use a fluorocarbon refrigerant (HFC-134a) and a hydrocarbon foam-blowing agent (cyclopentane and mixtures with n-pentane).

4.1.3 Japan

Japanese manufacturers have utilized all of the refrigerant and blowing agent options. HFC-134a has predominated as the primary refrigerant option, but isobutane has been utilized as well. In 2000, approximately 40% of Japanese refrigerator production used HFC-141b blown foam and 60% used hydrocarbon blown foam. Both HFC and HC blowing agents are being considered for replacing HCFC-141b.

4.1.4 Developing Countries

Developing countries have followed several basic routes thus far in addressing CFC use in household refrigerator designs. Many nations have developed full fluorocarbon designs while others have incorporated hydrocarbons fully or partially into their products. The last route is to continue to use CFC's because of economic considerations and uncertainty caused by criticism of fluorocarbon technologies, and the high cost and safety issues associated with hydrocarbons.

4.2 Basis for These Decisions

The basis for these decisions is dependent on a number of complex variables. Assessments take into account aspects such as the basic design, government regulations, manufacturability, corporate and regulatory safety requirements, energy efficiency, international regulations, workplace safety, warehousing, transportation, consumer usage, service, and disposal procedures.

4.2.1 Design

The US appliance industry redesigned household refrigerators without CFC's after accounting for national and international regulatory requirements. The US consuming public is accustomed to large, auto-defrost refrigerators that perform for twenty years or more without significant service. The goal of US manufacturers was to replace CFC's in household refrigerators without changing the performance expectations of the American consumer, therefore, the transition needed to be transparent. Fluorocarbons provided this advantage.

4.2.1.1 Refrigerant Options

The refrigerants that have been used to replace CFC-12 in domestic refrigerators are HFC-134a and isobutane. As indicated in Table 4-1, the Montreal Protocol phase-out of CFC-12 resulted in the adoption of non-ozone depleting HFC-134a in much of the world and of non-ozone depleting isobutane (HC-600a) in parts of Europe, particularly Germany.

A detailed discussion of the design and manufacturing factors that need to be considered when replacing CFC-12 with HFC-134a or isobutane is contained in [UNEP, 1998, Section 3]. The key considerations for applying HFC-134a and isobutane are:

- To replace CFC-12 with HFC-134a, a small increase (~18%) in compressor displacement was required and the compressor lubricant was changed from mineral oil to a synthetic, polyolester (POE) lubricant. Other material compatibility considerations were addressed – e.g., XH7 or XH9 mole sieve dryer instead of XH6 typically used with CFC-12, and motor insulation material. In production, better control of both moisture and overall internal refrigeration system cleanliness is required, due to the hygroscopic nature of POE lubricants and the detergency of POE lubricants. Various oils and waxes that have been used as cutting fluids, motor winding lubricants, and drawing lubricants in system component fabrication are not soluble with HFC-134a, so their use should be avoided. HFC-134a is chemically stable in a sealed refrigeration system. When moisture is controlled to allowable levels, the HFC-134a charge will last for the life of the refrigerator. Manufacturers have implemented the necessary process procedures to maintain low moisture and contamination levels, which has resulted in improved reliability in the field, compared to earlier, CFC-12 based units. While these issues are not technically complex, they must be addressed in a competent manufacturing operation.

- To replace CFC-12 with isobutane requires nearly twice (80% larger) the compressor displacement. Lubricant, material compatibility issues, and historic cleanliness practices that have been applied to CFC-12 are all suitable for isobutane. Both HFC and HC servicing and manufacturing requires care in this regard, but it is not difficult.
- The flammability of isobutane typically requires that the product is configured so that electrical components are isolated from areas with potential refrigerant leaks. In no-frost designs, the design of the defrost heater must preclude it becoming an ignition source. In manufacturing, flammable vapor safe charging and repair stations are needed – among other things, hydrocarbon vapor monitoring, proper ventilation, and explosion proof factory electrical systems are needed. Instead of brazing operations to seal charged systems, lock ring joints are used. The small charge size requires higher precision charging equipment.

4.2.1.2 Wall Insulation

As indicated in Table 4-1, the Montreal Protocol phase-out of CFC-11 foam blowing agent was followed by the widespread use of HCFC-141b and cyclopentane. HCFC-141b has one of the higher ODP values among the transitional alternatives; in the U.S. and Japan it has been put on an earlier phase-out schedule than other transitional alternatives. The non-ozone depleting alternatives include several HFCs, as well as pentane and cyclopentane. Foam blowing agents like nitrogen and carbon dioxide result in much higher foam thermal conductivities, and while they are used in other foam applications, are not serious candidates for this application.

In qualitative terms, production foaming equipment for manufacturing home refrigerators is readily available for both HFC and hydrocarbon blowing agents. Cyclopentane foaming systems are already fully operational with necessary fire safety provisions – extra ventilation, explosion-proof electricals, and hydrocarbon vapor monitors – included and adding to the capital cost (note that for application in the US additional features along with VOC emission controls would be required; European VOC regulations are just coming into play). The changeover from HCFC-141b to alternatives is currently in process, and will be complete in the U.S. by January 1, 2003. The HFC blowing agents with the best thermal performance (e.g., HFC-245fa, HFC-365mfc) result in foams having thermal conductivity comparable to HCFC-141b foams and about 10% lower than cyclopentane blown foam [AHAM Research Consortium results].

Vacuum panel insulation has attracted considerable technical interest over the past decade, and has been developed with a variety of fillers and envelope materials. However, the reality is that vacuum panels require tight quality control and are one of the least cost-effective refrigerator design options for energy efficiency. Furthermore, their reliability has not been demonstrated. Foam insulation is required in conjunction with vacuum panels for structural integrity of the cabinet. Vacuum panels are not a viable foam replacement option for refrigerators produced worldwide and have not been considered in this study.

4.2.1.3 Systems Design

Refrigerators differ considerably in design as well as function in different regions of the world. The predominant design in Europe is about a 10 cubic foot manual defrost all-refrigerator unit popular in a culture where everyday market visits are commonplace. Weekly or bimonthly grocery shopping in the US has resulted in the most common design being 18 to 22 cubic foot automatic defrost refrigerator/freezers. The European designs have fewer internal electricals to contend with in their decision to utilize a small hydrocarbon charge. The US designs have numerous electrical components, and, because of their large size, would require a larger hydrocarbon refrigerant charge. Therefore, zero ozone depleting HFC-134a was chosen as a CFC replacement refrigerant.

4.2.1.4 Energy Efficiency

As discussed below, approaches to energy efficiency vary from country to country, as do the product configurations that meet the preferences and resources of consumers in those countries. The U.S. has had a system of mandatory energy efficiency standards in place for more than two decades. Refrigerator standards went into effect in 1990, 1993 with the latest revision going into effect in July 2001. Europe introduced its first energy standards in 1999..

Foam aging has an impact on the lifetime average energy consumption of any refrigerator using plastic and foam wall insulation. Due to foam aging (the gradual diffusion of the blowing agent out of the foam and/or the diffusion of air into the foam), the thermal conductivity of the foam increases over time. As a result, the cabinet heat leak increases over time.

Figure 4-1 [from Johnson, 2000] summarizes energy test data over time for full-size, functional refrigerators with several different foam blowing agents. The energy consumption increases, but at different rates for each blowing agent. HFC-245fa foam exhibits the *most gradual* increase in energy consumption. Figure 4-2, from Wilkes, compares the change of thermal conductivity of foam panels blown with different blowing agents versus time. Consistent with Figure 4-1, HFC-245fa foam thermal conductivity increased more slowly than any of the other foams tested. HFC-245fa foam conductivity increased at only half the rate of conductivity increase of cyclopentane foam.

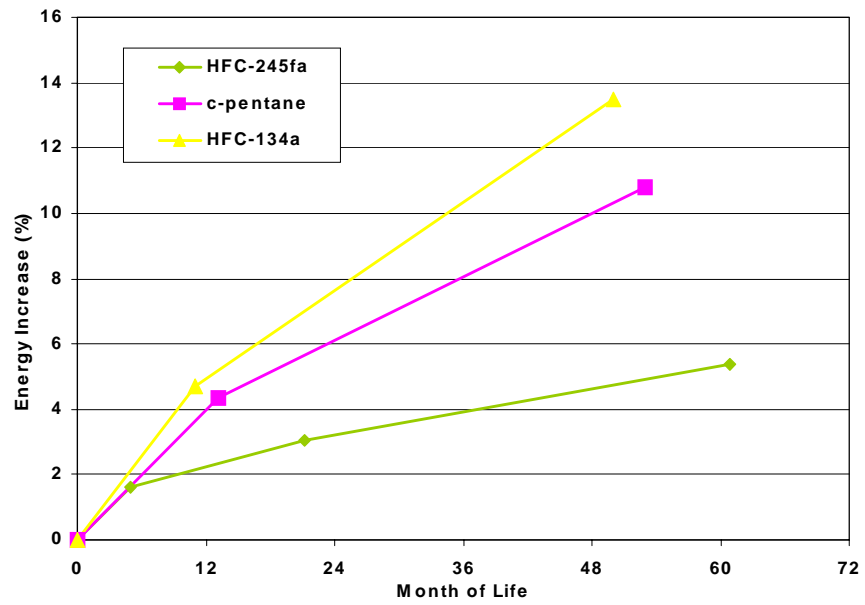


Figure 4.1: Comparison of Foam Aging – Effect of Aging on Refrigerator Energy Consumption [From Johnson, 2000]

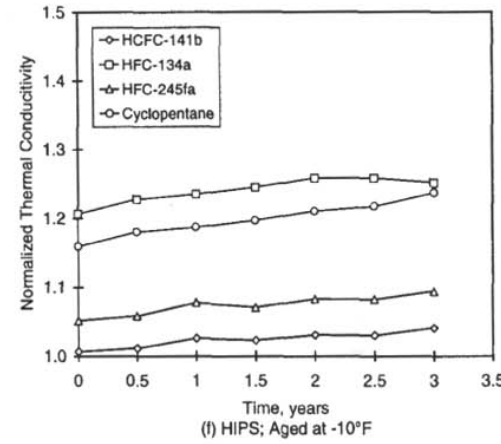
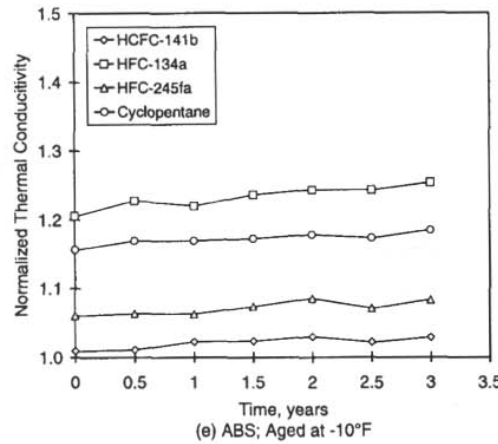
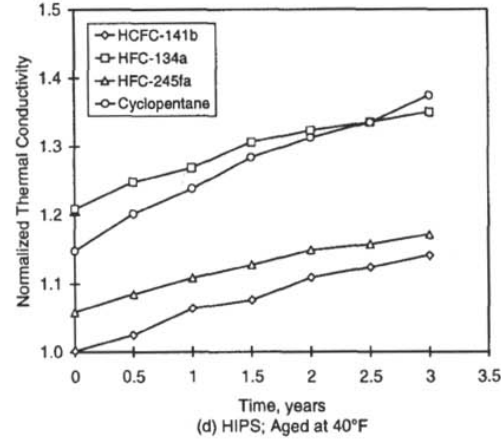
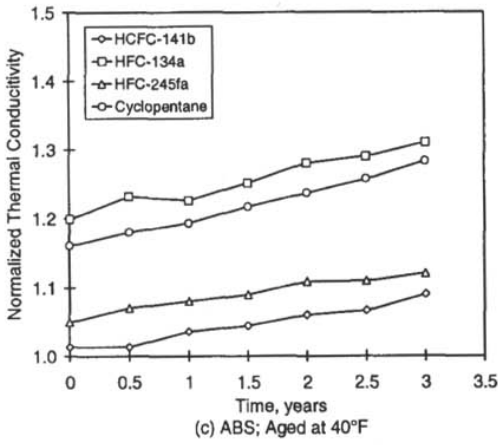
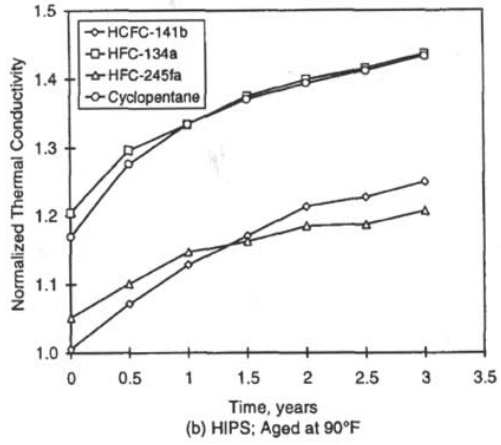
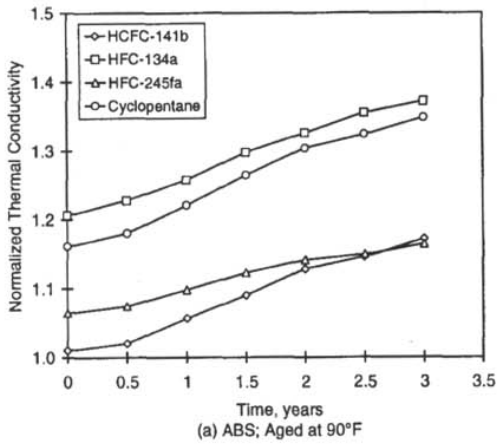


Figure 4.2: Comparison of Foam Aging – Effect of Aging on Foam Thermal Conductivity [From Wilkes, 2001]

4.2.1.4.1 US Requirements

In the U.S., the National Appliance Energy Conservation Act (NAECA) sets maximum energy consumption levels of home refrigerators and other domestic appliances. In July, 2001 a new energy efficiency standards level took effect, requiring, on average, a 30% reduction in energy consumption from the standard levels which had been in effect since January, 1993. Prior to July, 2001, the allowable energy of a typical 18 cubic foot no-frost, top freezer model (with a 4.5 cu. ft. freezer), was 688 kWh/year (1.89 kWh/day). In 2001, the allowable energy consumption for this prototypical refrigerator was reduced to 480 kWh/year (1.32 kWh/day).

4.2.1.4.2 International Requirements

The US rulemaking process that is followed under NAECA requires that the standard level is economically feasible, that is, cost-effective to the consumer. The July 1, 2001 standard levels were set with the assumption that HFC-245fa or an equivalent chemical, which provides comparable insulating performance to HCFC-141b, would be available as a foam-blowing agent. If HFC-245fa had not emerged as a realistic option during the rulemaking, alternate standard levels 10% higher would probably have been included in the final rule for HCFC-free refrigerators [Federal Register, April 28, 1997]. Thus, if hydrocarbons were the only available blowing agent, maximum energy consumption levels would have been set 10% higher. For the typical 18 cubic foot refrigerator, the resulting maximum energy consumption standard would have been 528 kWh/yr, instead of 480 kWh/year.

The international community has undertaken energy efficiency mandates for home appliances in a similar fashion to the current US regulations. The EU has mandatory energy efficiency requirements for refrigerators that took effect on September 1, 1999. These regulations are currently under review for more stringent efficiency levels in the years 2005-2006.

Canada and Mexico have identical energy efficiency regulations as the US for refrigerators sold in their countries. Japan is developing mandatory regulations for refrigerator efficiency as part of their country's commitment to the Kyoto Protocol. Many other countries are considering voluntary and mandatory energy efficiency requirements for household refrigerator/freezers.

4.2.1.4.3 Developing Countries' Limited Resources

As developing countries improve their quality of living, refrigerators become more desirable in homes. One third of all the food in developing countries goes to waste because of a lack of refrigeration. The increased usage of household refrigeration is placing a demand on limited resources in developing countries. Efficient refrigerator designs are going to be a critical aspect to the successful incorporation of home refrigeration in developing countries.

4.2.1.5 Warming Impact of Refrigerant Selection

In North American products, refrigerator designs are subject to a trade-off between manufacturing cost and energy efficiency. The design measures that could reduce energy consumption – more efficient compressors, fan motors, larger heat exchangers, thicker walls, etc. – add to the total product cost. It is noteworthy that the energy efficiency of HFC-134a versus isobutane is not significantly different, while the refrigerator thermal-mechanical design is otherwise similar. However, the U.S. appliance industry has estimated that the *safety measures* needed to use isobutane in a U.S. style refrigerator would add \$15 to \$30 to the direct manufacturing cost, which could result in a retail price increase between \$35-\$70. The rationale for mandating the use of isobutane would be in its lower direct global warming potential. However, when 90% of the original refrigerant charge is recovered at the end of the product life, the direct warming impact is considerably reduced:

- Only 10% of a typical 5 ounce refrigerant charge (14 grams) is actually emitted to the atmosphere
- For HFC-134a, the warming impact of 0.014 Kg of emitted refrigerant is only 19 Kg of CO₂ equivalent (based on a GWP for HFC-134a of 1313). In the U.S., 29 kWh of electric energy consumption is the same as the emission of 19 Kg of CO₂. Therefore, over the 20 year life of a refrigerator, a decrease in energy consumption of 0.3% will be equivalent to the HFC-134a lost in a products' lifetime.
- The U.S. appliance industry estimated that a 1% reduction in energy adds \$3 to direct manufacturing cost, so the cost of a 0.3% efficiency improvement could be approximately \$2 at retail, if these costs are passed through.

In other words, it is 30 times more cost effective to gain this incremental improvement in warming impact through a small improvement in energy efficiency than changing to isobutane refrigerant.

4.2.1.6 Warming Impact of Foam Blowing Agent Selection

The LCCP impact of a refrigerator consists of the indirect warming impact of the energy consumption and the direct warming impact of any refrigerant and blowing agent that is actually emitted over the complete life cycle of the refrigerator. Only the refrigerant and blowing agent that is actually emitted to the atmosphere has a warming impact. With current practices, refrigerant is charged into new refrigerators with negligible losses to the atmosphere and is contained throughout the life of the refrigerator. End of life refrigerant recovery is mandated, with only a small portion of the charge lost to atmosphere during the recovery process. Therefore, less than 10% of the refrigerant charge is actually emitted to the atmosphere.

Regarding the foam blowing agent direct emissions, after a small loss during foaming, the foam blowing agent is contained with the closed cells of the foam and by the inner liner and outer wrapper (outer sheet metal skin). Over time, blowing agent gradually

diffuses out of the foam. At the end of the useful life of the refrigerator, options for disposal include land filling, shredding and land filling, or incineration. Initial research [Kjeldsen and Scheutz, 2002] indicates that less than 25% of the blowing agent may be released upon shredding and before being land filled. Once the foam has been land filled, diffusion to the atmosphere is very slow. Moreover, recent laboratory and field studies [Scheutz and Kjeldsen, 2002] indicate that microbes in the soil breakdown a variety of fluorchemicals such as CFC 11 and 12 and HCFC-22, further reducing the amount emitted to the atmosphere. Additional research is being conducted to determine the extent to which these microbes also breakdown HFC blowing agents such as HFC-245fa.

The TEWI of a 22 cubic foot side-by-side refrigerator-freezer that meets the July, 2001 U.S. energy standards was analyzed by [Johnson, 2000], for three different combinations of refrigerant and blowing agent alternatives as follows:

- Isobutane refrigerant with HC foam
- HFC -134a refrigerant with 134a foam
- HFC-134a refrigerant with 245fa foam (assumed 10% lower energy consumption than the above 2 combinations). Note that recently reported data on the insulating performance of HFC-134a blown foam formulations shows improved insulating performance and reduced energy penalties, ranging from 4% to 7% versus HFC-245fa blown foam [Gurechi, 1998].

Refrigerant and blowing agent emissions, in terms of the initial charge of each, were assumed by Johnson to be:

- Refrigerant
 - 80% of original charge recovered at end of life ,i.e., lifetime emissions of 20% of the original charge (as stated previously, only 10% of the original charge is actually emitted to the atmosphere, but for conservative purposes, 20% was assumed in this analysis)
- Blowing agent
 - Up to 5% loss during production
 - ½% per year loss while in service (based on measurements of blowing agent remaining in refrigerator foam after 17 years of use)
 - At disposal, 50% of blowing agent destroyed, the remainder lost to atmosphere (again, a conservative estimate used by Johnson, compared to results published by Kjeldsen as noted above)

Figure 4-3 compares the TEWI over time, based on these assumptions, for the 3 combinations of refrigerant and blowing agents described above. Based on the recently reported improved insulating performance with HFC134a blowing agent, the TEWI plot for HFC-134a would fall between the plots for hydrocarbons and for HFC-245fa. Energy is the predominant contribution to the TEWI for all three blowing agent options, as shown by Figure 4-4.

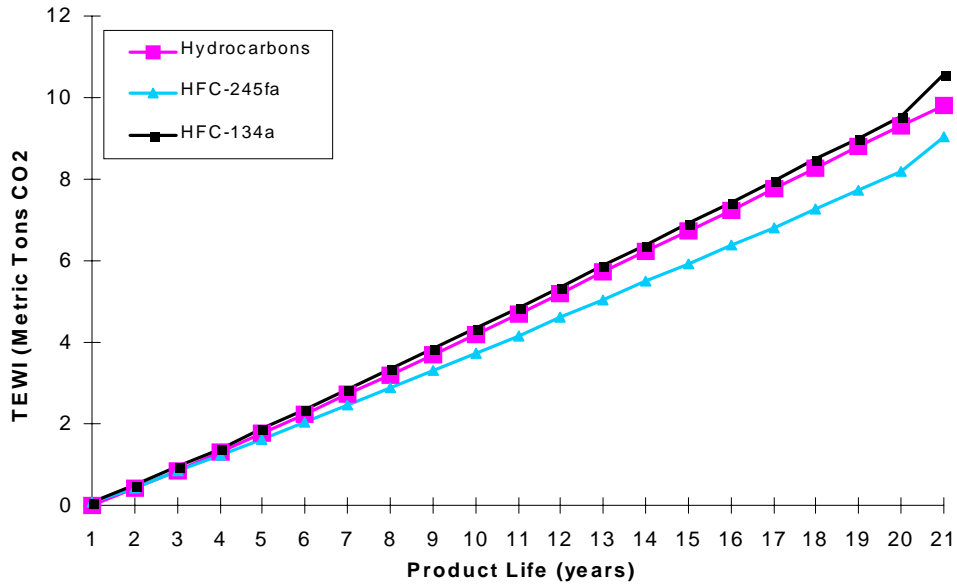


Figure 4-3: TEWI Over Time for Domestic Refrigerator in the U.S.

The results from an LCCP perspective demonstrate that HFC and HC options are essentially equivalent. Figure 4-4 shows that in the U.S., the direct effect from loss of blowing agent and refrigerant accounts for less than 10% of the total warming impact., making it clear that it is more important to work on energy consumption

Refrigerator TEWI Contributors (Typical for HFC product in USA)

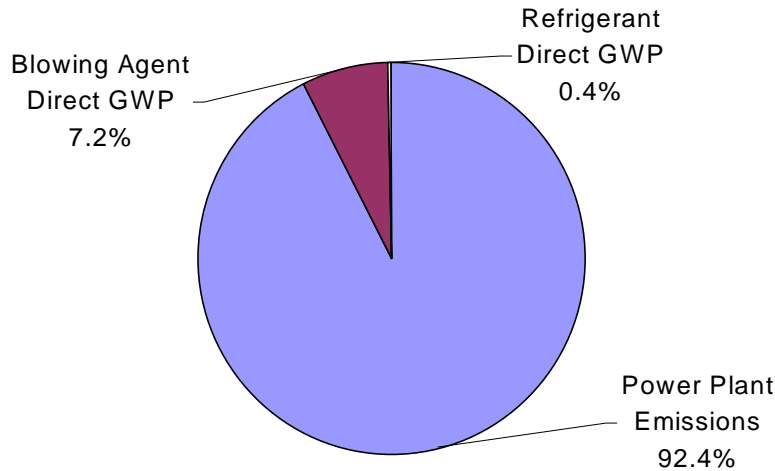


Figure 4-4: Breakdown of Energy, Refrigerant, and Blowing Agent Contributions to the TEWI of an HFC Based Domestic Refrigerator in the U.S.

4.2.2 Manufacture

Home refrigerators are mass-produced at high rates, with extensive automation throughout. The remarkably low prices paid by consumers are due largely to the continuing innovations in manufacturing processes that have been developed by the manufacturers. The impact of refrigerant and blowing agent on manufacturing process requirements is an important factor in the choice of refrigerants. HFC refrigerants with POE lubricants have imposed a new level of system cleanliness and moisture control requirements, while use of hydrocarbons requires that fire safety and local air pollution (VOC) regulations be met.

4.2.2.1 Workplace Safety

In the manufacturing environment, several specific safety measures must be taken:

- For cyclopentane or pentane foam, fixture ventilation, explosion proof electricals, hydrocarbon vapor concentration monitoring and alarms and emergency ventilation are among the safety measures that are needed to ensure a fire-safe, explosion-safe operation. An estimate of the additional capital cost of these safety measures for the U.S. appliance industry, with a total capacity of approximately ten million refrigerators per year, is \$250 million [Johnson, 1999].
- For isobutane refrigerant, the evacuation and charging stations require explosion proof electricals, hydrocarbon vapor monitors and alarms, and emergency ventilation.

No industry-wide estimate of these costs has been prepared, but the costs across the industry would be substantial.

Beyond the manufacturing environment, the costs of safety include the liability from potential accidents, a cost that will be reflected in the product liability insurance premiums paid by the manufacturers. No publicly available data exists to estimate the magnitude of this cost and risk, but in the U.S. legal environment the impact would be significant.

4.2.2.2 VOC Mandates

HFC-134a and the HFC foam blowing agents are exempt from volatile organic compound (VOC) emission regulations because they are sufficiently stable that they do not enter into the photochemical reactions involved in the formation of “smog” and ground level ozone. Both isobutane and the pentanes are subject to US VOC regulations. Depending on plant location and applicable local regulations, the small amounts of isobutane refrigerant that escapes during changing and of cyclopentane blowing agent that escapes during foaming must be captured by appropriate pollution control equipment, adding to the investment and operating costs of the manufacturing operation.

4.2.3 Warehousing and Transportation

With hydrocarbon refrigerants and blowing agents, warehousing and transportation arrangements must take the possibility of refrigerant leaks and outgassing of flammable blowing agents into account. No significant hazards exist with HFCs in this area.

4.2.4 Consumer Usage

4.2.4.1 Market Size

Worldwide production of household refrigerators reaches 65 million annually. Virtually all of the households in developed countries have a refrigerator with an approximate worldwide saturation of fifty percent. With this large number of refrigerators in service, even seemingly minor safety risks must be accommodated.

4.2.4.2 Safety

With HFC refrigerants and blowing agents, there is no significant consumer safety issue. HFCs are non-flammable and the refrigerant charge size is small in relationship to the room size and safe exposure levels. Specific design measures are required to address consumer fire safety issues with a hydrocarbon refrigerant. In European style refrigerators with cold-wall evaporators, double-wall construction is used, so a thick (2 mm) layer of the plastic inner liner material protects the evaporator. A potential danger that this addresses is puncturing the evaporator with an ice pick or other sharp object during manual defrosting. HC refrigerant charges must be limited to a small enough size so a hydrocarbon vapor concentration from a sudden release into a small kitchen will be well below the lower flammable limit.

4.2.5 Service

Modern refrigerators are highly reliable. On average in the U.S., approximately 1.5% of refrigerators require service of the sealed refrigeration system in the field over the product's lifetime. American consumers tend to dispose of refrigerators after 15-20 years, generally before enough deterioration has accumulated to cause any systems failures. American consumers also enjoy an electric power supply system that has ample capacity, with "brownout" conditions of low voltage occurring infrequently. The same is generally the case in other developed countries. Nevertheless, 1.5 percent of refrigerator sealed systems do require servicing during their lifetime, and the service technician must consider the characteristics of refrigerants being utilized.

In developing countries, the frequent occurrence of low voltage conditions leads to compressor motor burnouts. Refrigerators may be serviced several times in their lifetime. The net effect is that sealed systems in refrigerators are serviced more often in developing countries and it is common practice to rebuilt welded-hermetic compressors.

4.2.5.1 Technician Training

Whether the refrigerant is HFC-134 or isobutane, technicians must be trained to handle these new refrigerants. With HFC-134a, controlling moisture and contamination are the primary considerations. With isobutane, procedures to work safely with the flammable refrigerant are paramount.

4.2.5.2 Recovery/Recycling

Before the refrigeration system is opened for servicing, the refrigerant should be recovered and recycled, or properly disposed of, regardless of the type. The design of safe recovery systems needs to account for both HFC and HC refrigerants.

4.2.6 Disposal

Recovery of the refrigerant charge at disposal is mandated in most developed countries. Practices for disposing of the cabinet range from landfilling to shredding and incineration.

4.2.6.1 Disposal Safety

HFC refrigerants and foam blowing agents do not pose any significant hazards at disposal. Fire safety needs to be taken into account when disposing of a hydrocarbon refrigerator design. If the cabinet is shredded, hydrocarbon blowing agent can be released (even as most is retained in the foam) to form a flammable mixture in air.

4.3 Conclusions

4.3.1 Different Circumstances, Different Decisions

Refrigerant designs vary with housing configurations, consumer preferences, food shopping and preparation habits, as well as climatic conditions. For example, in Northern

Europe, manual defrost is satisfactory to most consumers, given the moderate climate conditions. In other areas, with warmer and more humid climates, consumers have shown a preference for no-frost models. In developing countries, design is driven toward simplicity and low cost. In each case, these differences and other factors drive the numerous choices of refrigerants and blowing agents.

4.3.2 One Size Does Not Fit All

Given the range of circumstances it is clear that one solution does not suit all requirements. Automatic defrost is approximately 95% of the U.S. market, whereas it is less than 10% of the European market. The typical European cold wall evaporator configuration accommodates hydrocarbon refrigerants safely. In the large no-frost refrigerators preferred by consumers in the U.S. and elsewhere, flammable refrigerant safety issues are more complex (and costly) to address effectively. The U.S. legal environment imposes significant financial risks on any refrigerator manufacturer who introduces flammable refrigerants into a market where other non-flammable alternatives are available.

4.3.3 International (Kyoto/Montreal) Protocols

The current international agreements addressing global environmental issues (the Montreal and Kyoto Protocols) already provide the guidelines needed to ensure that all refrigerant and blowing agent solutions are environmentally sound. The Montreal Protocol has provided for a reasonable, orderly, cost-effective phase-out of all ozone depleting substances. The comprehensive “basket” of greenhouse gases approach set under the Kyoto Protocol addresses global climate change in an integrated, comprehensive way. Both allow each individual country to develop its own most economically effective approach to meeting overall emission limits. With respect to refrigerators, the use of HFC refrigerants in refrigerators results in negligible emissions that can be most cost-effectively offset by even small energy efficiency improvements. HFC blowing agents, due to their superior insulating value, reduce total greenhouse gas emissions. Allowing for diversity of choice is critical to a successful global policy.

5. Mobile Air Conditioning

Prior to the 1970s, automobile air conditioning was a largely American phenomenon. By 1980, 80% of American new cars had factory-installed air conditioning and a large portion of the output of the Japanese auto industry was air conditioned as well. Over the 20 years between 1980 and now, penetration of air conditioning in car and light truck sales has approached 100% in both the U.S. and Japan and is becoming increasingly popular in Europe. Not only is vehicle air conditioning a preferred comfort feature, but in many car models total engine power (and fuel consumption) at highway speed is less with the windows up and the air conditioning running than it is with the windows down and the air conditioning off. Worldwide, approximately 45 million air-conditioned cars are produced annually.

Pre-Montreal Protocol, automobile air conditioning systems used CFC-12 refrigerant-based vapor compression cycles. CFC-12 was universally replaced with HFC-134a in the 1993-1996 time period. A significant investment, estimated by the Mobile Air Conditioning Society at U.S. \$5 billion [Vogelsburg, 1996] (\$3.5 billion by OEMs and \$1.5 billion by the service industry) by the automobile and fluorochemical industries in the development and evaluation of compatible lubricants, construction materials, and fine tuning of compressor design and heat exchanger capacities was required to make this change so that traditional performance, reliability, durability and safety levels were maintained. This change was made with full knowledge that the global warming potential of the replacement (HFC-134a) was significantly lower than the original fluid being used (CFC-12) and that the replacement did not deplete stratospheric ozone. However, despite the lower GWP of HFC-134a, the use of either of two so-called natural refrigerants has been advocated by some to avoid the global warming impact of HFC-134a emissions. The two alternatives in question are: a vapor compression cycle using flammable refrigerants (propane or HFC-152a) or a transcritical vapor compression cycle using carbon dioxide. These alternatives are evaluated below.

5.1 Technology Alternatives

In addition to the usual objectives of minimum weight and cost that drive the design of all automotive components, automobile air conditioning systems are designed, for a given vehicle, to meet cooling performance criteria that each vehicle manufacturer has established to represent competitive performance, meeting the expectations of their customers. In addition, systems are designed for suitability for assembly line installation into the vehicle, and for life (approximately 4,000 operating hours) and reliability consistent with the operating life of a passenger automobile.

A common automobile air conditioning system configuration has evolved to meet these requirements. Shown in Figure 5-1, the main features are:

- Belt driven, clutch actuated compressor hard mounted to the engine.

- Direct expansion evaporator located in the heating/cooling system interior air ductwork. The typical drawn cup – plate fin evaporator is a brazed assembly of thin (typically 0.020 inch thick) plates, which form the refrigerant passages in the heat transfer core and the refrigerant manifolds, and fin stock.
- Most commonly, fin-tube condensers are used, but alternatives have been adopted, including serpentine flat tube and fin and parallel flow flat tube and fin. To obtain the most effective cooling airflow, the condenser is located at the front of the car, usually in front of the radiator.
- An expansion device, to control the flow of liquid refrigerant from the condenser to the evaporator. Expansion devices in use range from orifice tubes to thermostatic expansion valves. For transcritical CO₂ systems, a different expansion device may be needed to accommodate the high pressure, super-critical state of the CO₂ entering the expansion device
- Use of numerous mechanical fittings (using O-rings or gaskets) to interconnect the major system components and tubing, creating potential leaks, but facilitating initial assembly and future servicing.
- Use of flexible rubber hoses to connect the compressor to the rest of the system, allowing for engine rock and vibration and assembly tolerances.

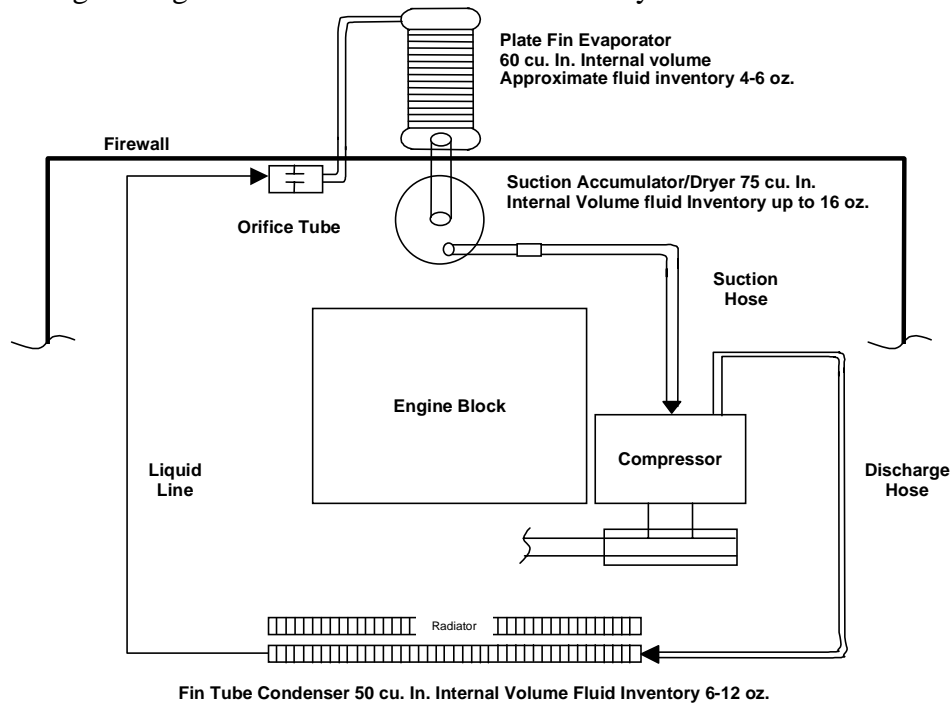


Figure 5-1: Conventional Automobile Air Conditioning System Configuration

Three alternative technologies to the HFC-134a vapor compression cycle will be evaluated here:

- An otherwise conventional vapor compression cycle with hydrocarbon – HC-290 (propane) – refrigerant and a secondary coolant loop. In this configuration, shown in Figure 5-2, the evaporator would be located in the engine compartment and would chill a secondary coolant, circulated to a heat exchanger in the passenger compartment (normally a DX evaporator) to cool the air. As discussed in Section 5.5, below, this arrangement, by itself, does not fully address the safety concerns.
- An otherwise conventional vapor compression cycle with HFC-152a refrigerant and a secondary coolant loop. In this configuration, shown in Figure 5-2, the evaporator would be located in the engine compartment and would chill a secondary coolant, circulated to a heat exchanger in the passenger compartment (normally a DX evaporator) to cool the air. HFC-152a can be used on a drop-in basis with components designed for HFC-134a. As discussed in Section 5.5, below, fire safety issues are less severe with HFC-152a than with hydrocarbons.
- A transcritical vapor compression cycle using carbon dioxide as the refrigerant. In this alternative, the arrangement of the components would be more or less consistent with conventional practice, but the individual system component designs would reflect the extremely high pressure levels of supercritical carbon dioxide (~ 2000 psig) (15 MPa). An intercooler between the suction line and the high pressure gas line is essential to system performance.

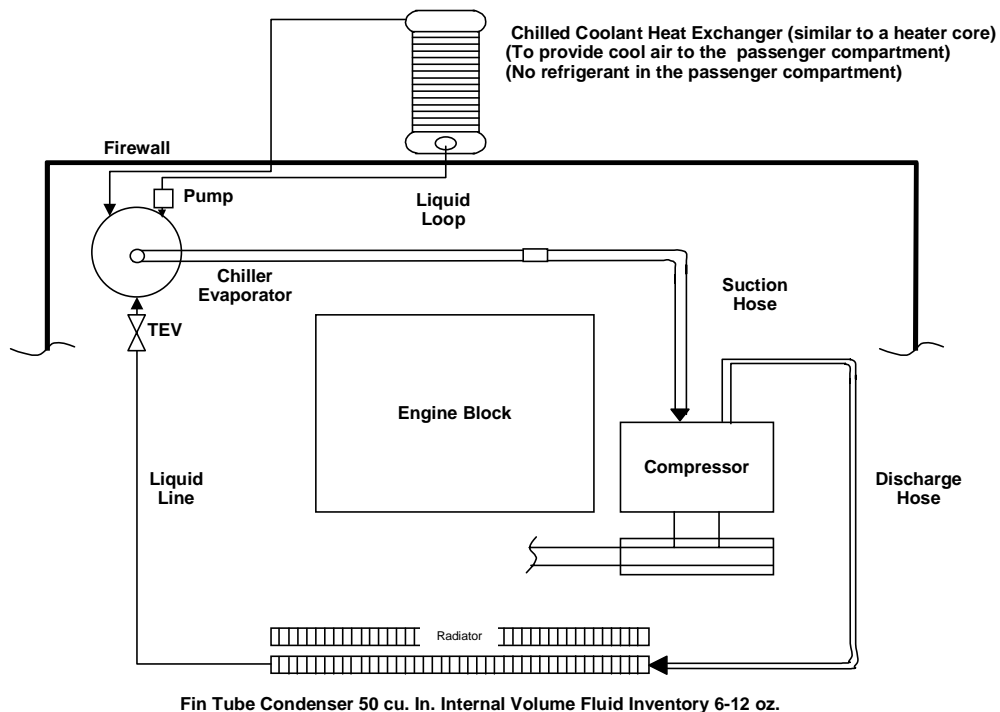


Figure 5-2: Configuration of Automobile Air Conditioning System with Secondary Coolant Loop to Passenger Compartment

In comparing the HFC-134a based vapor compression cycle with the alternatives, it is important to remember that the HFC-134a system is characterized on the basis of the fully developed, mass produced system that is installed in approximately 45 million automobiles annually, and meets the diverse range of competitive cost, performance, reliability, durability, and safety requirements outlined previously. The current HFC-134a based system is an evolutionary adaptation of its CFC-12 based predecessor, whose design evolved over a period of 50 years. Despite the evolutionary nature of the adaptation from CFC-12 to HFC-134a, an enormous resource expenditure was required to resolve material compatibility and performance issues and to ensure that traditional consumer expectations for cooling performance and reliability would be met. The two alternatives, CO₂ and hydrocarbon/secondary loop, have been prototyped and some performance test results are available to provide a basis for energy and LCCP analysis, but these designs would require substantial additional development to fully address the cost, performance, reliability, and safety requirements of the automobile customer. Therefore, the impact on the cost of an automobile to a consumer cannot be accurately assessed for either of these alternatives, beyond general expectations. First, to bring CO₂ based systems to production would require an enormous investment in new manufacturing equipment and facilities, simultaneously making obsolete the existing manufacturing base built up over the past decade, let alone the cost to the service industry. Second, it is reasonable to anticipate that the significantly higher operating pressures typical of CO₂ transcritical AC systems will increase hardware cost, as well. HC based systems will require additional hardware to address safety concerns, also increasing the cost. An HFC-152a/secondary loop system provides a low GWP refrigerant alternative that can utilize the existing HFC-134a production base. A transition to either CO₂ or flammable refrigerants would require substantial transition costs for service infrastructure and training.

5.2 Energy Impact

5.2.1 Comparison of Thermodynamic Cycle Coefficient of Performance

A detailed comparison of energy use of HFC-134a and the two alternative systems is cited below from the TEWI-3 study and the recently published GMR/ORNL studies. Prior to this, a simple, theoretical comparison of vapor compression cycle COPs is presented to help provide some perspective on the detailed results. Assuming the following, typical operating conditions:

- 30°F evaporating temperature, saturated vapor exiting the evaporator, heat transfer from the hot engine compartment to the suction hose results in 25°F of superheat at the compressor inlet;
- 80°F or 100°F ambient air (moderate conditions or extreme conditions, respectively);
- Corresponding vapor cycle condensing temperatures of 110°F or 130°F, respectively;
- 15°F liquid subcooling (approach to within half of the temperature difference between condensing and ambient);

- For the hydrocarbon vapor compression system, evaporating temperature of 25°F (5° lower than the others) to account for heat transfer/transport temperature differences (needed to drive heat transfer from the secondary coolant to the evaporating refrigerant). Ignore the parasitic power of the secondary coolant pump, and heat gain in the engine compartment.
- For the transcritical CO₂ vapor compression cycle:
 - CO₂ gas cooler exit temperature approach to within 10°F of ambient; and
 - CO₂ high side pressures of 1500 and 2000 psi, respectively.
 - An interchanger with 80% heat transfer effectiveness between the vapor leaving the evaporator and the supercritical vapor leaving the CO₂ gas cooler; no additional suction gas superheat at the compressor inlet
- Equal, 70% isentropic efficiencies for the compressors that would be used with each of these three working fluids was assumed.

Tables 5-1 and 5-2 summarize the cycle COP calculations for mild and severe ambient conditions, respectively. Thermodynamic property data was taken from ASHRAE thermodynamic property tables.

Table 5-1: Summary of Theoretical Cycle COP Calculations at Mild Ambient Temperatures

Parameter (Enthalpy in Btu/lb)	Values for			
	HFC-134	Propane	HFC-152a	Transcritical CO ₂
Refrigeration Effect:				
Enthalpy of saturated vapor leaving the evaporator	107	199	152	137
Enthalpy of refrigerant entering and leaving the expansion device	43	80	46	59*
Net refrigeration effect	64	119	106	78
Compressor Power:				
Enthalpy of vapor entering compressor	112	210	158	153*
Enthalpy of vapor leaving compressor (70% isentropic efficiency)	129	249	192	186
Compressor work	17	39	34	37
COP = Refrigeration effect/compressor work	3.76	3.05	3.11	2.11

*Includes the heat transfer in the interchanger

Table 5-2: Summary of Theoretical Cycle COP Calculations at Severe Ambient Temperatures

Parameter (Enthalpy in Btu/lb)	Values for			
	HFC-134	Propane	HFC-152a	Transcritical CO ₂
Refrigeration Effect:				
Enthalpy of saturated vapor leaving the evaporator	107	199	152	137
Enthalpy of refrigerant entering and leaving the expansion device	51	94	55	61*
Net refrigeration effect	56	105	97	76
Compressor Power:				
Enthalpy of vapor entering compressor	112	210	158	158*
Enthalpy of vapor leaving compressor (70% isentropic efficiency)	133.5	257	201	204
Compressor work	21.5	47	43	50
COP = Refrigeration effect/compressor work	2.60	2.23	2.26	1.52

*Includes the heat transfer in the interchanger

A higher COP corresponds to higher-energy efficiency, as it indicates that more cooling capacity is provided for the mechanical power input expended. At both mild and severe ambient conditions, the HFC-134a vapor compression system has the highest theoretical COP, exceeding that of propane or HFC-152a (with secondary coolant loop) by 15 to 20% and of transcritical CO₂ by more than 70%. The COP decrement of the propane cycle compared to HFC-134a is primarily caused by the lower evaporator temperature needed to accommodate the secondary coolant loop. The large difference in thermodynamic cycle COP between the transcritical CO₂ cycle and the R134a cycle is inherent in a transcritical cycle operating with heat rejection above the two-phase dome and with the evaporator operating within, but near the top of the dome, where the latent heat is small in comparison to the compression work. Note that an interchanger would improve the COP of an HFC-134a or HFC-152a or a hydrocarbon vapor cycle and that an interchanger adds to the manufacturing cost. In a real system, of course, other factors affect the energy consumption. A major factor is the transport properties of the refrigerant, which have a strong influence on the evaporating and condensing (or supercritical cooling) heat transfer coefficients. In a mobile air conditioning application, engine fuel consumption is attributable to both the compressor power consumption and to the portion of the traction power to move the weight of the air conditioning system, whether it is operating or not. A detailed analysis is beyond the scope of this study, but results of other studies are discussed briefly below.

5.2.2 Results of System Energy Analysis

The TEWI-3 study took the following into account:

- Refrigerant thermodynamic and transport properties
- A range of climates (using binned hourly TMY temperature data)
- A range of driving cycles
- A/C system component weight impact on traction power
- Parasitic (fans, pumps) power consumption
- Variations in system operating modes with variations in driving and climatic conditions

Recent work on flammable refrigerant (propane or HFC-152a)/secondary loop systems [Ghodbane, 1999], [Ghodbane,2000] indicates that the energy penalty for the secondary loop are considerably less than those estimated by the TEWI-3 study. In the TEWI-3 results, flammable/secondary energy use was 45% higher than the baseline HFC-134a system. Ghodbane’s results, which are based on a combination of experimental results and validated simulations, show that the average penalty for air conditioning system energy over a range of driving conditions is 15%, plus a 10-15% penalty for transporting the added weight of the secondary loop. The TEWI-3 results have been adjusted accordingly, assuming an air conditioning system energy penalty of 15% and an added weight penalty of 12% (compared to the baseline HFC-134a system).

The estimated energy consumption from TEWI-3, with hydrocarbon/secondary loop adjusted as discussed in the preceding paragraph, is summarized in Table 5-3, based on backing it out from the indirect TEWI contribution.

Table 5-3: Vehicle Lifetime Energy use for Mobile A/C, in Liters of Gasoline, for Technology Alternatives (based on TEWI-3)

Region	Refrigerant			
	Baseline HFC-134a	Secondary Loop Hydrocarbon*	CO ₂	
			A	B
Europe				
A/C Energy	541	622	667	883
<u>Weight</u>	<u>106</u>	<u>119</u>	<u>143</u>	<u>143</u>
Total Energy	647	741	810	1026
Japan				
A/C Energy	419	482	494	730
<u>Weight</u>	<u>66</u>	<u>74</u>	<u>89</u>	<u>89</u>
Total Energy	485	556	583	819
North America				
A/C Energy	1245	1432	1620	2113
<u>Weight</u>	<u>156</u>	<u>175</u>	<u>212</u>	<u>212</u>
Total Energy	1401	1607	1832	2325

*A/C energy and weight penalties have been modified from the original TEWI-3 report to reflect recent work on secondary loop systems [Ghodbane, 1999], [Ghodbane, 2000]

5.3 TEWI/LCCP

Both the TEWI and LCCP are intended to account for the warming impact of a product or a process over the complete lifetime of the product – from production of the raw materials and manufacturing through usage through end of life disposal. Early TEWI analyses typically included the direct global warming impact of fluorochemical emissions, but neglected the warming impact of the embodied energy and fugitive emissions associated with manufacturing the fluorochemicals. Embodied energy and fugitive emissions are included in the LCCP calculations. In principle, the embodied energy in the materials and processes used to produce the automobile air conditioning system components should be included in the LCCP calculations. It has been neglected in this analysis, because the magnitude is quite small and almost all materials used to construct the air conditioning system (primarily aluminum alloys) are recycled when a vehicle is scrapped.

The direct GWP of refrigerant emission is a significant part of the LCCP of HFC-134a emissions, so the assumed emissions over the vehicle lifetime is important. Table 5-4 summarizes three emissions scenarios that were used in the TEWI-3 study. The assumed 1 kg refrigerant charge corresponds to current practice for larger passenger cars. Actual charges range from about 0.5 kg for small cars to more than 1 kg for large vans and SUVs

Table 5-4: Refrigerant Emissions for Automobile Air Conditioning (North America) (Table 59 from TEWI-3)

Refrigerant Requirement	“As Manufactured”	1 Service Additions	2 Service Additions
Original Equipment Charge	1000 g	1000 g	1000 g
Service Additions	0 g	400 g	800 g
Total Refrigerant Usage	1000 g	1400 g	1800 g
End-of-Life Charge	650 g	600 g	800 g
End-of-Life Refrigerant Recovery	585 g	540 g	720 g
New Lifetime Refrigerant Usage: Emissions (Total Usage – Recovery)	415 g	860 g	1080 g

In June, 1998, the world’s major automobile manufacturers held a workshop in Phoenix, Arizona [Baker, 1998]. They developed a consensus estimate of lifetime HFC-134a emissions. For current vehicles, estimated lifetime usage is 1.26 system charges; for future vehicles, estimated lifetime usage is 0.71 charges. The former figure is somewhat higher than range of scenarios used in the TEWI-3 study; the latter falls within the range of scenarios.

The results of the first experimental study of HFC-134a leakage from mobile air conditioning systems were reported recently [Siegel, 2002]. Leakage rates were experimentally measured from a sample of 28 cars and light trucks. Vehicles from 5 manufacturers were tested, vehicle mileage ranged from 0 to 151,000 miles. Leakage

rates were measured in a Sealed Housing for Evaporative Determination (SHED) apparatus, with the vehicles not operating. With an adjustment to account for vehicle and air conditioner operating time, the average leakage rate was found to be 0.08 gram/day, or 29 gram/year. The study cites the work cited in the preceding paragraph [Baker, 1998], which found that losses of HFC-134a due to servicing and end of life disposal average 0.12 grams/day when recovery and recycling are practiced or 0.53 gram/day when the refrigerant is (illegally in the U.S.) vented. When the no-vent regulations are followed, the total lifetime loss of HFC-134a averages $0.08 + 0.12 = 0.20$ gram/day, or 730 grams over a 10 year vehicle life, within the ranges addressed in the TEWI-3 study.

Table 5-5 is based on Table 17 from the TEWI-3 study, where the Climate Change 95 GWP value for R134a was used. The LCCP values were derived by updating the TEWI values to include embedded energy and the pro-rata GWP of fugitive emissions from the production of HFC-134a (effective GWP of HFC-134a is increased from 1300 to 1313). The numbers for the direct effect of HFC-134a in Table 5-5 represent the range from as manufactured up to two service additions, as contained in Table 5-4, bottom row. The energy related contributions to the LCCP of the hydrocarbon/secondary loop system have been adjusted to reflect more recent data, as discussed in 5.2.2.

Table 5-5: LCCP Results for Mobile A/C (based on TEWI-3 Study)

Region	Refrigerant			
	Baseline HFC-134a	Secondary Loop Hydrocarbon*	CO ₂	
			A	B
Europe				
A/C Energy	1255	1443	1547	2048
Weight	245	275	331	331
<u>Direct Effect</u>	<u>545 to 1418**</u>	<u>4</u>	<u>1</u>	<u>1</u>
LCCP	2045 to 2918	1722	1878	2380
Japan				
A/C Energy	972	1118	1147	1694
Weight	154	173	208	208
<u>Direct Effect</u>	<u>512 to 993**</u>	<u>3</u>	<u>0.7</u>	<u>0.7</u>
LCCP	1638 to 2119	1294	1356	1903
North America				
A/C Energy	2889	3322	3759	4902
Weight	363	407	491	491
<u>Direct Effect</u>	<u>545 to 1418**</u>	<u>4</u>	<u>1</u>	<u>1</u>
LCCP	3797 to 4670	3733	4240	5393

* A/C energy and weight penalties have been modified from the original TEWI-3 report to reflect recent work on secondary loop systems [Ghodbane, 1999], [Ghodbane, 2000]

**Range: As manufactured up to 2 lifetime service additions (full size AC systems assumed except for Japan).

In general, the lower energy use of HFC-134a based systems more than offsets the direct effect of projected HFC-134a emissions. Overall, the LCCP results do not provide a compelling basis to favor one working fluid over the others, based on the conditions and

assumptions made. However, when other considerations, such as cost and safety are taken into account, HFC-134a systems demonstrate clear advantages. In addition, HFC-134a systems also have potential for further improvement from an LCCP viewpoint.

5.4 Results of the GMR/ORNL Study

General Motors Research and the Oak Ridge National Lab collaborated on an in-depth update of the TEWI-3 study analysis for mobile air conditioning. The results were presented at an SAE meeting on June 28th, 1999. As was the case in the TEWI-3 study, the impact of climate and driving cycles was taken into account. To include the effect of climate and regional differences in driving patterns, six cities were selected – Phoenix, Miami, Boston, Tokyo, Frankfurt, and Sydney. For each of these cities, hourly weather data was used to generate an annual distribution of temperatures and relative humidity levels. Local driving patterns were taken into account through the use of local fuel economy test cycles, e.g. the Federal Urban Driving Schedule in the U.S. Wind tunnel test data were used to relate condenser performance and CO₂ gas cooler performance to the driving cycle. The study attempts to more realistically model real world air conditioners, including the effect of recirculating hot air from the engine compartment through the condenser at idling conditions, based on wind tunnel data.

The primary focus of the GMR/ORNL study is comparing conventional HFC-134a based systems with transcritical CO₂ systems. The warming impact of HFC-134a emissions are a significant contributor to the TEWI. A range of HFC-134a emission scenarios (E1, E2, E3, and E4) were defined, corresponding to lifetime service additions of approximately 150, 300, 450, and 600 grams, respectively. TEWI values were calculated for CO₂ and HFC-134a systems, for small and mid-sized cars, in each of the six aforementioned cities. The impact on the TEWI of different emission rates and different levels of cooling air reentrainment at idling conditions was calculated, along with the impact of transporting the weight of the air conditioning system. Figure 5-3, which was reproduced from the paper, summarizes these results for a mid-size car (the results for the small car are similar).

The TEWI/LCCP results in Figure 5-3 are generally consistent with the TEWI-3 results, and show that for North America, where relatively more miles are driven annually in a warmer climate, the energy savings of an HFC-134a based system compared to CO₂ and the associated reduced indirect warming more than offset the direct warming of refrigerant emissions, making HFC-134a the best LCCP alternative. In Northern Europe, where the climate is milder and fewer kilometers are driven annually, the LCCP for CO₂ is less than the LCCP for HFC-134a, although this relationship would likely reverse in a warmer climate.

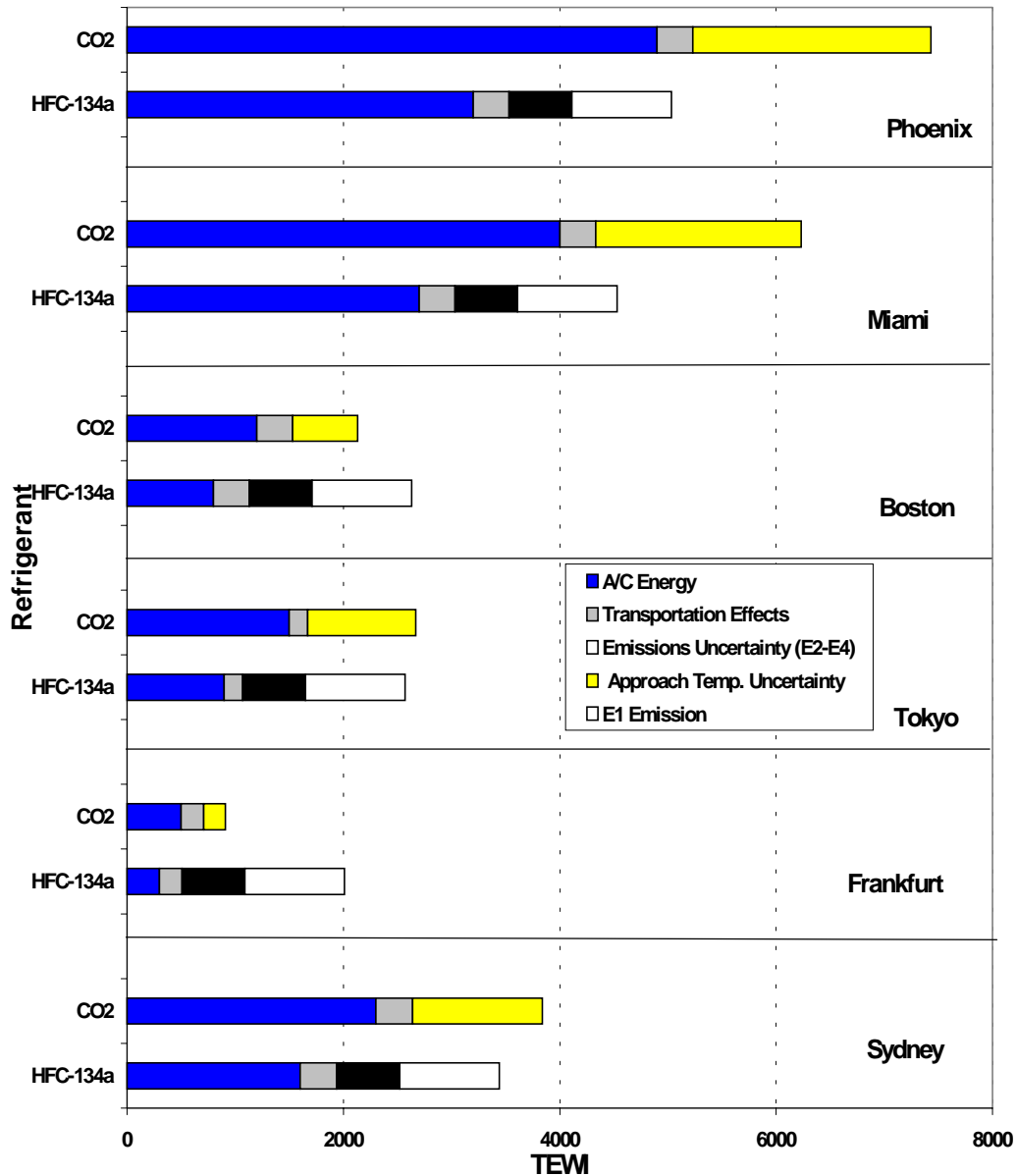


Figure 5-3: TEWI variations for the HFC-134a and CO2 systems for the Mid-size car. (Figure 12 from the GMR/ORNL study [Sumantran, et al., 1999])

5.4.1 Update of the ORNL/GMR Study

Subsequent to the publication of the ORNL/GMR study, additional analysis was undertaken by GMR. Three sets of TEWI charts were produced for 3 cases:

- Baseline, Figure 5-4, corresponding to the prior results shown in Figure 5-3.
- With embodied energy from refrigerant recycling and from production of refrigerant and the system components, Figure 5-5. This is essentially a complete LCCP, and it is apparent that the embodied energy is only a small increment in addition to the TEWI.
- With an improved HFC-134a system (30% less energy, 50% less leakage), Figure 5-6. Even in a mild climate, the LCCP with HFC-134a is comparable to CO₂.

The latter option is technically feasible and may be a more cost-effective, lighter-weight way to achieve low LCCP in a mild climate.

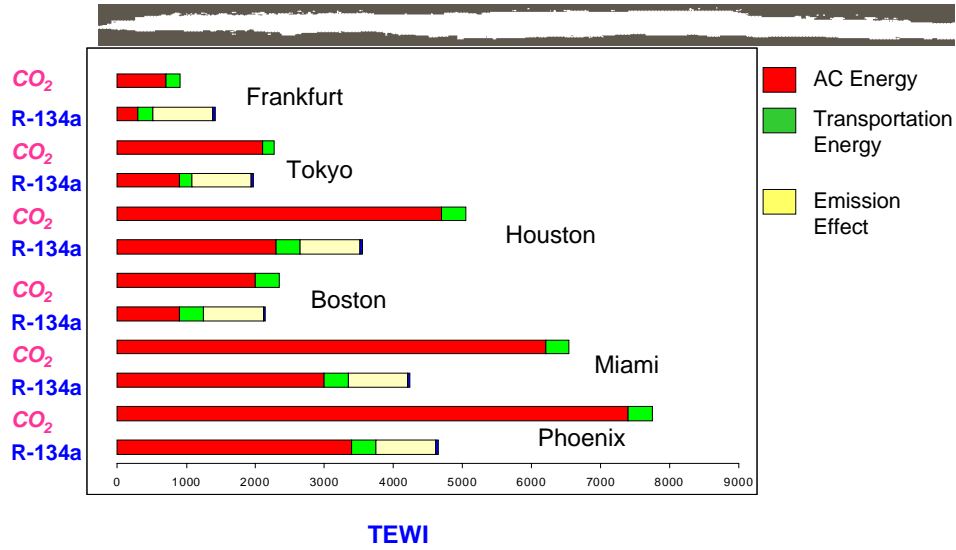


Figure 5-4: TEWI Analysis – R134a vs. CO₂ Systems Baseline

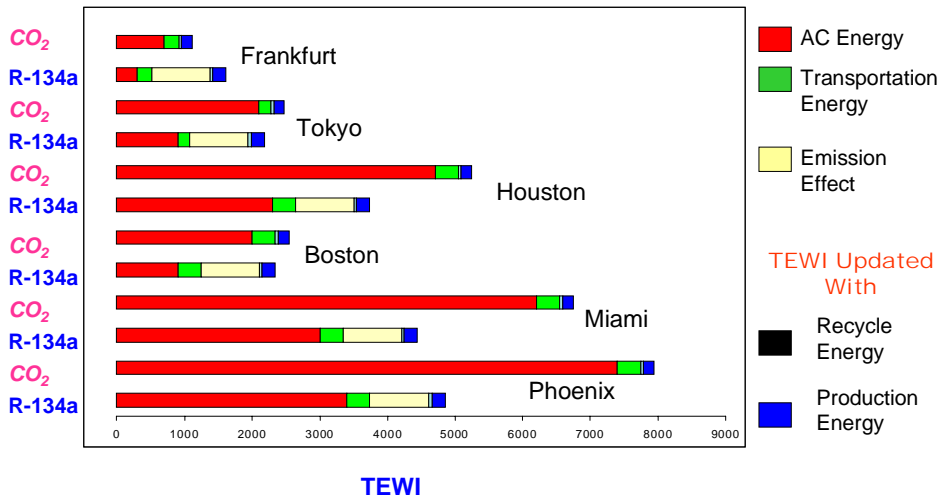


Figure 5-5: TEWI Analysis – R134a vs. CO₂ Systems With Life Cycle Analysis

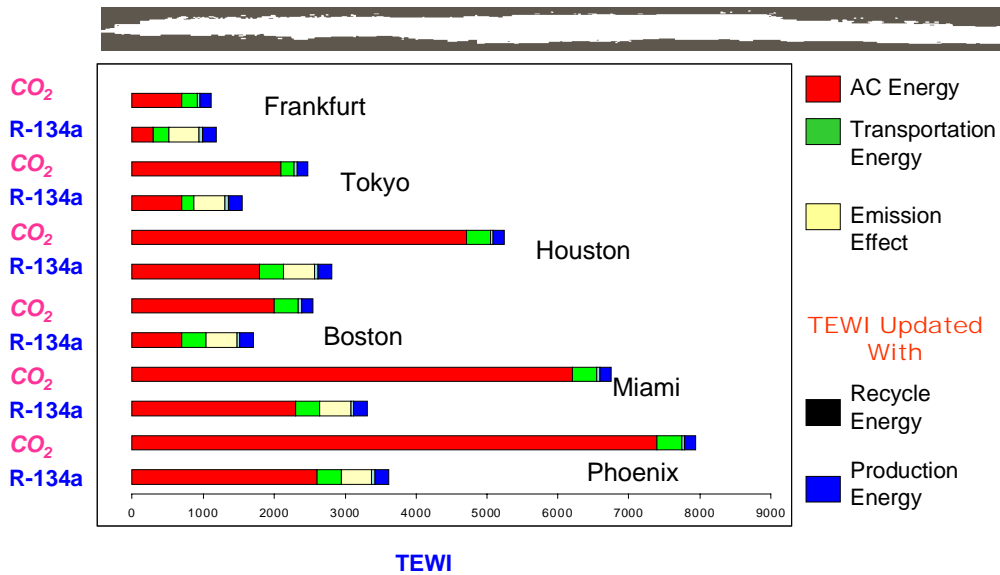


Figure 5-6: TEWI Analysis – Enhanced R-134a vs. CO₂ Systems (with assumption of 30% improvement in COP and 50% reduction in leakage for R134a)

5.5 Safety Considerations

Unlike other common uses of fluorocarbons, automobile air conditioning systems are mounted on a platform that is repeatedly exposed to the risk of road collision damage.

Of the four refrigerants being addressed for mobile air conditioning – HFC-134a, hydrocarbon HC-290, HFC-152a, and carbon dioxide – none have high toxicity concerns. However, HC-290 (propane) is highly flammable, HFC-152a is flammable, and carbon dioxide operates at significantly higher pressures (CO₂ high-side pressures are approximately 5 times higher than HFC-134a and CO₂ low-side pressures are 10 times higher than HFC-134a). The question of safely containing CO₂ pressures during operation, repair/maintenance, collision, and disposal at the end of life requires accurate definition of specific criteria. CO₂ is acutely toxic only in high concentrations, a potential concern if the evaporator were to rupture suddenly. The acute effects of CO₂ must be considered not only for healthy adults, but for children, elderly individuals, and individuals whose health is impaired. It is known that a rupture in the engine compartment can cause sheet metal to crumple.

In view of the greater risk for collisions of motor vehicles (than for stationary equipment) that could result in damage to the areas of the vehicle where air conditioning system components and tubing are installed, the question of fire safety when using a hydrocarbon refrigerant requires careful examination.

In the cradle-to-grave lifecycle of an automobile having a hydrocarbon refrigerant in the air conditioning system, there are several distinct events where fire safety issues must be considered:

- Refrigerant Manufacture and Transport. Propane is already commercially available and manufactured in production quantities. Safety procedures for production and transportation are well established, the cost of implementation is included in the market prices, and any residual fire risk is at levels that have been accepted by the producers, their employees, and society at large. HFC-152a is commercially available and produced in significant quantities for aerosol propellant and semi-conductor processing applications. Again, safe handling procedures are in place.
- Vehicle Assembly. There are substantive safety issues associated with introducing a flammable working fluid to the automobile assembly line. System charging on the vehicle assembly line, which is primarily a question of investment in the necessary equipment – explosion proof electricals, hydrocarbon vapor monitors, emerging ventilation systems, and fire suppression – to ensure a safe manufacturing operation. The safety issue in this phase of the product lifecycle is manageable, but at a cost.
- Leakage During the Life of the Vehicle. Vehicle air conditioning systems will all eventually lose refrigerant through fittings, the compressor shaft seal, O-rings, and permeation through hoses. Despite environmentally driven efforts to reduce refrigerant leakage, finite rates of working fluid leakage from automobile air conditioning systems remains a fact of life. However, the leakage rate is measured in small fractions of a pound per year, far too low of a leakage rate to allow a significant amount of a flammable refrigerant to accumulate at a flammable concentration in sufficient quantity to cause a serious fire. Even the most tightly constructed garage has sufficient air infiltration to dilute normal leakage/permeation to concentrations several orders of magnitude below the lower flammable limit. Even a sudden rupture of an HFC-152a system in a small garage would result in a refrigerant concentration less than 25% of the LFL. Some areas of potential concern are the condition of refrigerant containing components of older cars and gradual corrosion in certain geographical areas having higher than average humidity and local atmospheric concentrations of corrosive species.
- Servicing and Repairs. As with vehicle assembly, there are workplace safety issues to consider with flammable working fluid in automobile air conditioners. The equipment and infrastructure needed to recover and recycle rather than vent the refrigerant has already been developed for CFC-12 and HFC-134a, but with a flammable refrigerant, fire safety equipment and procedures are needed to ensure that flammable refrigerant releases and ignitions do not occur. A significant factor and difficulty is the large number of automobile service establishments, with different levels of training and staff turnover. Ensuring that appropriate safety standards

would be maintained at all times throughout the industry would be a major challenge. With high pressure CO₂, annual technician certification is mandatory.

- Collision Damage. This is the most significant risk area and is discussed below in greater detail.
- Disposal. When the vehicle is scrapped, any residual refrigerant can be reclaimed before the vehicle is stripped and shredded or crushed. Refrigerant reclamation equipment has been developed for this purpose. The refrigerant reclamation activity with flammable refrigerants will require fire safety procedures and specialized training. As is the case with servicing, the large number of geographically displaced automobile salvage operations leads to some concern about the consistency with which vigorous safety procedures would be followed.

5.5.1 Collision Fire Risk with a Flammable Refrigerant

As illustrated in Figure 5-1, in a typical automobile air conditioning system, interior cooling is provided by a direct expansion evaporator located in the climate control ductwork, within the passenger compartment. An alternative arrangement for a hydrocarbon refrigerant, illustrated in Figure 5-2, locates the chiller evaporator in the engine compartment. The evaporator cools a secondary coolant which is circulated to an air cooling heat exchanger located in the climate control ductwork where the evaporator normally would be located. This arrangement keeps the flammable refrigerant outside the passenger compartment. The arrangement of the compressor, condenser, and interconnecting refrigerant hoses and lines is similar for both configurations.

A large scale program to evaluate the fire safety of a conventional configuration air conditioning system with hydrocarbon refrigerant, or to redesign mobile a/c systems to use a hydrocarbon refrigerant with an acceptable level of fire safety has never been carried out, either within the automobile industry or under public sector sponsorship. Such a program would include fault-tree risk analysis, component testing, and collision testing and redesign and development effort as well, if the objective were to design a fire-safe flammable refrigerant based system. Some preliminary studies and tests have been undertaken.

In 1991, Dieckmann and Bentley did a preliminary fire risk analysis, using a flammable refrigerant in a conventional a/c system configuration. The study was focussed on the fire risk associated with collision, not the other phases of the product life cycle. The preliminary conclusion of the study was that fire risks *could* prove to be acceptably low. The specific points relative to fire risk in the report conclusions noted the major uncertainties involved, as did the detailed treatment in the report:

- The need for a larger sample of collision damaged cars where the observed breach of refrigerant containment can be related to the collision damage extent and location

- Sampling and analysis for the full range of car model sizes and configurations – this study focussed on a typical mid-sized car
- An experimental data based determination of overall ignition probabilities associated with a release of hydrocarbon refrigerant
- Full scale collision testing would be required to verify the fire safety of a resulting design configuration

Considerably more work would be needed to develop reasonably definitive estimates of passenger compartment and engine compartment fire risks and injury risks. This work would involve a combination of field data collection, characterization of potential ignition sources (both in the passenger compartment and in the engine compartment), and collision testing. Again, the report did not address refrigerant retrofit directly; in view of the level of front end collision damage related refrigerant system rupture in the engine compartment that was observed in the limited field survey work that was undertaken in the study, and the absence of hard data on ignition sources and ignition probabilities, the study did not provide a firm basis to conclude that the resulting occurrence of engine compartment fires would be acceptably low.

Interestingly, the preliminary results indicated that the primary fire issue with a hydrocarbon refrigerant may be collision-related fires originating in the engine compartment, rather than the passenger compartment. In the limited field sample (10 cars, a sample far too small to be the basis of a firm conclusion) of cars that had suffered severe (intrusion in excess of 12 inches) “A” pillar area passenger side impacts, the evaporators and refrigerant lines had not been punctured at all. In several instances, the evaporator had been displaced from its original position by close to 12 inches.

On the other hand, front-end collisions beyond minor “fender-benders”, resulted in a high percentage of refrigerant line ruptures. In the collision damaged cars examined in the limited field study, the hood latch often was driven into the upper rows of the condenser tubing, puncturing one or more tubes. Some relatively simple design changes could potentially reduce the susceptibility of AC system components to front-end collision damage, but no development program to this end has been pursued to date. *It must be emphasized that confining flammable refrigerant releases and potential ignitions to the engine compartment does not, by itself, satisfy the fire safety issue (the inherent assumption behind configuring an HC system with a secondary coolant loop to the passenger compartment).* Beyond the obvious increase in property loss, a hydrocarbon refrigerant fire in the engine compartment can spread rapidly, igniting plastic materials, the fuel, and in fairly short order can place at grave risk a passenger who is trapped by collision damage or unable to move due to injury.

Engine compartment ignition probabilities can be reduced by a battery/alternator disconnect switch which is activated by the air bag sensor. This switch is currently under development and may be widely implemented in the foreseeable future. The effect of

immediately disconnecting the battery in a front end collision is to greatly reduce, if not eliminate, the electrical system as a potential ignition source.

For a variety of reasons (in the U.S., product liability risk is one significant reason), the automobile industry has not invested the extensive effort and resources that would need to be invested to address the technical and societal issues outlined above.

5.5.2 CO₂ Safety Issues

The potential safety issues associated with high pressure CO₂ systems have not been studied in depth. Two issues have been identified:

- High pressure gas handling, the potential for tubing and hose ruptures to be quite violent
- The potential consequences of an evaporator rupture and rapid release of the entire CO₂ charge into the passenger compartment. A rough estimate is that a 1 kg CO₂ charge released into the vehicle interior would increase the CO₂ concentration to 20% - a level that results in rapid unconsciousness followed by death. Note that Tablia Biologica indicates that 9% is the lethal concentration of carbon dioxide for healthy adults. For individuals with impaired health, the lethal concentration is probably lower. More work is needed to determine the likely duration of high CO₂ concentrations compared to the range of human tolerance for these concentrations.

6. Unitary Air Conditioning

In much of the developed world, air conditioning has become a near necessity. In the U.S., more than 90% of newly constructed housing units are centrally air-conditioned [ACHRN, 1999]. Two thirds of all dwelling units in the U.S. have central air conditioning and another one-third have one or more room air conditioners. [Appliance, 1997] [U.S. Census Bureau, 2000] Virtually all-commercial building space in the U.S. is air-conditioned. The rapid population growth of the Sun Belt in the U.S. was facilitated, if not enabled, by the universal use of air conditioning. Acceptance of air conditioning varies throughout the developed world, but in general is increasing rapidly in all but the coolest climates. Use of air conditioning for commercial buildings is growing rapidly, even in cooler climates.

The majority of both the existing installed capacity and new production of air conditioning equipment is unitary equipment. Unitary air conditioning equipment is a broad category of air-to-air air conditioning systems and heat pumps, including:

- Residential central air conditioning systems and heat pumps, both single package and split systems, generally between 5 kW (1 1/2 tons) and 18 kW (5 tons) cooling capacity
- Packaged air-to-air systems and split systems for commercial air conditioning, ranging in cooling capacity from 10 kW (3 tons) to more than 350 kW (100 tons). The ubiquitous commercial rooftop air conditioner falls into this category
- Ductless split systems, both mini-splits for one room and larger systems having multiple indoor evaporator/fan units connected to a single outdoor unit
- Water-source air conditioners and heat pumps
- Room air conditioners (a.k.a. window air conditioners)
- Packaged Terminal Air Conditioners (PTAC), functionally similar to room air conditioners

Note that while ductless split systems, room air conditioners, and PTACs are air to air systems, they are not always classified as “unitary” in published market data. Water source air conditioners and heat pumps are used in approximately 2% of new air conditioner applications [U.S. Census Bureau, 1995]. In the TEWI-3 study, TEWI comparisons were developed for the first three of these types of unitary equipment, in a variety of climatic locations and at several different efficiency levels.

In the present study, the focus is limited to the first two of the above categories of unitary equipment, and energy and LCCP comparisons are presented for a typical residence and a typical small office building in Atlanta, a location whose climate is

somewhat warmer than the U.S. average. The prototypical systems that have been analyzed are two of the example systems used in the TEWI-3 study:

- 10.5 kW (3-ton) residential central air conditioning system (cooling only) or heat pump (heating and cooling). The baseline system (HCFC-22, 10 SEER, 6.8HSPF) is representative of a significant portion of the current (2002) market, meeting the current NAECA minimum SEER of 10 Btu/Watt-hr. This baseline system is compared to current/future systems using HCFC-22 or alternate refrigerants and with higher efficiencies (12 to 14 SEER), within the likely range of future efficiency requirements and of premium efficiency levels to qualify for electric utility rebate programs. Central air conditioners and heat pumps with efficiencies in this range are available commercially now.
- 26.4 kW (7.5 ton) single package commercial rooftop air conditioner (cooling only). The baseline system (HCFC-22, 10.3 EER) is representative of a significant portion of the current (2002) market. This baseline system is compared to current/future systems using HCFC-22 or alternate refrigerants and with higher efficiencies (11 EER).

6.1 Technology Alternatives

For several decades, virtually all of the unitary air conditioning types described above have operated on a reverse Rankine cycle, commonly referred to as the standard vapor compression cycle, using HCFC-22 as the refrigerant. Some unitary air conditioning products are now being produced with one of two HFC blends, R407C or R410A, and with HFC-134a. While the majority of unitary air conditioning in production today still uses HCFC-22 as the refrigerant, in the post-ODS phase-out context of this study the two HFC blends R407C and R410A are the baseline refrigerants. In the Alternative Refrigerant Evaluation Program (AREP), HFC-134a was also evaluated as a replacement for HCFC-22. HFC-134a requires a larger volume flow rate of refrigerant for a given cooling capacity, requiring a larger compressor displacement and larger diameter tubing throughout, increasing the cost. Consequently, limited unitary equipment is likely to be produced in the future with HFC-134a refrigerant, more in large commercial unitary equipment than in smaller capacities.

Alternatives to the vapor compression cycle include:

- Trans-critical vapor compression cycle with carbon dioxide refrigerant. There has been considerable research activity with CO₂ cycles in the past few years. Pressure levels are considerably higher with CO₂ than with conventional (e.g., HCFC-22, HFC-407C, HFC-410A) refrigerants. Consequently, experimental system designs have used microchannel heat exchangers for both the condenser and evaporator. The

higher pressures require heavy walled compressor shells. Basic refrigerant flow control between the condenser (gas cooler) and evaporator is more complex than with conventional vapor compression, because optimum control of the high side pressure needs to be accomplished, simultaneously with metering the optimum flow of refrigerant to the low side. An additional heat exchanger – an intercooler – is beneficial in improving the performance of CO₂ systems. Some component manufacturers have begun to develop prototype compressors, flow controls, and heat exchangers for this application, but large-scale commercialization would take a long time to happen and is not assured. Due to the higher operating pressures, it is expected that CO₂ systems will cost about 20% to 40% more than conventional systems.

- Vapor compression cycle with ammonia. Aside from toxicity and flammability considerations, ammonia is not well suited for use in the typical, cost-effective, unitary configuration that has evolved. Ammonia in the presence of water attacks copper, which is used extensively for refrigerant tubing, and many of the materials used in hermetic motors. Ammonia has not been evaluated further for unitary equipment in this study, however, it is expected that the higher discharge temperature of this fluid would further complicate its use in this application. Large commercial unitary equipment conceivably could be replaced with ammonia chillers, which are covered in the chiller section
- Vapor compression cycle with propane, or blends of hydrocarbons. Propane has a negligibly low GWP and performs well as a refrigerant, but due to its flammability, the cooling and heating capacity of a propane based air conditioner would need to be coupled to the interior space with a secondary coolant loop. A propane/secondary loop system is included in the comparison for residential sized equipment.
- Other cycles such as reverse-Brayton and reverse-Stirling. Reverse-Brayton tends to be considerably lower in efficiency than the standard vapor-compression cycle, while reverse-Stirling equipment would likely be considerably more expensive than conventional vapor compression cycle equipment, without offering any efficiency advantage. Both cycles have been well known for a very long time and neither has made significant inroads in the market for stationary air conditioning equipment. Neither technology is likely to become commercially viable in the foreseeable future.

6.2 Energy Impact

For the purposes of comparison of the energy consumption of the refrigerant alternatives, the prototypical 3 ton residential systems and the comparable capacity technical alternatives described above have been analyzed for a representative, 1800 sq.

ft. residential application in Atlanta. The prototypical 26.4 kW (7.5-ton) commercial rooftop unit has been analyzed for a representative light commercial application in Atlanta. The results have been calculated using the heating and cooling loads calculated in the TEWI-3 study analysis. In the TEWI-3 study, cooling and heating loads and performance were analyzed for several other locations as well, with comparable results.

6.2.1 Residential Air Conditioners and Heat Pumps

Tables 6-1 and 6-2 summarize the electric energy consumption of 10.5 kW (3 ton) central air conditioners in Atlanta and 10.5 kW (3 ton) heat pumps in Atlanta, respectively. Note that in the NAECA-efficiency-standards-driven market for this equipment, energy consumption does not vary with refrigerant choice, per se. For example, if the future NAECA minimum efficiency were to be 12 SEER (note that the rulemaking to determine this level is ongoing and the new minimum has not been determined yet), a large portion of the air conditioners and heat pumps manufactured would meet this level without exceeding it by much, absent significant market demand for higher efficiency systems. The inherent efficiency characteristics of each refrigerant alternative will impact the design (and cost) required to provide the required minimum level of performance.

The differences in the inherent efficiency characteristics of the fluorocarbon alternatives are due to differences in thermodynamic and heat transport properties, and system operating pressure. Among R-22, R-407C, and R410A, these differences, and differences in refrigerant prices, can lead to “comparatively small” differences in manufacturing cost. An analysis of these differences is beyond the scope of this project, but it is recognized that even “comparatively small” differences in manufacturing cost can have a meaningful impact on gross and net profit given the highly competitive nature of a market having more than a half dozen strong manufacturers and scores of smaller manufacturers seeking greater market share.

To use propane as the refrigerant, it is assumed that a secondary loop must be used to deliver the cooling and heating capacity to the building interior. The secondary loop consumes parasitic pumping power and adds a heat transfer temperature difference to the overall thermodynamic lift. To overcome the resulting efficiency loss and meet a minimum efficiency level requires significant offsetting design modifications (e.g., larger heat exchangers, more efficient, but higher cost fan motors) to increase the efficiency. The associated costs, along with other costs associated with the safe use of propane will result in a significant (hundreds of U.S. dollars) increase in manufacturing costs and a larger increase in end-user prices.

Results reported by [Hrnjak, 1999] at the International Congress of Refrigeration indicate that it is technically feasible to make a CO₂ transcritical cycle air conditioner with a single speed compressor having an SEER of approximately 10 to 11 (based on measuring the steady state EER at the DOE “B” – 82°F outdoor temperature test point and accounting for the compressor drive motor efficiency and air moving power).

However, the EER of a CO₂ cycle decreases with increasing outdoor temperature more rapidly than occurs with conventional vapor cycle air conditioners. As a result, at more stringent (e.g., 95°F) outdoor ambient temperatures, a CO₂ based air conditioner will be approximately 10% less efficient than a conventional HCFC-22 vapor-compression cycle having a comparable SEER, an issue where peak electric utility loads are a concern. Development of CO₂ based air conditioners is still in the early research stage, providing little basis for projecting manufacturing cost vs. efficiency for comparison with conventional alternatives. Qualitatively, higher costs would be expected due to the higher pressure compressor shell requirement, larger and more costly microchannel heat exchangers, and the need for additional components such as an inter cooler. Additionally, there would be costs for developing and implementing an infrastructure capable of servicing carbon dioxide based equipment, to include new tools, service equipment, and training for technicians.

Table 6-1: Energy Consumption for a Representative Residential Air Conditioning Application in Atlanta (Cooling Only, Annual Cooling Load 33.8 million Btu, per TEWI-3)

SEER Level	Refrigerant	Annual Electric Energy kWh
10	HCFC-22	3,380
12	HCFC-22	2,817
	R-407C	2,817
	R-410A	2,817
	Propane/secondary	2,817
	CO ₂	2,817
14	HCFC-22	2,414
	R-407C	2,414
	R-410A	2,414

Table 6-2: Energy Consumption for a Representative Residential Heat Pump (Heating and Cooling) Application in Atlanta (Annual heating and cooling loads of 34.8 million Btu and 33.8 million Btu, respectively, per TEWI-3)

SEER/HSPF Levels	Refrigerant	Annual Electric Energy Input, kWh		
		Cooling	Heating	Total
10/6.8	HCFC-22	3,380	5,120	8,500
12/7.4	HCFC-22	2,817	4,700	7,520
	R-407C	2,817	4,700	7,520
	R-410A	2,817	4,700	7,520
	Propane/secondary	2,817	4,700	7,520
	CO ₂	2,817	4,700	7,520
14/8	HCFC-22	2,414	4,350	6,765
	R-407C	2,414	4,350	6,765
	R-410A	2,414	4,350	6,765

6.2.2 Commercial Air Conditioning

The annual electric energy consumption of a 7.5 ton commercial rooftop air conditioner in a typical application in Atlanta is summarized in Table 6-3. The general comments,

above, on inherent efficiency differences among refrigerants in residential air conditioning equipment are applicable here as well.

Table 6-3: Energy for Rooftop Air Conditioner in Atlanta

EER Level	Refrigerant	Annual Electric Energy kWh
10.3 (Current Technology)	HCFC-22	12,230
11 (2005 Technology)	HCFC-22	11,455
	R-407C	11,455
	R-410A	11,455
	HFC-134a	11,455
	Propane/secondary	11,455
	Carbon Dioxide	11,455

6.3 LCCP

The Life Cycle Climate Performance (LCCP, see Section 1.3) for unitary cooling or unitary cooling and heating is made up of the indirect warming associated with the energy consumption summarized above plus the direct warming associated with refrigerant emissions (the warming effect of the refrigerant plus the embodied energy and fugitive emissions associated with manufacturing). The refrigerant charge size and charge loss rates that were assumed in the TEWI-3 study are summarized in Table 6-4. The GWP values are summarized in Table 6-5, which includes both the GWP of the refrigerant and the equivalent GWP of the energy and fugitive emissions associated with manufacturing and transporting the refrigerant.

Table 6-4: Refrigerant Charge Size and Charge Losses for Baseline Unitary Equipment

Equipment Type	Refrigerant (R22 or R407C) Charge* kg	Annual Make-Up		End of Life Loss
		2002	2005	
Ducted Residential (3 ton)	2.8	2%	2%	15%
Single Package Roof top (7.5 ton)	6.9	1%	1%	15%

*For R22 and R407C. Based on density differences, the charge with R410A is 83% of the charge with R22, however the heat transfer and pressure drop characteristics of R-410A allows for a reduction in the size of heat exchangers and the use of smaller diameter tubes, which could further reduce R-410A refrigerant charge.

Table 6-5: GWP of Refrigerants and Warming Impact of Energy and Fugitive Emissions During Refrigerant Manufacturing

Refrigerant	GWP 100 yr. ITH*	Refrigerant Manufacturing	Total
R22	1500	390	1890
407C	1525	13	1538
410A	1725	14	1739
HFC-134a	1300	13	1313
Propane	11	<0.5	11
CO ₂	0	~1	1

*Source: Climate change 1995. Note that in general the accuracy/precision of these values is +/- 35%.

6.3.1 Residential Air Conditioners and Heat Pumps

The LCCP for residential cooling only units in Atlanta is summarized in Table 6-6, for R22, R407C, R410A, propane, and CO₂ at several SEER levels. The LCCP for residential heating and cooling is summarized in Table 6-7.

Table 6-6: LCCP for Residential Air Conditioning in Atlanta (2005 Technology)

SEER Level	Refrigerant	Indirect (Energy) Warming kg CO ₂ **	Direct Warming		LCCP kg CO ₂ Equivalent
			Lifetime Refrigerant Emissions, kg	Warming Impact kg CO ₂ * Equivalent	
10	HCFC-22	32,955	1.26	2381	35,340
12	HCFC-22	27,466	1.26	2381	29,850
	R-407C	27,466	1.26	1940	29,400
	R-410A	27,466	1.03	1802	29,300
	Propane	27,466	0.6	6	27,500
	CO ₂	27,466	1	1	27,500
14	HCFC-22	23,357	1.26	2381	25,700
	R-407C	23,357	1.26	1940	25,300
	R-410A	23,357	1.03	1802	25,150

*Lifetime refrigerant emissions x (GWP + manufacturing) from Table 6-5.

**At U.S. average electrical generation, 0.65 kg CO₂/kWh, per TEWI-3

Table 6-7: LCCP for Residential Heating and Cooling in Atlanta (2005 Technology)

SEER/HSPF Level	Refrigerant	Indirect (Energy) Warming kg CO ₂	Direct Warming		LCCP kg CO ₂
			Lifetime Refrigerant Emissions, kg	Warming Impact kg CO ₂ * Equivalent	
10/6.8	HCFC-22	83,090	1.26	2381	85,470
12/7.4	HCFC-22	73,320	1.26	2381	75,700
	R-407C	73,320	1.26	1940	75,260
	R-410A	73,320	1.03	1802	75,120
	Propane	73,320	0.6	6	73,320
	CO ₂	73,320	1	1	73,320
14/8	HCFC-22	65,960	1.26	2381	68,340
	R-407C	65,960	1.26	1940	67,900
	R-410A	65,960	1.03	1802	67,760

*Lifetime refrigerant emissions x (GWP + manufacturing) from Table 6-5.

Tables 6-6 and 6-7 are based on an efficiency standards-driven scenario, where the energy efficiency and energy consumption are the same, regardless of refrigerant. As a result the two “natural” refrigerant alternatives, CO₂ and propane, with their low GWPs, have the lowest LCCP. However, at an SEER equal to a conventional fluorocarbon refrigerant based system, both propane and CO₂ based systems are more costly to manufacture, propane due to the fire safety measures that must be included and CO₂ due

to the higher pressure, more complex system and larger heat exchangers required to achieve a given efficiency level. If this added cost was spent to produce a higher efficiency fluorocarbon refrigerant based unit, lower TEWI might be achieved through the reduced lifetime energy consumption and the associated reduction of energy related CO₂ emissions. Work reported by Keller, et. al. [Keller, 1996] and [Keller, 1997] show that this is the case. With a conventional 12 SEER, HCFC-22 system as the baseline, a hypothetical fire-safe propane based system reduced the warming impact by 10%. With the same incremental cost of the propane system applied to a higher efficiency R-410A system, the TEWI was reduced by at least 12%, providing a lower lifetime warming impact for the same investment (without any fire safety uncertainties).

6.3.2 LCCP for Commercial Air Conditioning

The LCCP for a single package rooftop in Atlanta is summarized in Table 6-8.

Table 6-8: LCCP for Commercial Rooftop in Atlanta (7.5 Ton Rated Capacity)

EER Level	Refrigerant	Indirect (Energy) Warming kg CO ₂	Direct Warming		LCCP kg CO ₂
			Lifetime Refrigerant Emissions, kg	Warming Impact kg CO ₂ * Equivalent	
10.3	HCFC-22	119,270	2.07	3,912	123,200
11	HCFC-22	111,682	2.07	3,912	115,600
	R-407C	111,682	2.07	3,185	114,900
	R-410A	111,682	1.71	2,995	114,700
	HFC-134a	111,682	2.07	2,718	114,400
	Propane	111,682	1.1	12	111,700
	CO ₂	111,682	2	2	111,700

*Lifetime refrigerant emissions x (GWP + manufacturing) from Table 6-5.

6.3.3 Overall Perspective on LCCP Values

The basic observations that can be drawn from the LCCP values in Tables 6-6 through 6-8 are:

- The direct warming effect due to refrigerant emissions is < 5% of the total LCCP, for fluorochemical refrigerants
- Differences in efficiency have a much greater effect on LCCP than the direct effect of refrigerant emissions
- While the direct warming effect with propane is insignificant, the added energy due to the secondary loop must be offset by larger heat exchangers and other efficiency enhancements, so the cost would be increased significantly, by on the order of \$1,000 to a residential end-user.
- While the direct warming impact of carbon dioxide refrigerant emissions is negligible, much higher manufacturing cost and price to the consumer would be

expected. Substantial investments would be required to convert to CO₂ which would essentially obsolete the current capital equipment base for manufacturing compressors and finned-tube coils.

6.4 Safety Considerations

With the exception of its high level of flammability, propane appears to be a suitable replacement for R-22 in all respects. Because of the flammability, and the several kg charge size of typical residential unitary equipment, to use propane for residential air conditioning, it is necessary to restrict the propane charge to outdoor equipment, and couple the cooling and heating to the interior with a secondary loop. While this might adequately eliminate the possibility of an explosion occurring within the confined interior space, further fire-safety measures would be needed in the outdoor unit:

- Propane vapor detection and alarm
- Placement of all electrical contacts (and any other potential ignition sources) clear of any potential propane leaks and/or in an enclosure that could contain an ignition – either explosion proof or sealed with a flame arresting vent.
- To reach a given efficiency level, e.g., a NAECA minimum SEER, larger heat exchanger coils and other efficiency enhancements are needed to offset the losses of efficiency due to the secondary loop.
- In addition, fire-safety risks must be addressed in the manufacturing environment and service personnel must be properly trained to service propane-based systems safely. The latter is particularly challenging, given the high turnover rate of HVAC service technicians.

All of the measures described above are technically feasible and involve well-known technology. However, they would add significantly to the cost. When Lennox evaluated this option in the early 1990's, they concluded that the necessary fire safety measures would add 30% to the cost of a residential central air conditioning system.

7. Chillers

The chilled water or brine provided by chillers is used for commercial building air conditioning and for a wide variety of process cooling applications. Most of the chiller capacity is used for commercial air conditioning applications, and the energy and LCCP analysis herein is restricted to these applications.

The majority of chiller capacity produced each year is based on the vapor compression cycle, complemented by a moderate amount of absorption chiller capacity. Chillers are usually referred to by the type of compressor used, with four types now common:

- Centrifugal, primarily large tonnage [above 1000 kW (300 tons)]
- Screw [200-1,500kW (50 – 400 tons)]
- Scroll [up to 200 kW (up to 50 tons)]
- Reciprocating [up to 500 kW (up to 150 tons)]

Centrifugal chillers most commonly use a low-pressure refrigerant such as HCFC-123 or a medium pressure refrigerant such as HFC-134a. Higher pressure HCFC-22 is sometimes used in unusually large capacity units. Centrifugal chillers usually are water cooled, so that at design conditions the temperature lift and pressure ratio fall comfortably within the performance capabilities of a single stage compressor.

The other three compressors are all positive displacement compressors, and use either HCFC-22, HFC-134a, R407C or R410A. Both air and water-cooled versions are available.

7.1 Technology Alternatives

Table 7-1 summarizes the technology alternatives – both refrigerant and alternative cycle – that are potentially commercially viable. While engine-or-turbine-driven vapor-compression is an alternative, it is really as the prime mover that the engine or turbine is the alternative (to an electric motor). Engine driven vapor compression is subject to the same refrigerant selection issues as conventional electric motor driven vapor compression cycles, therefore engine or turbine driven vapor cycle is not treated here as a separate alternative.

Table 7-1: Chiller Technology Alternatives

Cycle	Compressor	Typical Capacity Range	Refrigerant Alternative
Vapor Compression	Centrifugal	>700 kW (200 ton)	HCFC-123 HFC-245fa HFC-134a HCFC-22
	Screw	200-1500kW (50-400 ton)	HFC-134a HCFC-22 R-407C R-410A
	Scroll	75-300kW (20-80 ton)	HFC-134a HCFC-22 R-407C R-410A
	Reciprocating	75–500 kW (20-150 ton)	HCFC-22 R-407C R-410A
Absorption	N/A	> 700 kW (200 ton)	LiBr/Water

7.1.1 Refrigerants

Most of the entries in Table 7-1 identify both the refrigerants that are currently in use and alternative refrigerants that can be used.

HCFC-22 is currently used in a large proportion of positive displacement compressor based chillers and in some larger tonnage centrifugal chillers. These uses predate the Montreal Protocol, but will be phased out as part of the overall HCFC phase-out. In the U.S., HCFC-22 cannot be produced for use in new equipment after Jan 1, 2010.

HFC-134a is currently used in many screw chillers and in many centrifugal chillers. It replaced CFC-12 in these uses, and is more widely used than CFC-12 was for these applications.

HCFC-123 is currently used in “low pressure” centrifugal chillers, having replaced CFC-11 in this use. New equipment using HCFC-123 can be manufactured in the U.S. until 2020.

Ammonia (R717) can be used in open drive screw chillers, provided that safety issues are addressed. It is not suited for hermetic motor applications, because of material compatibility consideration, and is not well suited for centrifugal chillers because of its low molecular weight.

R410A is a near azeotropic HFC blend (50/50 wt. % HFC-32 and HFC-125) that is intended for HCFC-22 replacement. Because it is near azeotropic it may be suitable for use in the flooded evaporator configuration that is typical of large chillers. Pressure

levels with R410A are almost 50% higher than with HCFC-22, so components have needed to be developed to use R410A in chiller and in other air conditioning applications. The large potential market in unitary applications has spurred the development and commercialization of a wide variety of compressors and other components for R410A.

R407C is another HFC blend that is intended for HCFC-22 replacement. R-407C vapor pressures are close to those of HCFC-22, but R-407C is zeotropic and not suited for use in a flooded evaporator. R-407C is being used in reciprocating and other positive displacement chillers with direct expansion evaporators. Many HCFC-22 components have been easily adapted to R407C use, so a wide selection of compressors, heat exchangers, and other components are available.

HFC-245fa has been developed primarily to replace HCFC-141b as a foam-blowing agent, but it is potentially applicable as a non-ozone-depleting refrigerant to replace HCFC-123 for low-pressure centrifugal chillers. HFC-245fa has a higher vapor pressure than HCFC-123 and equipment using HFC-245fa must comply with pressure vessel requirements. Commercial production of HFC-245fa will begin in the later part of 2002.

The assessment of energy and LCCP, which follows, is based largely on the TEWI-3 study assumptions and results. In TEWI-3, energy efficiency levels for individual refrigerants were based on the performance of then currently commercially available chillers using each refrigerant and industry input predicting the efficiency levels that are likely to be available in 2005. Estimated efficiencies were arrived at by this method for screw and centrifugal chillers using HCFC-22, HFC-134a, HCFC-123 (centrifugal only), and ammonia (screw compressor only). For the alternative refrigerants HFC-245fa and R-410A, no current product based efficiency estimate is available. To arrive at an estimate of the efficiency level, the theoretical (ideal cycle) efficiencies of HFC-245fa and HCFC-123 are compared and the theoretical efficiencies of HCFC-22 and R-410A are compared. Table 7-2 summarizes the ideal cycle COPs for these refrigerants, based on the REFPROP thermodynamic property subroutines. For comparison, the ideal COPs calculated by ORNL in the TEWI-3 Study for HCFC-22, HCFC-123, HFC-134a, and ammonia are included in this table and agree closely (well within ½%) with the REFPROP based ideal COP values.

Table 7-2: Ideal Cycle COPs for Alternative Refrigerants for Chillers

Refrigerant	Ideal COP* @ Subcooling/Superheat			Source
	0/0	5°F/5°F	10°F/10°F	
HCFC-123	6.78	6.92	7.05	ADL, using REFPROP thermodynamic property subroutines
HFC-245fa	6.58	6.76	6.92	
HFC-134a	6.27	6.47	6.66	
HCFC-22	6.35	6.48	6.66	
Ammonia	6.66	6.69	6.72	
R-410A	5.95	6.11	6.26	
HCFC-123	6.74	6.89	7.03	TEWI-3
HFC-134a	6.29	6.48	6.66	
HCFC-22	6.33	6.46	6.58	
Ammonia	6.60	6.64	6.68	

*At condensing temperature of 40.6°C (105°F) and evaporating temperature of 4.4°C (40°F). Note that for water-cooled chillers, the condensing temperature at standard rating conditions can vary between 95°F and 105° or higher, depending on the condenser capacity selected.

Comparing theoretical COP values, the COP of HFC-245fa is 2 to 3% less than the COP of HCFC-123. Absent any rationale to the contrary, an HFC-245fa based chiller is assumed to have an integrated part load value¹ (IPLV) 3% higher than the IPLV of a corresponding HCFC-123 based chiller.

The theoretical cycle COP of R410A is approximately 6% less than the theoretical COP of HCFC-22. This thermodynamic property disadvantage is offset by the 50% higher pressure and vapor density, the superior transport properties, and lower pressure drop of R-410A, which result in increased refrigerant side heat transfer coefficients. The higher density and pressure of R410A also allows the use of smaller diameter tubing (saving cost, which can then be applied to incremental efficiency improvements) and larger pressure drops (providing increased velocity, increasing the heat transfer coefficient). It isn't clear to what extent these potential performance disadvantages and advantages of R410A translate into net performance advantages for large chillers. For the purposes of this analysis, it is assumed that large chiller efficiencies with R410A are equal to large chiller efficiencies with HCFC-22.

7.1.2 Absorption Chillers

A portion of the large chillers sold are absorption chillers, either steam powered or direct fired. For the purposes of this study, a direct (natural gas) fired, double-effect lithium bromide-water (LiBr-water) chiller is assumed. The assumed seasonal average COP for both 350 ton and 1,000 ton chillers is:

¹ Integrated part load value (IPLV) is a single-number figure of merit based on part load kW/ton expressing part-load efficiency of chillers on the basis of weighed operation at various load capacities for the equipment.

- 1.07 for 1996 technology, based on the higher heating value (HHV) of the natural gas consumed to fire the chiller
- 1.15 for 2005 technology, based on the HHV of the natural gas consumed to fire the chiller

7.2 Energy Impact

The focus of this section is larger tonnage chillers. Energy consumption and LCCP are compared for centrifugal, screw, and absorption. The annual cooling loads and energy vs. IPLV calculated by the TEWI-3 study are used in this material. The baseline assumptions for energy efficiency used in TEWI-3 has been updated based on discussions with manufacturers and are summarized in Table 7-3.

Table 7-3: Assumed Chiller Energy Efficiency (IPLV) Levels Best Currently Available (for U.S. Applications)

Equipment	Integrated Part Load Value (IPLV)*, kW/ton	
	For 1200 kW (350 RT)	For 3500 kW (1000 RT)
<u>Screw Chillers</u>		
HCFC-22	0.47	NA
HFC-134a	0.50	NA
R-717 (ammonia)	0.54	0.57
<u>Centrifugal Chillers</u>		
HCFC-22	0.53	0.48
HFC-134a	0.52	0.48
HCFC-123	0.45	0.40

Source: Input from chiller manufacturers

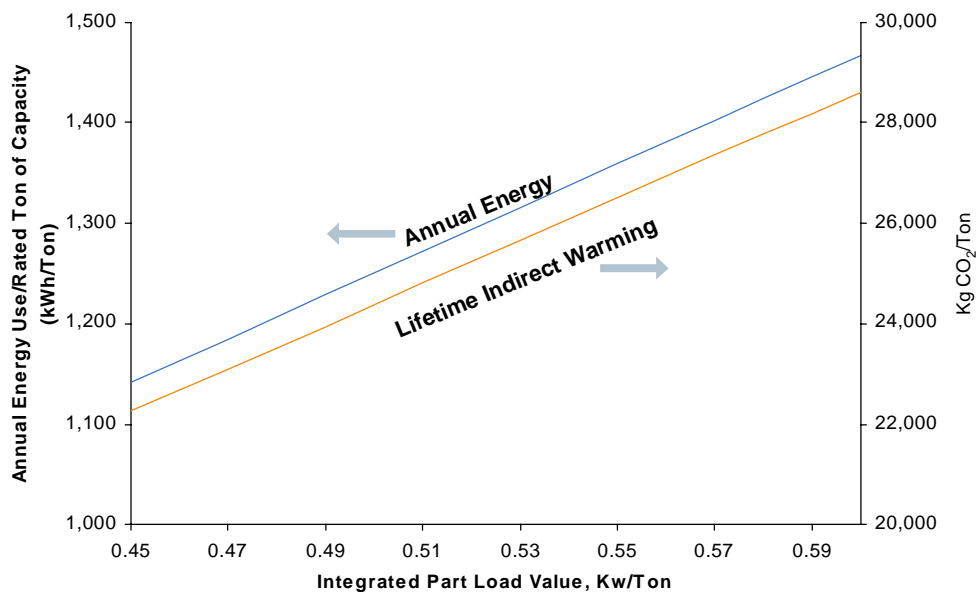
*The use of variable speed drives (VSD) in centrifugal chillers above 300 tons can significantly improve IPLV

The integrated part load value (IPLV) values in Table 7-3 were based on inputs provided by chiller manufacturers. IPLV values were used to best represent the seasonal performance. Large chillers are offered in a range of efficiency levels. Higher efficiency levels are obtained by using larger heat exchangers in relationship to the capacity, bringing the condensing temperature closer to the entering cooling water temperature and the chilled water closer to the evaporating temperature. In many applications, the increased cost of selecting and specifying a chiller at the upper end of the range of available efficiencies is quickly repaid by the resulting energy savings. As a result, many chillers are specified at, or close to, the upper end of the range of available efficiencies. The IPLVs chosen in Table 7-3 represent the best, or nearly the best, efficiency levels available in current (2002) equipment. The market demand for high efficiency large chillers has been sufficient to drive large chiller product offerings close to practical efficiency limits. For refrigerants other than those in Table 7-3, the

IPLV was estimated based on the ratio of theoretical COPs. In the TEWI-3 study, energy and TEWI were estimated for application to an office building in Atlanta, under the following basic assumptions:

- 2125 annual operating hours
- 30 year equipment life
- 0.65 kg CO₂ /kWh (power plant CO₂ emissions)
- Condenser side parasitics - water pump and cooling tower fan power consumption - are accounted for, as described in appendix F of the TEWI-3 Report (for both electric and gas absorption chillers).

Annual energy, including the condenser side parasitics, and the corresponding indirect warming effect is plotted vs. IPLV for this Atlanta office application, in Figure 7-1.



Source: TEWI-3 Study, Table 42

Figure 7-1: Annual Energy Use and Lifetime Indirect warming for a Prototypical Office Building in Atlanta, as a Function of IPLV

The annual energy use for the commercially relevant chiller technologies in the hypothetical Atlanta office building is summarized in Table 7-4 for a 350 ton chiller and in Table 7-5 for a 1000 ton chiller, both at current (2002) efficiency levels as discussed above.

Table 7-4: Annual Energy Use of 1200 kW (350 ton) Chiller in Atlanta, Current (1999) Efficiency Levels

Technology	Refrigerant	IPLV**, kW/ton	Annual Energy, kWh
Centrifugal	HCFC-123	0.45	399,700
	HFC-245fa	0.485	426,300
	HFC134a	0.52	452,700
	HCFC-22	0.53	460,300
Screw	HCFC-22	0.47	414,800
	HFC-134a	0.50	437,500
	R-410A	0.47	414,800
	R-717	0.54	468,000
Absorption*	LiBr-water	1.15 (COP) + .15 kW/ton	7.8 x 10 ⁹ Btu, gas HHV + 111,500 kWh

*Direct fired, double-effect LiBr/water

**The use of variable speed drives (VSD) on centrifugal chillers above 300 tons can significantly improve IPLV.

Table 7-5: Annual Energy Use of 3500 kW (1000 ton) Chiller in Atlanta, Current (1999) Efficiency Levels

Technology	Refrigerant	IPLV**, kW/ton	Annual Energy, kWh
Centrifugal	HCFC-123	0.40	1,015,000
	HFC-245fa	0.42	1,074,000
	HFC134a	0.48	1,207,000
	HCFC-22	0.48	1,207,000
Screw	R-717	0.57	1,402,000
Absorption*	LiBr-water	1.15 (COP) + .15 kW/ton	22.9 x 10 ⁹ Btu, gas HHV + 318,800 kWh

*Direct fired, double-effect LiBr/water

**The use of variable speed drives (VSD) on centrifugal chillers above 300 tons can significantly improve IPLV.

The annual energy consumption levels in Figures 7-4 and 7-5 actually fall within a reasonably narrow range. They are representative of a warmer than average climate, requiring a large number of full-load-equivalent operating hours. The site energy consumption of the double-effect absorption chiller is not directly comparable to the site energy of the electrically powered chiller. On a primary energy basis, the absorption chiller consumes approximately 65% more energy than the electric chillers.

The preceding analysis assumes, in effect, that the chiller plant consists of one chiller, whose output modulates between zero and full load (the basis for the IPLV). In many installations – one manufacturer estimates 85% of all new installations, currently – the chiller plant consists of *multiple* chillers, so that a much higher proportion of the operating time of any given chiller is at high – 70% to 100% of full load - capacity levels, and at higher efficiency. While a detailed analysis is beyond the scope of this

study, for many, if not most, applications, energy consumption levels potentially are lower than those indicated in Tables 7-4 and 7-5.

7.3 LCCP

The LCCP for the chiller alternatives in the prototypical, Atlanta office building, was calculated by combining the indirect warming due to energy consumption with the direct warming. The direct warming was calculated on the basis of adjusted GWP values to account for the embodied energy and fugitive emissions (as presented in Appendix A). The indirect warming impact is taken from Figure 7-1 at the appropriate IPLV value. The direct warming impact depends specifically on the GWP and embodied energy and fugitive emissions impact of the refrigerant and the lifetime charge loss. The refrigerant charge size is summarized in Table 7-6 and is based on inputs provided by large chiller manufacturers. Charge losses assumed in TEWI-3 are summarized in Table 7-6 and are based on industry input collected by ARI. The GWP values are summarized in Table 7-7.

Table 7-6: Refrigerant Charge and Annual Losses

Chiller	Refrigerant Charge		Annual Emission Rate (percent of charge / kg/y)		
	(kg/kW)	(kg)	0.5% (kg/y)	1% (kg/y)	4% (kg/y)
<u>1200 kW (350-ton) Screw or Centrifugal Chiller</u>					
HCFC-123	0.40	480	2.4	4.8	19.2
HFC-134a	0.36	432	2.2	4.3	17.2
HCFC-22	0.36	432	2.2	4.3	17.2
R-717	0.20	240	1.2	2.4	9.6
<u>3500 kW (1000-ton)-Screw or Centrifugal Chiller</u>					
HCFC-123	0.35	1225	6.1	12.3	49.0
HFC-134a	0.32	1120	5.9	11.2	44.8
HCFC-22	0.32	1120	5.9	11.2	44.8
R-717	0.18	630	3.2	6.3	25.2

Note: Additional data for computing direct effect includes equipment lifetime of 30 years, refrigerant GWPs, and assumed end-of-life loss (refrigerant lost when the equipment is retired).

Source: TEWI-3 Study, Table 9

Table 7-7: GWP and Manufacturing Warming

Refrigerant	GWP 100 yr ITH	Refrigerant Manufacturing	Total
HCFC-123	90	9	99
HFC-245fa	820	12	832
HFC134a	1300	13	1313
HCFC-22	1500	390	1890
R-410A	1725	14	1739
R-717	--	--	--

Based on industry input via ARI, a modern large chiller will on average lose 0.5% of its charge annually due to leakage and servicing. This represents a considerable improvement over designs from 10 or more years previously. For this analysis, an average loss of 1.0% annually has been assumed to account for some end of life charge loss and accidental losses in the field. Table 7-8 summarizes the LCCP for the hypothetical 350-ton chiller in an Atlanta office building, at the upper end of currently (in 1999) available efficiency levels. The character of the comparison among technical alternatives is similar for 1000 tons capacity.

Table 7-8: LCCP for 1200 kW (350 ton) Chiller in Atlanta Office Building, Current (1999) Efficiency Level

Refrigerant/ Technology	Indirect (energy) kg CO ₂	Lifetime Refrigerant Emissions, kg	100 Yr. GWP & Manufacturing kg CO/kg	Direct Warming kg CO ₂	LCCP kg CO ₂ eq.
Centrifugal:					
HCFC-123	7,798,000	144	100	14,400	7,812,400
HFC-245fa	8,312,800	144	832	119,800	8,432,600
HFC-134a	8,827,600	129	1,313	169,380	8,997,000
HCFC-22	8,975,800	129	1,890	243,800	9,219,600
Screw:					
HCFC-22	8,088,600	129	1,890	243,800	8,232,400
HFC134a	8,535,000	129	1,313	169,380	8,704,400
R-410A	8,088,600	129	1,739	224,330	8,312,900
R-717	9,126,000	72	2	144	9,126,100
Double-effect LiBr-Water	13,080,600 <u>2,174,200</u> 15,254,800	--	--	--	15,254,800

For all of the alternatives in Table 7-8, the major portion of the LCCP is the indirect warming associated with the energy consumption, with direct warming due to refrigerant emissions only amounting to between 0.2 and 3percent of the total LCCP. In other climates, the annual cooling can be more (e.g., Miami) or less than Atlanta, and the direct/indirect portions of the LCCP will vary accordingly. Because a significant portion of the cooling load of a large building is due to internal loads (lights, office

equipment, elevator machinery, people), the cooling load and the corresponding direct impact vary less with climate than is the case with smaller residential buildings.

In the TEWI-3 Study, TEWIs were calculated for annual charge loss rates up to 4% per year (four times the level assumed here). Even with this high (for current technology, practices, and regulation) loss level, the direct warming is less than 10% of the LCCP.

The LCCP of direct-fired, double-effect LiBr-Water absorption is about 70% higher than the average LCCP for the vapor compression cycle chillers. However, in practice a large portion of these machines are operated to meet peak loads only, as a means of reducing electric demand charges, and, as a result, operate for considerably fewer equivalent full load hours per year.

The LCCP values of the vapor compression alternatives fall within a reasonably narrow range and do not provide a compelling reason to favor one alternative over another.

7.4 Safety Considerations

Large chillers are most commonly located in mechanical equipment rooms, within the building they are air conditioning. If a hazardous refrigerant is used, e.g., ammonia, the equipment room must meet additional requirements typically including minimum ventilation airflows and vapor concentration monitoring.

In many urban code jurisdictions, the use of ammonia as a refrigerant is prohibited outright. For large chillers, the refrigerant charge is too large to allow hydrocarbon refrigerants in chillers located in a mechanical equipment room.

8. Commercial Refrigeration

Commercial refrigeration is a broad equipment category that includes:

- Central refrigeration systems for supermarkets. These systems consist of a central refrigeration system located in a mechanical equipment room, connected to the variety of refrigerated and frozen food display cases that are used in typical supermarkets.
- A wide variety of self-contained refrigerated and frozen food display cases, reach-in refrigerators and freezers, beverage merchandisers and vending machines, and other specialized configurations for large and small retailers and for food service establishments.
- Walk in refrigerators and freezers
- Ice machines

While the category is broad, the essentials can be represented by two commonplace configurations:

- Supermarket central refrigeration systems based on several sets of rack-mounted compressors, connected via long runs of liquid and suction vapor lines to the refrigerated/frozen food display cases in the store. The centralized supermarket system is a unique configuration and is treated in detail in this section
- At the risk of oversimplifying, the various self-contained products are similar to domestic refrigerators and are not treated separately in this study. It should be recognized, however, that significant differences between domestic refrigerators and the self-contained commercial counterpart include the range of refrigerated storage volumes, refrigeration capacities and pull-down characteristics, the range of refrigerants used, and applicable energy efficiency regulations, as discussed further in 8.5.

8.1 Technology Alternatives

Focusing on central supermarket systems, the prototypical system includes various refrigerated and frozen food display cases, connected to a central refrigeration system, typically located in a mechanical equipment room or a rooftop enclosure. The typical direct expansion (DX) central refrigeration system consists of several sets of rack mounted compressors that independently serve a portion of the refrigeration load in the store. Often there are two racks for medium temperature, fresh food loads and two racks for low temperature, frozen food loads, but the exact configuration varies depending on the store size and other factors. Traditionally, the long runs of liquid and suction vapor lines connecting the display cases with the central compressor system in the DX

configuration have been a source of refrigerant leaks, due to the large number of tubing joints and the significant movement caused by thermal expansion during hot gas defrosts. Pre-Montreal Protocol, CFC-12, CFC-502, and HCFC-22 were the refrigerants used; as the CFC phase-out date has passed, a complicated transitional regime of refrigerants is in use that still includes CFC-12 and CFC-502 from some existing equipment, along with HCFC-22, HCFC-22 based blends, and HFC blends that replace CFC-502, including R404A and R507. In the post-ODS phase-out context of this study, the relevant baseline refrigerants are the HFC blends, most commonly R404A or R507. Alternate refrigerants include ammonia and carbon dioxide (there is very little use of CO₂ in this application on a commercial basis), although modified system configurations are needed:

- Due to significant safety concerns, ammonia and hydrocarbons would only be used in a centralized system located in an equipment room with appropriate safety features, with the refrigeration capacity delivered by a secondary heat transport fluid. Ammonia with a secondary loop is considered in this study.
- Carbon dioxide potentially could be used in a direct expansion configuration, but the cycle would be a transcritical cycle. To obtain reasonable efficiencies, evaporatively cooled condensers would probably be needed, along with mechanical subcooling. This option has not been investigated extensively for commercial refrigeration, nor have the safety issues associated with handling a large charge of high-pressure CO₂. Due to the inherently low efficiency of this cycle, it has not been considered further in this study.
- Alternate, vapor cycle based configurations include:
 - Water-cooled distributed systems. In these systems smaller refrigeration units are distributed among the refrigerated and frozen food display cases. Each unit rejects heat to a central water cooling system
 - Secondary loop systems, where a secondary coolant or brine is circulated from the central refrigeration system to the display cases

A major part of the rationale for the two alternate vapor cycle systems is to significantly reduce the refrigerant inventory, and to minimize the length of refrigerant tubing and number of fittings that are installed in the field.

8.2 Energy Impact

While not subject to efficiency regulation, common practice in supermarket system design has been to design for high efficiency. This is an economically driven practice, owing to the high duty cycle of the equipment and the fact that supermarket energy costs are comparable to bottom line profits.

Recent developments in the rapidly evolving food retailing business have obsoleted many of the underlying assumptions of the TEWI-3 study. This subsection provides an updated estimate of typical energy use, based on input supplied by Hussmann [Thomas, 1999]. The most significant change, that began around 1990, is the increase in the size of the average supermarket that is being built. From the average size of 25,000 square feet for existing supermarkets cited in the TEWI-3 study, the average size of newly constructed supermarkets today is approaching 60,000 square feet. Given the 8-10 year remodeling/renewal cycle of the industry, this will be the average store by the mid to later part of this decade. Based on an average of six recent Hussmann installations throughout the U.S., a “typical” U.S. supermarket and its refrigeration system can be characterized by the following assumptions [Thomas, 1999]:

- Average store size is 60,000 square feet
- Average design load for low temperature is 330,000 Btu/hr, average 80 horsepower
- Average design load for medium temperature is 1,150,000 Btu/hr, average 175 horsepower
- R-404A and R-507 are the predominant refrigerants for both low and medium temperature. However, HCFC-22 is broadly used in medium temperature, as well as some low temperature systems.
- Average connected electric load is 440 kW, 55% -57% of which, or 245 kW is used to operate refrigeration equipment
- 1.2 million kWh/year is consumed by refrigeration equipment (direct expansion equipment with an up-to-date design)
- The average duty cycle of the refrigeration compressors is 85% for low temperature and 55% for medium temperature
- Compared to state of the art direct expansion, the energy consumption of alternative systems is:
 - Comparable or less for distributed systems. In essence, the efficiency losses due to the heat transfer ΔT and pumping power of the heat rejection loop are comparable in magnitude to the efficiency losses in the DX configuration due to low side pressure drops (the long runs of suction line and EPR valves) and to suction line heat gain (i.e., non-useful superheat).
 - The efficiency of secondary loop systems is about 10% less than for DX systems, due to the heat transfer ΔT and pumping power in the secondary loop, while being subject to heat gains in the secondary loop piping that are comparable to DX system suction line heat gains.

On the basis of the preceding, representative refrigeration energy consumption in a typical, newly constructed supermarket is:

- For DX systems: 1.2 million kWh/year
- For Secondary Loop systems: 1.4 million kWh/year
- For Distributed systems: 1.1 million kWh/year

This is a representative level of energy consumption for comparing these alternatives as applied in a particular store. Obviously, many variables influence actual energy consumption.

8.3 LCCP

Refrigerant emissions are a more significant contribution to the LCCP in conventional DX systems in supermarkets than in smaller, factory assembled self-contained equipment, so the assumed charge sizes and emission rates have a significant impact on the calculated LCCP.

The GWP and manufacturing impact for the refrigerants of interest are summarized in Table 8-1.

Table 8-1: GWP and Manufacturing

Refrigerant	GWP 100 yr. ITH	Refrigerant Manufacturing	Total
R404A	3,260	18	3,278
R507	3,300	18	3,318
R410A	1,725	14	1,739
R717	0	2	2

LCCP estimates for U.S. supermarkets have been prepared based on the energy consumption discussed in 8.2 and the following assumptions about refrigerant charge size and emissions [Thomas, 1999].

- With current practice, the typical refrigerant charge of a DX system in pounds is 6% of the floor area in square feet – 3,600 lb. for a 60,000 square foot store
 - Secondary loop refrigerant charges are 11% of DX
 - Distributed system charges are 25% of DX
- Refrigerant loss rates, in percent of charge loss per year, are:
 - 15% for DX in an optimum installation
 - <5% for distributed , 4% is assumed
 - 2% for secondary loop systems

Historically, leakage rates of 30% have been cited for DX systems, but over the past decade considerable effort has gone into improving this. The most recent draft of the UNEP TOC reports indicates that leakage rates of 10-15% are economically attainable and cites instances of leakage rates having been reduced to 5%.

100% EOL refrigerant recovery is assumed and an average system life of 15 years is assumed. Table 8-2 summarizes the resulting LCCP for four configurations:

- DX with R404A or R507 refrigerant
- Secondary loop with R404A or R507 refrigerant
- Secondary loop with ammonia refrigerant
- Distributed system with R404A or R507 refrigerant

Table 8-2: LCCP for Refrigeration Alternatives in Typical 60,000 Sq. Ft. U.S. Supermarket Constructed in 1999

Configuration	Refrigerant	LCCP Million Kg CO ₂		
		Indirect*	Direct**	Total
DX	R404A/R507	11.7	12.1	23.8
Distributed	R404A/R507	10.7	0.8	11.5
Secondary Loop	R404A/R507	13.6	0.18	13.8
	Ammonia	13.6	0.0001	13.6

*15 years of energy consumption, 0.65 Kg CO₂ per kWh

**15 years of refrigerant emissions, GWP and refrigerant manufacturing GWP as summarized in Table 8-1, average of R404A and R507 is 3,298

8.4 Safety Considerations

For direct expansion and distributed systems, that place the refrigerant charge throughout the store, the amount of refrigerant charge that could potentially be released into the store is large and the use of flammable or high toxicity refrigerants is not feasible. Store operators in the U.S. and some other countries will not accept the safety and legal risks and safety codes prohibit such large quantities of flammable refrigerant to be used in a publicly occupied space.

With secondary loop systems, potentially hazardous refrigerants such as ammonia and hydrocarbons could be used, but additional costs of safety precautions will be incurred.

8.5 Comments on Self-Contained Commercial Refrigeration Equipment

A wide-range of self-contained commercial refrigeration equipment is manufactured, ranging from beverage vending machines, beverage merchandisers, beer coolers, undercounter refrigerators, refrigerators for commercial food service, ice machines, and drinking water coolers, to name a few. Most of this equipment uses welded hermetic compressors (some semi-hermetics are used as well) and brazed joints to connect the refrigerant tubing and components in the refrigeration system. Foam insulation is used in most of this equipment. From a global warming perspective, this equipment is similar to domestic refrigerators. Refrigerant emissions are minimal because of the welded hermetic construction of the systems and foam blowing agent stays largely contained in the foam. Warming impacts are predominately caused by the energy consumption of the equipment,

which is considerably higher than for domestic refrigerators due to higher duty cycles. (e.g., frequent door openings, large beverage cool down loads, ice maker throughput). The major opportunity for reduced warming impact is improved energy efficiency.

An important distinction between domestic refrigeration equipment and commercial refrigeration equipment is the typical refrigerant charge size. While domestic refrigerators typically have fluorocarbon refrigerant charges under 150 grams, self-contained commercial refrigerator charges range from 300 grams to several kilograms. Consequently, a parallel cannot be drawn between self-contained commercial refrigerators and the adoption of isobutane as a refrigerant for domestic refrigerators in Europe (with isobutane charges of 50 grams or less). The potential safety hazard, based on charge size alone, is significantly greater. Moreover, many of the design measures used to ensure the safety of hydrocarbon based refrigerators – cold wall evaporators, location of all electricals outside the refrigerated space – cannot be applied readily to most types of self-contained commercial refrigerators.

9. Foam Insulation

Rigid and flexible plastic foams have a variety of applications that utilize combinations of the inherently high insulating value, resilience, low density, and lightweight characteristics of this class of materials. Major types of foam materials and their applications are categorized in Figure 9-1.

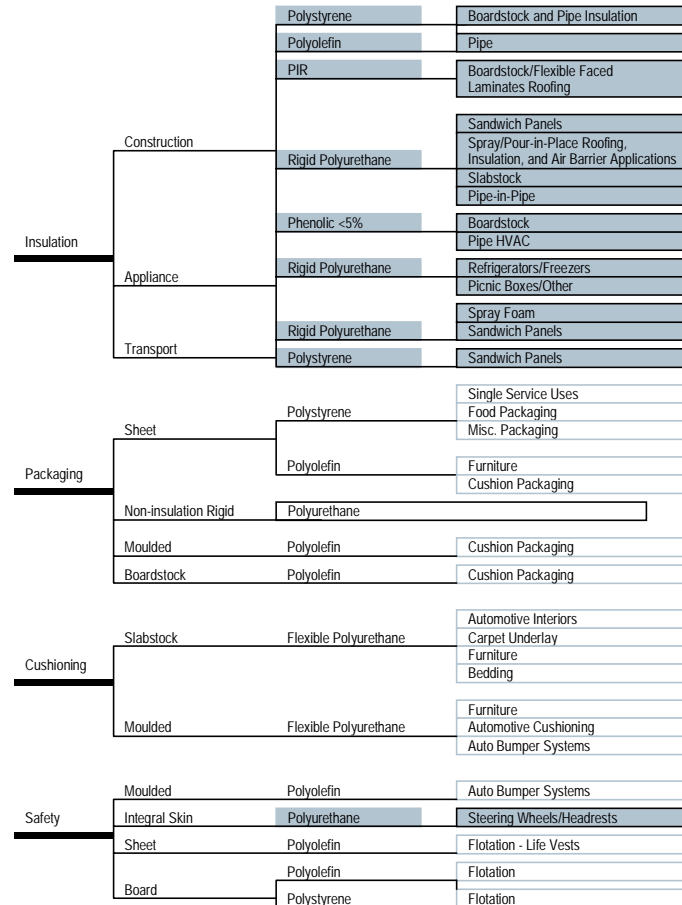


Figure 9-1: Major Applications and Types of Foam

As is apparent from Figure 9-1, plastic foams are used in a diverse range of applications. The applications highlighted in Figure 9-1 include those most likely to require, and to sufficiently value, the properties of HFCs to justify the comparatively high cost. In the range of applications including packaging foams, resilient cushioning foams, and insulating foams such as boardstock, sandwich panels and slabstock, a variety of other blowing agents, including hydrocarbons and CO₂ (water blown, gaseous, and liquid CO₂) are in the process of being adopted.

In this study, the scope is limited to insulating foams, where the majority of HFC blowing agent use is likely to occur and the thermal properties of the blowing agent and the resulting foam have an impact on energy consumption. A major application of insulating

foam, refrigerator and freezer wall insulation, *is covered in Section 4 of this report*, which addressed both refrigerant and foam blowing agent alternatives for home refrigerators and freezers.

The other major foam insulation application, *which is addressed in this section*, is building insulation. Foam products used for this purpose include:

- Polyisocyanurate (PIR) board stock, which is widely used for building wall and roof insulation,
- Extruded polystyrene (XPS) board stock, which is widely used for building wall, roof and foundation insulation, where a variety of compressive strength and moisture resistance is needed,
- Spray polyurethane foam (SPF) roofing which is used for commercial building roof and wall insulation and air barrier applications. SPF provides a means to apply a continuous (without seams or joints) layer of roofing that is water tight and infiltration tight,
- Sandwich panels with pour in place polyurethane or XPS or PIR boardstock
- Foam core entry doors and garage doors

Applications of foam building insulation reflect the diversity of building construction methods that are in use worldwide. Some of the more common applications include:

- Insulation for steel deck/steel truss-joist roof construction that is typical for low rise, flat roof commercial and industrial buildings. The foam is applied directly over the steel deck and covered with membrane or built-up roofing. In this application, foam insulation is required, because the insulation must support compressive loads. All three of the foam types covered here are used for this purpose.
- Foam board stock is used as an added layer of insulation over conventional woodframe walls and roofs with fiberglass batts filling the space between the studs or rafters.
- Insulation of below grade foundation (basement) walls in commercial and residential construction. In addition to reducing heat loads, insulation of foundation walls prevents moisture condensation during cold weather. Closed cell foam is required, because the insulation must withstand compressive loading and continuous exposure to water in the ground.
- Foam board stock is used in solid masonry construction, often between a concrete block structural wall and a brick outer facade.

9.1 Technology Alternatives

Applications for PIR board stock, SPF and XPS board stock overlap to a degree, but the processing technologies are sufficiently unique that blowing agent alternatives need to be addressed individually with respect to each of these three products. Table 9-1 summarizes the progression of blowing agent selections and options through the CFC and HCFC phaseout.

Table 9-1: Blowing Agent Options

Foam Type	Blowing Agent Selection/Option		
	CC (Pre1996)	Transitional	Non-Ozone Depleting
PIR Board Stock	CFC-11	HCFC-141b	HFC245fa HFC-365mfc Blends of pentane isomers
SPF	CFC-11	HCFC-141b	HFC-245fa HFC-365mfc HFC-134a Water blown CO ₂ Blends of the above
XPS	CFC-12	HCFC-142b	HFC-134a CO ₂

In information provided by the U.S. plastic foam industry to the UNEP Flexible and Rigid Foams Technical Options Committee, the industry estimated that HFC blowing agent use for all applications globally (including domestic refrigerators) would be approximately 75,000 metric tonnes in 2004 (following the HCFC-141b production phase out in the U.S. in 2003), growing to 115,000 tonnes in 2010. By 2010, growth rates will fall in line with growth rates in foam consumption. At this point, HFC will be used as the blowing agent in only 20% of all rigid foam.

9.1.1 Polyisocyanurate Board Stock (polyiso)

Following the phase-out of CFC-11 at the end of 1995, the majority of foam board stock and SPF has been produced with HCFC-141b blowing agent, which provides insulating values close to those obtained with CFC-11. HCFC-141b is a low-cost blowing agent, which is important to the competitiveness of insulating board stock and SPF relative to other alternatives. HCFC-141b has the highest ODP (0.11) of any of the transitional alternatives to the CFCs and will be phased out in the future in much of the developed world (Jan. 1, 2003 in the U.S.)

There are three main applications for polyisocyanurate board stock in building applications – roof insulation, wall insulation, and residential air barrier applications. Residential wall sheathing insulation also avoids thermal bridging, resisting heat movement in all directions and provides reliable performance under varying climatic conditions. This better climate control saves energy and makes the building more comfortable for the occupants. Polyisocyanurate board stock has a high aged R-value of 6.0 per inch and is used as the primary thermal insulation in over 60% of all commercial low-slope roofing. Light colored covering membranes, frequently used over the polyiso, reduces summer roof temperatures and solar heat gain and winter radiant heat loss.

The alternatives to HCFC-141b that are under evaluation include several HFCs and hydrocarbons:

- Cyclopentane, normal pentane, iso pentane, and blends
- HFC-245fa
- HFC-134a
- HFC-365mfc and blends with HFC-227ea (will not be available as a blowing agent in the U.S. due to patent/license agreements)
- And blends of all of the above

The HFC blowing agents will provide foam thermal conductivities and R-Values that are very close to those currently provided by HCFC-141b. With early non-commercial formulations with the pentanes, R-Value losses up to 10% were experienced. Fire-safety issues must be addressed in manufacturing and in use. The major manufacturers in the boardstock industry have decided to convert to hydrocarbon blowing agents, due to the higher cost of HFC blowing agents.

9.1.2 Extruded Polystyrene (XPS) Board Stock

XPS is very versatile and suited for a variety of diverse applications such as: cavity walls, steel or wood framed wall sheathing, furred walls, foundation walls, precast and tilt up concrete walls, under concrete slabs, and in decks. It is also ideal for roofing applications including single ply, tapered, built up roofing, and protected membrane systems.

XPS has numerous performance benefits including:

- High R-value which achieves net savings in energy consumption and greenhouse gas emissions
- Excellent moisture resistance which prevents the loss of thermal performance in the presence of water
- High compressive strength for a variety of applications
- Resistance to mold and mildew
- Lightweight for ease of handling and U.S. marketplace constraints for insulation products

XPS is produced by injecting a blowing agent (whose boiling point is below room temperature) in the molten polystyrene before it reaches the extrusion die. As this mixture exits the extrusion die the blowing agent vaporizes, expanding the molten resin into foam and creating a fine cell structure. As the foam leaves the extrusion die, it expands in width and thickness. Originally CFC-12 was used as the blowing agent; since the CFC phase-out in the early 1990's, HCFC-142b has been used. The phase-out date for HCFC 142b is not until 2010. Thus, unlike some of the other foams in this chapter, a commercially-viable, technically-feasible substitute alternative has yet to be identified. The XPS industry continues to conduct research to develop technically-feasible alternate

blowing agent options. At this date, the most viable non-ozone depleting alternatives for the XPS industry are HFC-134a and CO₂ or blends thereof.

Very preliminary research shows that using 100% HFC-134a as the blowing agent, the aged R-value would yield an R-Value of 5 (°F/in)/(Btu/hr-ft²) for the resulting foam, the same as currently obtained with HCFC-142b. However, it would be difficult with known technology, to make a commercially-viable foam for the U.S. building and construction marketplace using 100% HFC 134a. When CO₂ is used, preliminary research shows the R-value drops by 10-15% to approximately 4.3 to 4.4 per inch. XPS would be processed the same way with any alternative; but most likely, a blend of blowing agents will be required which would lower the theoretical R-value of HFC 134a blown XPS foam to something less. Since an acceptable alternative for XPS has yet to be identified, much less used in actual commercial applications, the industry cannot predict the actual amount of any R-Value loss that might occur using alternative blowing agents.

9.1.3 Spray Polyurethane Foam (SPF)

There are three main applications for spray polyurethane foam (SPF) in building applications – roof insulation, wall insulation, and air barrier applications.

9.1.3.1 SPF roofing

SPF roofing is a fast-growing segment of the building insulation foam market. SPF roofing is applied in a continuous layer on top of the roof deck of commercial buildings, at a density of 2.5 to 3.0 lb/ft³. SPF roofing provides numerous performance benefits, some relating directly to building energy consumption:

- SPF is applied in a continuous layer on top the roof deck, eliminating thermal shorts (thermal bridging) through fasteners and structure
- The continuous, joint-free layer of SPF is an effective infiltration barrier, eliminating both the latent and sensible loads associated with infiltration
- SPF has a high aged R-value of 6.0 per inch
- Light colored coverings (typically used) over the SPF reduce summer roof temperatures and solar heat gain and winter radiant heat loss

Other advantages of SPF roofing relate to the overall service life and cost effectiveness of the building operation:

- The effective infiltration barrier reduces moisture infiltration and condensation related damage, over time, to the building structure and interior
- SPF provides an extremely durable, impact (such as hail) resistant, long-lived, easily maintained roofing system

- SPF contributes to the structural strength of the roof
- SPF roofing is applied with minimal construction waste
- SPF roofing can be applied directly over an existing roof

9.1.3.2 SPF Wall Insulation

Three SPF systems are used within the building envelope; high density (1-1/2 – 2 lb/ft³), low density (less than 1/2 lb/ft³), and sealant foams. Low density (< 1/2 lb/ft³) foams are open celled and are normally water blown.

High density SPF is used when strength, high moisture resistance and high insulating value is desired.

Low density SPF is used when insulation, air barrier and sound control is desired.

Sealant foams are used to caulk around windows, doors, sill plates and other locations to seal against unwanted air infiltration

SPF by providing a continuous air barrier, preventing moisture infiltration through air leakage, minimizing dew point problems and condensation within the building, avoiding thermal bridging, resisting heat movement in all directions and providing reliable performance under varying climatic conditions provides better climate and moisture control. Better climate control saves energy and makes the building more comfortable. Better moisture control reduces building deterioration increasing the life of the building. SPF's climate control ability enables a downsizing of the heating and cooling equipment of a building, further reducing energy use. Side-by-side energy efficiency comparisons have shown up to 40% energy savings by using SPF over the commonly specified insulation materials. The use of high density SPF within the building can add significant structural strength minimizing damage from building movement and racking events [NAHB, 1996], [NAHB, 1992].

SPF is foamed on site, using a liquid blowing agent. The non-ozone-depleting blowing agent options are the same as for polyisocyanurate boards stock. Worker safety considerations favor the use of a non-flammable HFC blowing agent.

9.1.4 Other Insulating Materials

Not in kind alternatives to foam board stock include other insulating materials traditionally used in the building industry, such as mineral wool and fiberglass. Traditionally, vacuum panels would be cost-prohibitive for building insulation applications, but newer, low cost vacuum panels have been developed that might make them a viable alternative for the future for specific, thickness sensitive, building insulation applications. Insulation for flat roofs and below grade foundation walls

requires the compressive strength and moisture resistance of closed cell foam and cannot be replaced with other insulating materials.

9.2 Energy Impact

Plastic foam insulation saves significant energy for heating and cooling buildings by reducing both winter heat loss and summer heat gain. In conventional wood-frame, fiberglass batt insulated residential/light commercial construction, PIR and XPS board stock sheathing provides a means of increasing the overall wall or roof R value by 25% to 50% that is low cost, maintains high-value interior floor space, and results in a negligible increase in the outside dimensions of the building. For building foundation walls and flat, steel deck roofs, foam insulation is the only viable method of insulation. For foundations, the compressive strength and water resistance of closed cell foam is essential. For flat, steel deck roofs, the compressive strength of plastic foam is essential. The energy impact of foam insulation and blowing agent is calculated for representative applications of each of these insulation applications in the subsections that follow.

9.2.1 Insulation of Flat, Steel Deck Roofs – Commercial and Industrial Buildings

The energy impact of foam roof insulation is illustrated by comparing the heating and cooling energy use per square foot of roof area for an uninsulated roof with roofs having 4 inches of XPS insulation or equivalent. The energy savings of the insulated roofs were calculated using the Owens Corning Global Energy Master, Version 1.12, computer model. To arrive at an estimate that is representative of the U.S. climate as a whole, energy savings were calculated for roofs located in Knoxville, Los Angeles, Orlando, Providence and Minneapolis, with the average results for heating and cooling taken as representative. The results are summarized in Table 9-2.

Table 9-2: Average Annual Space Conditioning Energy Savings Per Square Foot in the U.S. for Flat, Steel Deck Roofs in Commercial and Industrial Buildings (Compared to no Insulation)

Insulation Type	Blowing Agent	Insulation R-Value** (°F/in)/(Btu/hr-ft ²)	Energy Savings Per Sq. Ft. Roof Area Per Year (Versus No Insulation)	
			Heating Btu/year*	Air Conditioning kWh Electric
XPS board stock (4" Thick)	HCFC-142b	5.0	77,050	15.5
	HFC-134a	5.0	77,050	15.5
	Liquid CO ₂	4.2 – 4.3	76,300	15.3
PIR board stock (3.6" thick)	HCFC-141b	6.0-7.2 [#]	77,400	15.6
	HFC-245fa	6.0-6.5 ^{##}	77,800	15.7
	HFC-365mfc	5.8-6.2 ^{##}	77,400	15.6
	Cyclopentane	5.8-6.1	77,400	15.6
SPF (3.3" thick)	HCFC-141b	6.0	77,050	15.5
	HFC-245fa	6.0	77,050	15.5
	HFC-365mfc	6.0	77,050	15.5

*With 80% efficient heating system

** Commercially published (unless noted otherwise) 6 month aged R-values, permeable faces. Precise values depend on the test method.

[#] R values of HCFC-141b blown PIR board stock range up to 7.2 for impermeably faced foam or for several inch thick slabs of permeably faced board stock used in roofing applications

^{##} R-values determined for precommercial production samples of HFC-245fa and HFC-365mfc blown foam, [Honeywell, 1997], [Eury and Wu, 2001]

9.2.2 Insulation of Flat, Steel Deck Roofs –Commercial and Industrial Buildings

A study recently completed by [Franklin Associates, 2000] compared energy for conventional wood frame residential wall construction with and without an added layer of 5/8 foam board stock sheathing. Typical residential housing was examined in the United States and in Canada, and heating and cooling load calculations were performed for a range of climatic regions – ranging from the very warm in the Southern U.S. to the very cold in Northern Canada. The potential energy savings nationwide with a mix of 60% XPS and 40% PIR boardstock sheathing were calculated. The results are summarized in Table 9-3, for application to all single family homes in the U.S. and Canada.

Table 9-3: Estimated Potential Energy Saving with Foam Insulating Sheathing (60% XPS, 40% PIR) in All Single Family Homes in the U.S. and Canada

	U.S.	Canada
Annual Energy Saving 10^{12} Btu	349	121
50-Year Energy Saving 10^{12} Btu	17,400	6,040
Manufacturing energy 10^{12} Btu	711	5.05
Energy payback period, years	2.04	0.42

9.3 Life Cycle Climate Performance (LCCP)

The LCCP has been estimated, using the energy savings calculated above and comparing with the greenhouse gas emissions associated both with blowing agent emissions and manufacture of the foam board stock.

The AFEAS/DOE sponsored TEWI-1 study compared CFC-11 and CFC-12 blown PUR/PIR boardstock with various HCFC blowing agents and with other alternatives including expanded polystyrene and fiberglass type insulation. The TEWI 1 study addressed a wide range of residential and commercial building wall and roof configurations and supported the importance of building insulation in addressing global warming concerns. The TEWI-2 study updated the results of the TEWI-1 residential cases and attempted to begin the comparison of HCFC blown foams with various replacement blowing agents. This report suffered from the lack of available thermal performance data (in 1994) of foams produced with new blowing agents. SPF roofing was not addressed in the TEWI-1 or 2 studies. No other systematic TEWI/LCCP analysis of building systems was found in the literature.

Blowing agent losses/emissions occur at several stages of the life cycle of closed cell foam. On the order of 10% is emitted during manufacture of the foam product. Over the time that the insulating material is installed in the structure, very gradual diffusion of blowing agent out of (and of air into) the foam occurs. Even after many years of service, a significant amount of the blowing agent is retained in the foam. If the foam is removed from the building, or if the entire building is demolished, options for disposal include

land filling, shredding and land filling, or incineration. Initial research [Kjeldsen and Scheutz, 2002] indicates that less than 25% of the blowing agent may be released upon shredding and before being land filled. Once the foam has been land filled, diffusion to the atmosphere is very slow. Moreover, recent laboratory and field studies [Scheutz and Kjeldsen, 2002] indicate that microbes in the soil breakdown a variety of fluorochemicals such as CFC-11 and 12 and HCFC-22, further reducing the amount emitted to the atmosphere. Additional research is being conducted to determine the extent to which these microbes also breakdown HFC blowing agents such as HFC-245fa. Absent hard quantitative data, the highly conservative assumption is made that 75% of the initial blowing agent is emitted within a relevant time scale.

9.3.1 Insulation of Flat, Steel Deck Roofs

LCCP calculations are summarized in Table 9-4, based on the energy impacts summarized in Table 9-2, a 50 year life, and lifetime emission of 75% of the blowing agent. In all cases, the reduction of indirect warming impact due to energy savings attributable to effective roof insulation exceeds the direct warming impact of blowing agent emissions by a factor of 10 to 20.

Table 9-4: Average LCCP for Space Conditioning Per Square Foot in the U.S. for Flat, Steel Deck Roofs in Commercial and Industrial Buildings

Insulation Type	Blowing Agent	LCCP Reduction Per Sq. Ft. Roof Area, kg CO ₂ Equivalent			
		Direct Due to BA	Savings of Indirect Warming		Net Reduction
			Heating*	Air Conditioning	
XPS board stock (4" Thick)	HCFC-142b	82	215	504	637
	HFC-134a	41	215	504	678
	Liquid CO ₂	0	212	499	711
PIR board stock (3.6" thick)	HCFC-141b	24	216	506	698
	HFC-245fa	34	217	509	692
	HFC-365mfc	37	216	506	685
	Cyclopentane	0	216	506	722
SPF (3.3" thick)	HCFC-141b	22	215	504	697
	HFC-245fa	31	215	504	688
	HFC-365mfc	33	215	504	686

*Based on natural gas .0559 kg CO₂/1000 Btu gas input

9.3.2 Insulating Sheathing for Wood Frame Residential Construction

LCCP calculations are summarized in Table 9-5. The basis of the calculation is the energy savings summarized in Table 9-3 and 10% blowing agent loss between manufacture and installation. Energy for manufacture of foam is included. For both the XPS and the PIR insulating sheathing, the annual reduction of energy consumption and the associated carbon dioxide emissions offset the warming impacts of manufacturing the foam within 3 to 4 years of installation. Over the first 30 years that the insulation is in place, the reduction in energy related carbon dioxide emissions will be about ten times the warming impacts associated with manufacturing the foam.

Table 9-5: LCCP of Foam Boardstock Insulating Sheathing for Residential Wood Frame Walls

Greenhouse Gases, billion pounds CO ₂ Equivalent	U.S.	Canada
	Plastics mnfg - energy Released during use over 50 years	274 ~1350
Avoided from annual energy savings	49	8.57
Greenhouse gas payback period, years	12.5	3.0
Avoided from 50 yr. Energy savings	2,470	429
Net greenhouse gases saved	845	332

These results show that far more energy is saved than consumed by manufacturing the foam and that far more greenhouse gas emissions due to space condition energy consumption are avoided than are emitted in the manufacture of the foam.

9.4 Safety Considerations

There are three primary safety considerations involved in the use of HC blowing agents in building foam insulation – manufacturing plant/job site safety, transportation of the foam and polyol premixes containing HC blowing agents, and the fire rating of the foam.

9.4.1 Foam Board Stock

Fire safety issues associated with flammable hydrocarbon blowing agents arise at several stages of the product life cycle.

- Manufacturing – during manufacturing, hydrocarbon blowing agent vapors are a fire hazard and also a VOC issue. As discussed in other parts of this document, the methods to handle flammable liquids and vapors safely in a manufacturing environment are well known, but add both capital cost and operating cost
- Transportation of the foam product – during the period immediately after a foam product is produced, it is not unusual for some blowing agent to outgas. However, boardstock products are shipped on open trailers so no extra precautions are expected to be necessary
- Prior to commercial use, boardstock foams must pass a series of fire tests in order for their installation to be approved under current model building codes. These tests evaluate the complete product and account for any differences in blowing agent flammability.

The major manufacturers of PIR foam board stock have decided to convert from HCFC-141b to hydrocarbon blowing agents, so these issues are being addressed. The major XPS manufacturers are focused on considering HFC alternatives.

9.4.2 SPF Roofing and Wall Insulation

SPF roofing and wall insulation favors a non-flammable blowing agent due to worker safety considerations during installation. In many code jurisdictions, fire safety regulations currently prohibit the use of a flammable-blowing agent.

10. Solvents

Many approaches were taken to replace CFC-113 in solvent cleaning applications while this material was being phased out under the provisions of the Montreal Protocol, and a progressively increasing permit pound tax was being imposed. They included use of HCFC-141b, aqueous cleaning, semi-aqueous cleaning, no clean fluxes and flammable solvents. HCFC-141b was an interim solution since it already has been phased out for most solvent applications. To date, the replacement percentage of CFC-113 by HFC solvents is probably no more than 2 %.

10.1 Technology Alternatives

Competing solvents to the HFCs, and not in kind technologies include: HCFC-141b, ($\text{CH}_3\text{CCl}_2\text{F}$), HCFC-123 (CF_3CHCl_2), HFEs, volatile methyl siloxanes, n-propylbromide, flammable hydrocarbons, alcohols and ketones, aqueous cleaning, semi aqueous cleaning, no clean fluxes, and inert gas soldering. Diagrams of a vapor phase degreaser, an aqueous cleaning machine, and a semi-aqueous cleaning machine are shown in Figures 10-1 through 10-3, respectively.

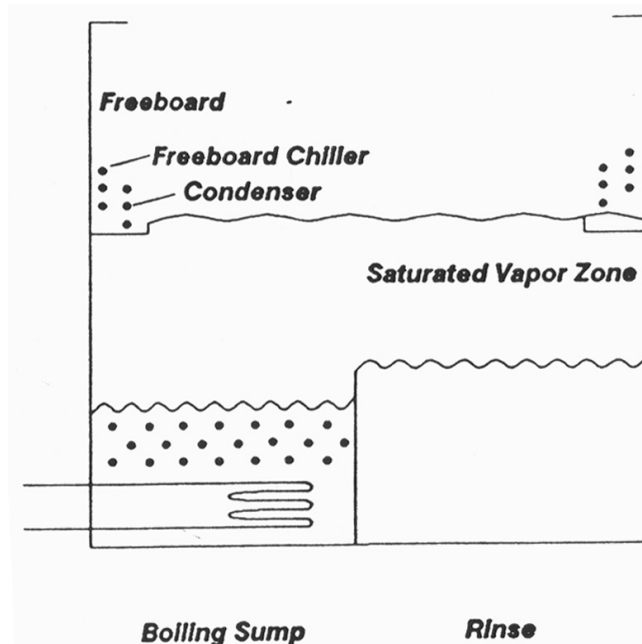


Figure 10-1: Batch Solvent Cleaning System (Vapor Degreaser)

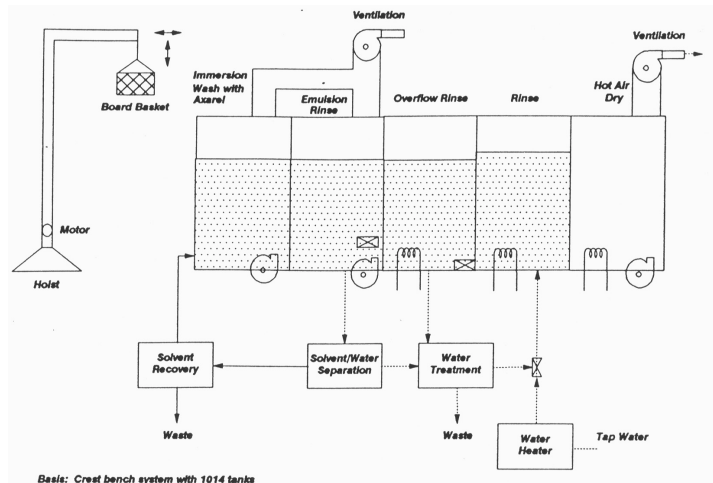


Figure 10-2: Batch Type Semi-Aqueous Cleaning System

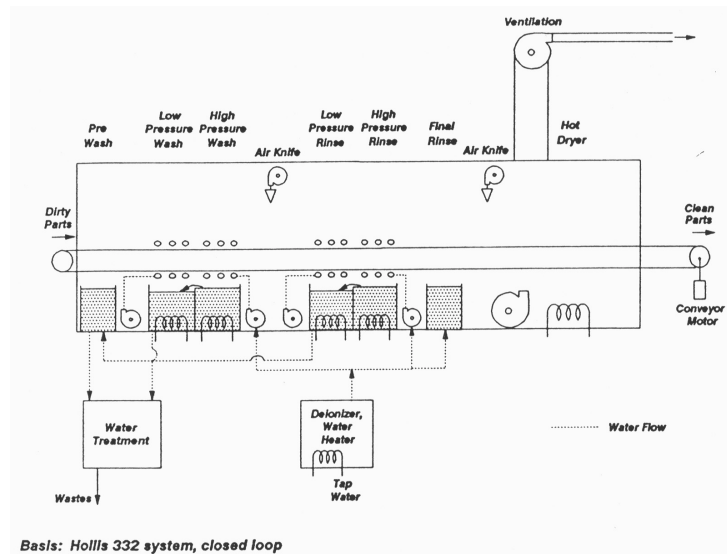


Figure 10-3: In-Line Aqueous Cleaning System

10.1.1 HFC-43-10 - $\text{CF}_3\text{-CHF-CF}_2\text{-CHF-CF}_3$

HFC-43-10 is a mild solvent that is generally very compatible and stable in the presence of many metals, plastics and elastomers, and has also been blended with alcohols and other substances to increase solvency and reduce material cost. This material has a moderate boiling point, does not have a flash point and possesses a moderate level of toxicity where the recommended exposure level is 200 ppm. Since the cost for this solvent is high, it is generally used for defluxing and/or degreasing high value parts and printed wiring assemblies (PWAs, i.e., printed circuit boards). Vapor degreasing machines using this solvent would need secondary cooling along with an extended freeboard in order to minimize solvent losses. Open top vapor degreasers would not be suitable and would require retrofitting.

10.1.2 HFC-365mfc - CF₃-CH₂-CF₂-CH₃

HFC-365mfc is a mild solvent that is generally very compatible and stable in the presence of many metals, plastics and elastomers, and has been blended with other substances to increase solvency and produce nonflammable mixtures. This material has a moderate boiling point and low flash point. However, due to the distinctive properties of HFC-365mfc a relatively wide range of nonflammable mixtures can be created. This solvent possesses a low level of toxicity. Since the cost for this solvent is lower than for other highly fluorinated solvents, it is generally used for blends with these other materials for defluxing and/or degreasing parts and PWAs. Vapor degreasing machines using this solvent would need secondary cooling along with an extended freeboard in order to minimize solvent losses due to the lower boiling point/high volatility of these blends. Open top vapor degreasers would not be suitable and would require retrofitting.

10.1.3 HFC-245fa – CF₃-CH₂-CHF₂

HFC-245fa (1,1,1,3,3-pentafluoropropane) is a new HFC solvent which was developed to replace HCFC-141b and other halogenated solvents in specialty cleaning applications. HFC-245fa is nonflammable, and exhibits excellent stability and compatibility properties. It is a mild solvent that may be blended with various co-solvents to improve solvency. In this regard, numerous useful azeotropes have been identified. HFC-245fa has good toxicological properties, with a recommended exposure limit of 300 PPM. The cost of this solvent is low compared to other nonflammable fluorinated alternatives. HFC-245fa has a much lower boiling point than most traditional solvents. Boiling at 15 degrees C (59.5 degrees F), it is not well suited for use in open-top vapor degreasers unless they are designed for very low emissions. However, HFC-245fa is well suited for specialty cleaning applications such as flushing, spraying, etc.

10.1.4 Methyl perfluorobutyl ether - CH₃-O-C₄F₉

Methyl perfluorobutyl ether is a mild solvent that is generally very compatible and stable in the presence of many metals, plastics and elastomers, and has also been blended with alcohols and other substances to increase solvency and reduce material cost. This material has a medium boiling point, does not have a flash point, and possesses a low level of toxicity where the recommended exposure level is 750-ppm. Since the cost for this solvent is high, it is generally used for defluxing and/or degreasing high value parts and PWAs. Vapor degreasing machines using this solvent would need secondary cooling along with an extended freeboard in order to minimize solvent losses. Open top vapor degreasers would not be suitable and would require retrofitting.

10.1.5 N-propylbromide - CH₃-CH₂-CH₂Br

N-propylbromide is an aggressive solvent with a moderate boiling point that generally requires a stabilizer package and does not have a flash point. This solvent possesses a moderate- high level of toxicity. The EPA has tentatively suggested an exposure level of 50-100 ppm pending a review of the toxicity data. However, recently published study results addressing the male reproductive, neurotoxicity and liver toxicity suggest that the exposure guideline for n-propylbromide will need to be much lower to be adequately

protective of workers. The necessity to control exposures to far lower levels than originally thought may limit the utility of n-propylbromide in many traditional solvent applications. Studies to address the carcinogenicity of n-propylbromide will begin in 2002. [Atofina, 2001]. In addition n-propylbromide is a volatile organic compound (VOC) and is being considered by the Montreal Protocol process.

N-PropylBromide (Decisions XIII/7):

Parties are requested to inform industry and users about concerns surrounding nPB use and emissions and their potential threat to the ozone layer, and to urge them to consider limiting its use to applications where more economically feasible and environmentally friendly alternatives are not available. As well as to minimize exposure and emissions during use and disposal. The TEAP is requested to report annually on nPB use and emissions.

The cost of this solvent is moderate, and may function as a replacement for 1,1,1-trichloroethane in some applications provided that the cleaning equipment would be engineered to ensure that worker exposure levels do not exceed the recommended value.

10.1.6 Volatile methyl siloxanes $(\text{CH}_3)_3\text{-Si-O-}[\text{Si}(\text{CH}_3)_2\text{-O}]_n\text{-Si-(CH}_3)_3$ n = 0-2

The volatile methyl siloxanes are mild, VOC solvents, have a flash point, and possess a moderate level of toxicity with a recommended exposure level of 200 ppm. Since the cost for this solvent is high, it is generally used for defluxing and/or degreasing high value parts and PWAs, and is suited primarily for cleaning silicone and other light, nonpolar residues. In many instances this solvent is used for cold cleaning and wiping. Vapor degreasing machines using this solvent need secondary cooling along with an extended freeboard in order to minimize solvent losses. Open top vapor degreasers are not suitable and would require retrofitting.

10.1.7 Aqueous cleaning

The cleaning formulations consist primarily of water containing one or more additives, including detergents, surfactants, saponifiers, inhibitors, pH buffers, and others. The advantages of aqueous cleaning systems are as follows:

The formulations can be custom made to fit the cleaning task;
The formulations have a very low toxicity and are not flammable;
They are good at cleaning inorganic salts, polar soils, oils and greases;
The cost of chemicals is very low; and
Ultrasonics can be used more effectively in water-based than in organic-based cleaning systems.

The disadvantages of the aqueous cleaning system are as follows:

- It is difficult to clean parts with crevices;
- It is difficult to rinse some of the additives from the surface of the parts;

- Drying may be difficult and may require extra time and energy due to the high enthalpy of vaporization for water;
- More floor space is required for aqueous equipment compared to vapor phase degreasers using organic solvents;
- More energy is required to clean and dry parts than for organic-based systems;
- Additional cost and equipment is required for wastewater disposal and/or recycle;
- Corrosion may be greater with some metals than for an organic-based solvent system due to exposure to water; and
- Control and engineering of aqueous systems may be more complicated than with organic-based processes.

10.1.8 Semi-Aqueous Cleaning System

Semi-aqueous cleaning is carried out through the following steps. First the part is washed in a sump containing a hydrocarbon/surfactant mixture which may be followed by an aqueous wash containing a detergent. Then the part is rinsed in a deionized water sump, followed by forced air-drying.

The advantages of semi-aqueous processes are as follows:

- Lower water consumption compared to an aqueous process;
- Good cleaning for heavy oils, greases, and tars;
- Less solvent consumption compared to an organic solvent process; and
- Less attack on metals compared to an aqueous since alkaline additives are usually not used.

The disadvantages of the semi-aqueous system are as follow:

- System must be carefully engineered to counteract the flammability resulting from spraying of hydrocarbon/surfactant mixture;
- Odors from the terpene cleaners may be objectionable;
- Some of the compounds used are VOCs.
- Drying may be difficult and may require extra time and energy due to the high enthalpy of vaporization for water;

- More floor space is required for semi-aqueous equipment compared to vapor phase degreasers using organic solvents;
- More energy is required to clean and dry parts than for organic-based systems;
- Additional cost and equipment is required for waste water disposal and/or recycle; and
- Additional cost will result if a deionized water rinse is necessary

10.1.9 Alcohols

Alcohols are polar solvents that have flash points and are very effective cleaners. However, alcohols are VOCs and the equipment must be carefully engineered to avoid the flammability hazard, and there has been some reluctance to utilize this type of system even with the controls.

10.1.10 No Clean Fluxes

One approach to avoid the necessity of cleaning PWAs is to use low solid fluxes. In some cases activators are used that sublime at the soldering temperature. This approach saves money since cleaning equipment and solvent are not required. With no-clean fluxes, it is often necessary to specify higher cleanliness levels of the PC boards and components.

However, this process could not be applied universally since for some applications, the level of contaminants left on the board would be too high to meet cleanliness specifications. Also, use of the “no clean” fluxes might serve only to postpone the need to clean since additional contamination can occur due to subsequent processes on the PWA.

10.1.11 No Clean - Inert Gas

Another approach to avoid the necessity of cleaning PWAs is to use a continuous nitrogen purge to reduce the oxygen level on the wave soldering machine to about 5 ppm to minimize oxidation of the flux, which along with the use of activators that sublime at the soldering temperature, avoids the need for solvent cleaning. So far, this type of system has not made a lot of inroads. Potential drawbacks include high capital cost, high cost of nitrogen, and the level of contaminants left on the board may be too high in some instances to meet cleanliness specifications.

10.2 LCCP

The Arthur D. Little TEWI II Solvent Report has been updated to reflect the 1995 IPCC GWP values, and has included TEWI calculations for three new solvents: n-propylbromide, a hydrofluoroether ($\text{CH}_3\text{-OC}_4\text{F}_9$), and a volatile methyl siloxane $[(\text{CH}_3)_3\text{-}$

Si-O-(CH₃)₃]. A diagram showing the sources of CO₂ and other greenhouse gases generated during the cleaning is shown in Figure 10-4; a diagram showing the major material flows in the cleaning process, including both parts and solvent is shown in Figure 10-5 below.

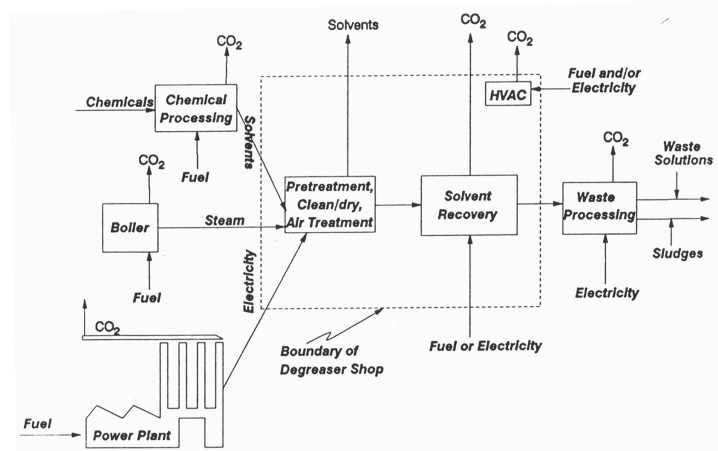


Figure 10-4: Sources of CO₂ and Other Greenhouse Gases in Cleaning Processes

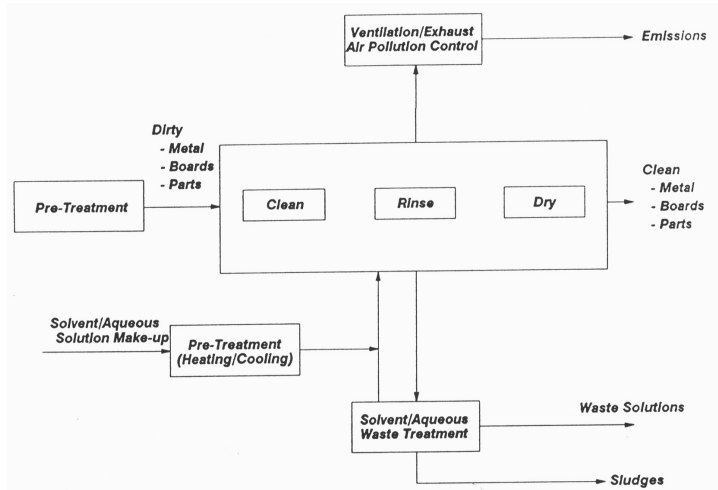


Figure 10-5: Major Material Flows in Cleaning Processes

Graphs showing the indirect contribution, direct contribution, and total TEWI for batch cleaning of metal parts, batch cleaning of printed wiring assemblies (PWAs), and in line cleaning of PWAs are shown respectively, in Figures 10-6, 10-7 and 10-8, below.

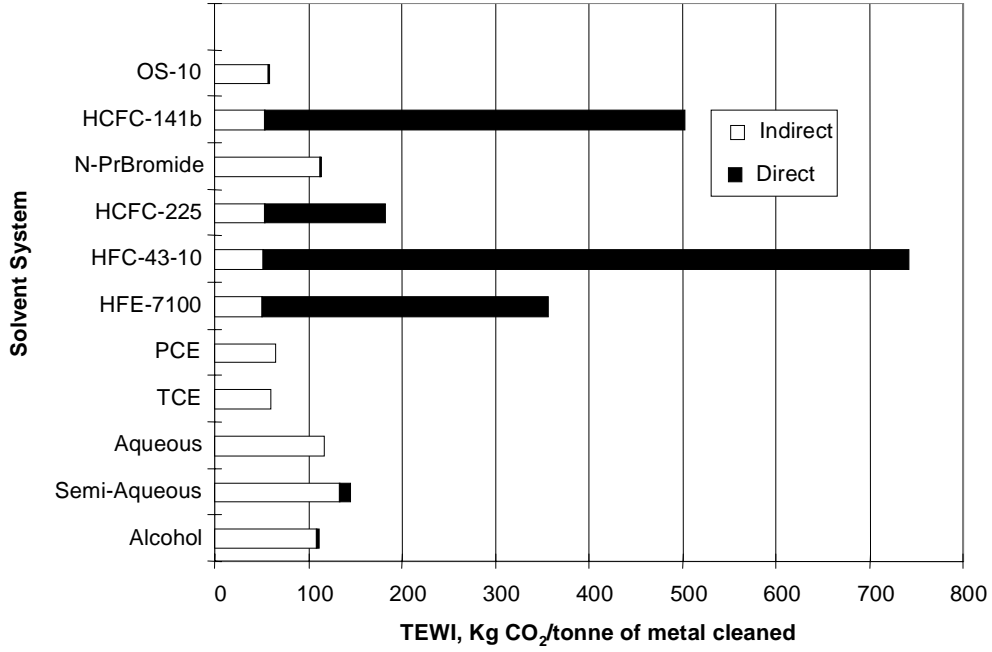


Figure 10-6: TEWI Batch Metal Cleaning - 100 Year ITH

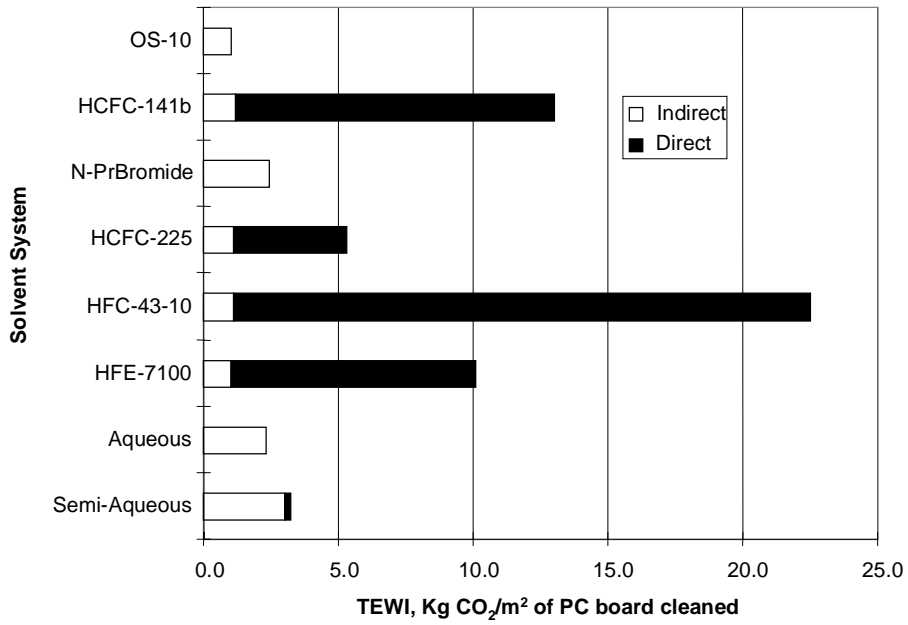


Figure 10-7: TEWI Batch PWA Cleaning - 100 Year ITH

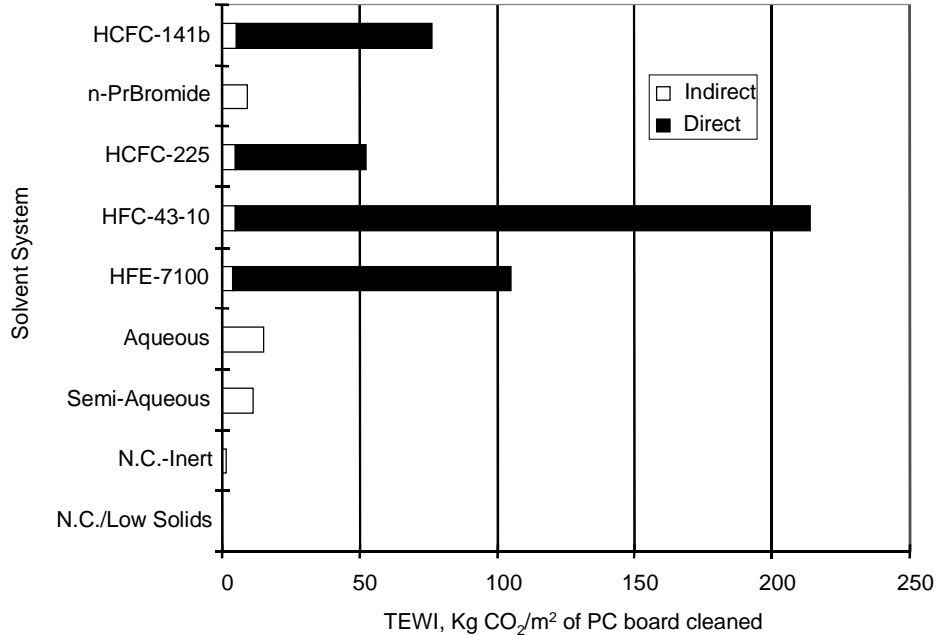


Figure 10-8: TEWI In-Line PWA Cleaning - 100 Year ITH

Major findings from these studies are as follows:

- HFC, HCFC, HFE and volatile siloxane solvents use less energy per unit work (indirect contribution) than aqueous or semi aqueous systems;
- Aqueous and semi aqueous systems have a lower TEWI than HFC, HFE or HCFC solvent cleaning systems
- N-propylbromide has an indirect contribution comparable to the aqueous and semi aqueous systems, and a lower TEWI than the HFC, HCFC, HFE and volatile siloxane systems;
- The TEWI for the HFC, HCFC and HFE systems can be lowered by improved control technology to reduce the escape of solvent vapors;
- Inert gas soldering and no-clean fluxes have a negligible TEWI; and
- TEWI should be one of the criteria for selecting a solvent system, along with other factors including cleaning performance, cost of solvent and equipment, throughput; size of equipment; system performance, ease of maintenance, toxicity, ease of recycling, waste disposal costs.
- The direct contributions to the TEWI are due to evaporative and drag out losses. These values were determined in the Arthur D. Little TEWI II study by determining

these losses for HCFC-141b/HCFC-123, and calculating the drag out and evaporative losses for the other solvents.

The 3M company carried out a batch metal cleaning study to calculate the TEWI for HFC-7100, HCFC-141b, and compare the values to an aqueous and semi aqueous cleaning process. The vapor phase degreaser used extended freeboard and secondary cooling coils to minimize vapor loss. There was a 1-minute dwell time in the freeboard and a 1-minute dwell time in the vapor zone. The TEWI for HFC-43-10 was estimated based on the similarity of the drag out loss curve for HFC-43-10 compared to HFE-7100 and similarity of the boiling points.

The data are plotted in Figure 10-9 below.

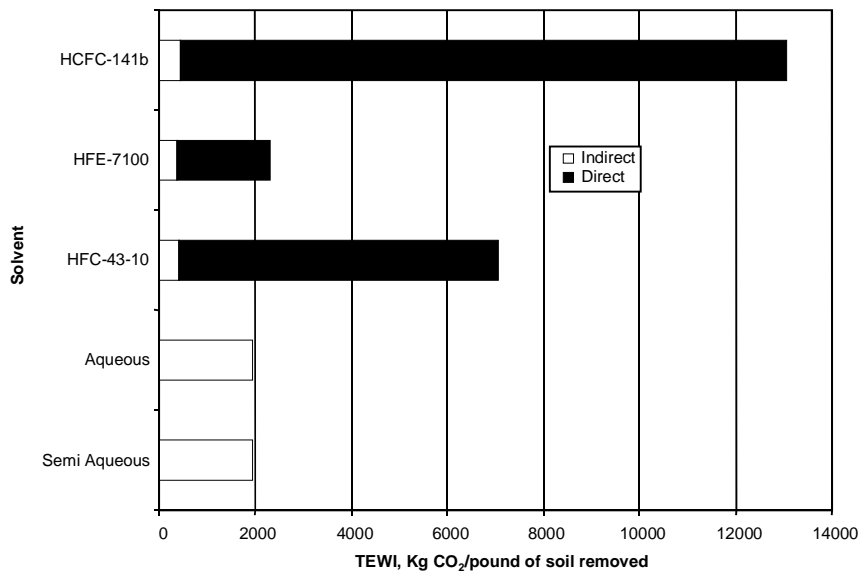


Figure 10-9: TEWI Batch Metal Cleaning - 3M Study

Unlike the TEWI data in Figures 10-6 through 10-8, where the drag out losses were calculated based on scaling experimental results on HCFC-141b/HCFC-123 systems (80/20) weight percent, the data in the 3M study are based on actual experimental data where care was taken to minimize solvent vapor loss. In this case the direct contribution from both HFC-7100 and HFC-43-10 were less than for the lower boiling HCFC-141b. Also, the TEWI for HFE-7100 was comparable to the aqueous system.

Since HFC-43-10 is a mild solvent and high priced and HFC-365mfc is being used in blends with higher priced solvents, they are being utilized only for the cleaning of high value added parts where good solvent compatibility and stability would be an issue. Furthermore, the use of higher end vapor phase degreasers with high freeboards, and secondary cooling systems are required and economically justified in order to minimize loss of expensive solvent.

The total use of HFC-43-10 has been estimated to be less than 2 million pounds per year which translates to $<3.2 \times 10^{-1}$ MMTCE. Use of HFC-365mfc as a solvent is under development, with an industrial-scale plant expected to come on stream at the end of 2002.

10.3 Safety Considerations

CFC-113 and CFC-113 azeotropes containing alcohol a provided a solvent cleaning alternative that was comparatively safe – non-flammable, low toxicity – and chemically stable, with good solvency, at a moderate price. No environmentally acceptable substitute has been identified that duplicates these characteristics. While many cleaning processes that formerly were solvent based have changed to water or dry-ice based processes, no-clean processes, or other non-organic solvent based alternatives, some cleaning and drying requirements can only be met with organic solvents. The available, environmentally acceptable alternatives all fall short of providing the combination of properties of CFC-113, particularly with respect to safety. The HFC solvent systems, though expensive, do approach the level of safe handling and chemical stability provided by CFC-113. The high cost of these materials inherently limits their use to applications where these characteristics are truly needed.

11. Aerosols

Fluorocarbons have represented only a small niche of the U.S. aerosol market for the past 2 decades. Originally, CFCs were the dominant propellant in the 1960s and 1970s. However, even prior to the 1977 EPA ban on the use of CFCs in aerosols, allowing an exception for critical uses such as metered dose inhalers (MDIs) and those technical aerosol products where the propellant was the active ingredient, such as dusters and signal horns, etc., there was a small erosion in the size of the CFC market for aerosol applications. Higher prices for the CFCs were a significant driver for these inroads, in spite of the non-flammability and low toxicity of the CFCs. In anticipation of consumer concern regarding the use of CFC-11 and CFC-12 in aerosols after the Rowland-Molina hypothesis was published in 1974, the trend toward replacement of CFCs by hydrocarbons was accelerated. In 1977 the EPA banned the use of CFCs in aerosols for almost all applications. Certain technical aerosol products were allowed to use CFCs because no effective replacement for the propellant was available.

One option in response to the 1977 ban was to replace the CFCs by HCFCs and/or HFCs. However, the substitution ratio was low due to the higher price of these materials compared to CFCs, and the lower cost of options such as hydrocarbon propellants, reformulating using water-based blends (e.g. dimethyl ether/water) to lower flammability, and alternative delivery systems such as pumped spray.

Currently, for non-pharmaceutical technical aerosols, about 4.5% of the volumetric total of propellants used in the US is HFCs based on consolidated industry estimates from the hydrocarbon, dimethyl ether and HFC and aerosol product producers. The transition began in 1993/94 when the use of HCFCs in technical aerosols was prohibited in the U.S. and Europe. A very large GWP was reduced by transitioning from CFCs to HCFCs (in 1990) to HFCs in 1993/94.

Consumers select aerosol products because: they are hermetically sealed and will not leak, go stale, or evaporate; are pre-mixed for maximum formulation effectiveness; are far reaching, allowing penetration of hard to get to areas and no contact with the surface (important in obtaining uniform coatings, thorough cleaning, and where sanitary application is required); are uniquely capable of creating stable foams; and are recyclable when empty. Aerosols are efficient in that ingredients are not wasted through spilling or dripping.

11.1 Technology Alternatives and Applications

Competing propellants include the hydrocarbons: propane, butane, and isobutane, dimethyl ether, and compressed gases; alternative delivery systems include pumps, sticks, nebulizers, piston can systems, and roll-ons. HFC propellants are primarily used for selected applications where there is a concern about flammability, safety, or compliance with ambient air quality regulations or where there are unique performance requirements.

11.1.1 Metered Dose Inhalers

A metered dose inhaler (MDI) is a small, hand-held, pressurized multiple dose delivery system that delivers small doses of medication to the lungs, giving rapid symptomatic relief from asthma and chronic obstructive pulmonary disease (COPD). An MDI consists of the following components: a storage canister, a medicinal formulation containing a propellant and active ingredient, a metering valve to control delivery of a precise dose, and an actuator. When the piston is depressed to release the dose, the propellant flash evaporates, creating a fine mist of the drug suspended or dissolved in the propellant. This mist can easily penetrate into the small passageways of the lungs, where it is deposited.

The MDI is a vital therapeutic option for the estimated 300 million people worldwide who suffer from asthma and the many millions more affected by a variety of other respiratory diseases. Proper treatment makes a critical difference in these patients' ability to lead full and active lives. For some patients, it may mean the difference between life and death.

The parties to the Montreal Protocol have made an exception and allowed continued production of CFCs for use in MDIs, since these devices are essential for the treatment of asthma and COPD. Recognizing the need to develop alternatives to CFCs for use in MDIs, the pharmaceutical industry undertook an extensive research effort to develop MDIs utilizing alternatives. These medical aerosols must have the following characteristics: (1) Appropriate boiling point and vapor pressure, i.e., can be liquefied in a closed container at room temperature; (2) Low toxicity; (3) Nonflammable; (4) Appropriate density; (5) Good stability; (6) Appropriate solvency characteristics for the drug; and (7) Acceptable to the patient in terms of taste and smell.

After an extensive search, the only two propellants found to meet these stringent criteria were HFC-134a ($\text{CF}_3\text{-CH}_2\text{F}$) and HFC-227ea ($\text{CF}_3\text{-CHF-CF}_3$). An extensive research and testing effort was undertaken to develop new HFC-based therapeutic formulations for use in MDIs. These potential formulations must also undergo extensive toxicological, stability and clinical testing before they can obtain necessary regulatory approval and then be introduced to patients. Thus far, this effort has taken more than a decade. The worldwide effort to transition patients from CFC MDIs to CFC-free alternatives is underway, but is not yet complete. This patient transition is expected to be completed in 2005 in the European Union, but will likely not be concluded in other significant developed markets, such as the United States, until 2008-2010. The pace of the transition in the developing world is unclear, but it could continue beyond 2010.

In addition to furthering the environmental objectives under the Montreal Protocol, the CFC transition will also have important benefits for the climate because HFCs have a significantly lower global warming potential than CFCs.

In light of the ongoing CFC transition, complex patient health issues, lengthy drug development timelines, and the high cost of emission reduction opportunities, it is difficult to address HFC emissions associated with patient use of MDIs. A recent

comprehensive, independent, study in Europe concluded that the cost of reducing these emissions would be over 500 Euros per tonne of HFC reduced. [Enviros March, 2000].

The MDI industry has widely implemented good manufacturing practices in the production of MDIs, thereby significantly minimizing fugitive losses associated with the manufacturing process.

11.1.1.1 Social Utility – Metered Dose Inhalers

HFCs play a vital role in the operation of MDIs, a drug delivery system used by millions of patients to treat serious and life threatening illnesses. The success of the CFC MDI transition depends on patient use and acceptance of HFC MDIs. Several HFC based formulations are now available around the world. The transition from CFC-based to HFC-based formulations is underway and will continue well into the next decade .

It is also important to bear in mind that emissions associated with patient use of MDIs are extremely small. By 2010, the warming impact of HFC emissions from MDIs are projected to be approximately 1.4 MMTCE (5.1 Tg CO₂ Eq.) [EPA, 2001], only 0.07% of the warming impact of total US greenhouse gas emissions by that time. Physicians, patients, and industry must be assured that MDIs, the mainstay of inhalation therapy, will remain an available treatment option. Consideration of any measures affecting their use should be made in consultation with all appropriate parties, including physicians, patients, and the healthcare industry.

11.1.2 Tire Inflators

Tire inflators consist of an aerosol can containing a rubber latex sealant, a solvent/diluent, and a propellant. They are used to reinflate a flat tire allowing the driver to proceed to a repair station to have the tire fixed or replaced.

The advantages of using a tire inflator instead of jacking up the car and replacing the damaged tire are as follows:

1. Minimizing exposure time to hazards from rapidly moving traffic and inclement weather;
2. Reducing potential for attack by assailants; and
3. Providing a less strenuous way to temporarily repair a damaged tire, allowing the driver to effect immediate repairs that may otherwise be difficult due to age or infirmity.

Hydrocarbons, dimethyl ether, or HFC-134a are used as the propellant. However, highly flammable propellants such as hydrocarbons have been linked to deaths and injuries caused by explosions occurring in the repair shop when a torch was used to repair a brake drum adjacent to the inflated tire.

These developments led to reformulation to ozone depleting compounds by Nationwide Industries in the 80's, the recall and eventual withdrawal from the market by STP and

Prestone brands in the early 90's and subsequent reformulation to HFC-134a by Pennzoil in 1999.

11.1.2.1 Social Utility – Tire Inflators

The main reason for using a hydrofluorocarbon as a tire inflator, in this case HFC-134a, is to avoid potential injuries involving explosions when using a highly flammable propellant.

Total yearly usage in N. America is estimated to be approximately 3.1 million metric tons CO₂ equivalent.

11.1.3 Electronics Cleaning

Electronics cleaning aerosols consist of a solvent such as a hydrochlorofluorocarbon (e.g. HCFC-141b), a hydrofluorocarbon (e.g. HFC-43-10 or HFC-245fa) or a hydrofluoroether (e.g., such as CH₃-OC₄F₉), or a hydrocarbon. HFC-134a or carbon dioxide are used as propellants in order to ensure nonflammability. A finer spray is achieved when using HFC-134a rather than carbon dioxide.

These formulations are used primarily for spot rework to remove residues from high value components while minimizing potential damage due to incompatibility, thereby ensuring the proper functioning of the component subsequent to the cleaning process.

11.1.3.1 Social Utility – Electronics Cleaning

Use of these aerosol products for electronics cleaning helps to ensure the proper functioning of high value components and systems, reducing the frequency and expenses associated with malfunctions, failures, and/or warranty rework. HFC-134a is used as the propellant to reduce flammability in those niche applications where a finer spray characteristic is desirable.

The estimated volume of HFC-134a propellant is low because compressed gases are acceptable for most applications. The HFC propellant contribution is approximately 0.1 metric tons CO₂ equivalent.

The estimated total volume of HFC-43-10 used in aerosols is very low due to its high cost.

11.1.4 Dust Removal/Freeze Sprays/Signaling Devices

These products consist entirely of propellant, which is the active ingredient. Almost 100% of these products use HFC-134a or HFC-152a. They are used for:

1. Removal of dust from hard to reach space and crevices for maintenance of electronic equipment including computer components, imaging equipment, and high technology equipment in the laboratory, optics, and laser sectors; personal computers, PDAs, etc.
2. Removal of dust and/or particles from electronic components during the repair or manufacturing process;
3. Freezing of circuit components to test for dead faults; and

4. Marine and industrial safety alarms

In the first and second instance, the spraying of propellant gas against plastic substrates, especially in the presence of dust could create a static charge that would function as an ignition source. In the second instance hot soldering irons are quite often present in the vicinity, also constituting a potential source of ignition. In the third instance there are energized circuits potentially constituting a source of ignition. In the fourth instance, there could be a buildup of static charge and/or potential sources of ignition nearby. In the fifth instance, such alarms are used in inherently hazardous locations, often to signal for help due to fire.

HFC-134a is used in dust removal and circuit freezing because it is non-flammable, thereby eliminating the potential of fires in the presence of sensitive and/or energized electronic equipment. In some applications, notably office and home office dusters, HFC-152a has proved to be an effective, far lower GWP replacement. Although HFC-152a is moderately flammable, dusters have been developed utilizing this propellant that would not require a flammable label on the container according to 16 CFR 1500.3 (c) (6), and do not require special warehousing attention according to NFPA 30B. As a result of 152a substitution for 134a in office dusters, the warming impact of the “business as usual” scenario has been reduced by 2.75 MMTCE since 1999. However, in service and manufacturing areas, where duster use is more than incidental and sources of ignition are more prevalent, the totally non-flammable HFC-134a is preferred for reasons of worker safety.

HFC-134a and HFC-152a are more effective dusting agents than hydrocarbons or compressed gases on an equivalent volume basis due to their higher molecular weight. Compressed nonflammable gases, such as CO₂ and nitrogen, are not a viable option, since a very heavy, thick walled cylinder would be required to handle the pressure (more than ten times the maximum pressure rating of an aerosol can). If the propellant were solely in the gas phase, the pressure and thus the spray characteristic would change as the contents are discharged and the number of discharges per can would be severely reduced. The energy required to liquefy a compressed gas, so as to achieve a reasonable number of discharges, would be prohibitive. Also, the cost of using such a thick walled cylinder along with a valve capable of handling the high pressure would cost in the neighborhood of \$100.

Compressed air from a mechanical compressor may be considered an alternative. However, compressed air is inherently dirty and moist and, to provide equivalent functionality, an air compressor would be required to maintain a high-pressure level continuously so as to be available for intermittent sprays. Compressor systems are subject to continuous leakage through reed valves, check valves, hoses and fittings, tank fittings and the gun. When the cumulative effect of these leaks causes tank pressure to drop below a minimum level, the compressor cycles on to rebuild the level. The energy requirement has not been tested but is expected to be significant. Additionally, compressors typically cost hundreds of dollars and are not very portable.

Non-flammable, portable signaling horns that meet Coast Guard prescribed decibel ratings has long been an important part of boating safety. Similarly, warning horns are used in remote areas of chemical plants, refineries, and construction sites to summon help in emergencies. There are no known equivalent substitutes for HFC-134a in these applications.

11.1.4.1 Social Utility – Dust Removal/Freeze Sprays/Signaling Devices

These products play a key role in the successful and safe operation of manufacturing and maintenance process for selected segments of industry. They are used primarily where potential sources of ignition may be present and user safety would be compromised by use of less efficient, more flammable, VOC propellants.

The North American volume of HFC-134a used for these applications has been estimated to represent about 5.0 million metric tons of CO₂ equivalent. For certain dust removal where HFC-152a can have sufficient flame suppression, the volume has been estimated to represent about 0.1 million tonnes CO₂ equivalent. The share of 152a vs.134a in the office/home office duster segment appears to be growing. This will serve to reduce the total contribution to climate change from this category.

11.1.5 Mold Release Agents

These aerosol formulations contain lubricants such as silicones or fluoropolymers. The inside of the mold is sprayed to facilitate the release of injected or laid-up material, usually a plastic or a synthetic fiber, to avoid having any of the material sticking to the surface. Propellants include HFC-134a, and dimethyl ether. HFC-134a is used as a propellant in many instances to avoid flammability, since the mold release aerosol is sprayed on hot surfaces.

11.1.5.1 Social Utility – Mold Release Agents

These aerosol products using 134a play a key role in avoiding flammability incidents in the injection molding and textile industries. The volume of HFC-134a used for this application has been estimated to contribute less than 0.7 million metric tons CO₂ equivalent.

11.1.6 Formulated Consumer Products

Major categories include personal products such as hair care items, antiperspirants and deodorants, household products, spray paints, and automotive products. For many products, alternative, often less expensive, delivery systems exist side by side with an aerosol counterpart. The aerosol form continues due to consumer preference for its performance and functionality.

Propellants used in these products include hydrocarbons, dimethyl ether, compressed gases and HFC-152a.

A major driving force for incorporating HFCs in these products in the U.S. has been compliance with standards set by U.S. EPA under the Clean Air Act Amendments.

These standards have limited content of photochemically reactive volatile organic compounds (VOCs) in consumer products as part of the effort to reduce ambient ozone, one of the most health-damaging of irritants in smog. Additionally, some jurisdictions, notably in California and some northeastern states have promulgated regulations more stringent than the EPA standards in order to attain mandated ambient air quality levels that are uniquely difficult due to geography and topography.

Formulators of consumer products whether in aerosol, pump spray, solid forms, or liquids have had to deal with reductions in VOC content by the substitution of non- or exempted, low reactivity, VOC products for such common ingredients as alcohols, mineral spirits, and hydrocarbon propellants. The list of non-VOC materials includes water and most solids. The list of exempted materials includes acetone, CFCs, HCFCs, HFCs, and very low volatility liquids such as viscous oils.

The *practical* list for many products has been reduced to water, acetone, and HFCs, due to functionality and environmental requirements. For many personal products, the toxicity of acetone has limited its use, leaving water and HFCs as the only major VOC substitutes available to the formulator.

Due to the price disparity between HFCs and water, we find that HFCs are predominantly used where high levels of water are deleterious to the intended use of the product. A typical example would be antiperspirants, intended to prevent moisture. Other niche applications have been in finishing hair sprays for very fine hair where the weight and curl straightening impact of water cannot be overcome by other means. Some very highly effective insecticides require HFC use where active ingredient compatibility and crevice penetration issues with water are a problem.

11.1.6.1 Social Utility – Formulated Consumer Products

Limited use of HFC propellants will play a role toward reducing the VOC content in consumer product aerosols, thereby reducing the amount of organic material present in the atmosphere that can be photochemically oxidized to produce smog and deteriorate air quality. A U.S. state's failure to adequately reduce VOCs can lead to a loss of matching Federal Highway funds. This action would have a great impact on state economies by either delaying the repair and construction of new highways, and/or requiring increased in taxes, and/or requiring reprioritization of key budget items.

The volume of HFC-152a used for these applications in North America has been estimated to contribute approximately 0.9 million metric tons CO₂ equivalent.

Virtually all marketers of formulated consumer products have chosen HFC-152a over HFC-134a when they have needed to use an HFC because of its significantly lower GWP. These stewardship decisions have been reinforced in informal discussions with producers and EPA.

11.2 Energy Impact

Unlike refrigeration, air conditioning, and foam applications, the use of aerosols entails primarily the dispersal of chemicals, and the indirect contributions from this spraying would be minimal. Therefore, instead of carrying out LCCP analyses, estimates have been made for the amount of greenhouse gas emitted expressed in units of million metric tons of carbon dioxide equivalents. The estimated embedded energy and GWP of the fugitive emissions associated with manufacturing the Aerosol propellant is included in these figures.

11.3 LCCP

In the preceding discussion, an estimate was provided of the total North American annual carbon dioxide equivalent emissions for each of the primary aerosol propellant applications that use HFCs. Table 11-1 summarizes this information.

Table 11-1: Summary of Fluorocarbon Aerosol Propellant Application and North American Annual Emissions

Application	Propellant	GWP+ Manufacturing kgCO ₂ /kg	Annual Consumption and Emissions	Percent of US Greenhouse Gas Emission Inventory 2
			Million Metric Tons CO ₂ Equiv.	Percent
MDI ¹	134a	1313	0.25	0.0042
Tire Inflators	134a	1313	3.0	0.05
Electronic Cleaning	134a	1313	0.1	0.0085
Dust Removal, Freeze Spray, Signal Devices	134a 152a	1313 150	4.7 0.1	0.083
Mold Release Agents	134a	1313	0.6	0.010
Formulated Consumer Products	HFC-152a	150	0.9	0.016
Total	-	-	10.0	0.17

¹ In the United States, the transition from CFC MDIs to HFC MDIs is just now beginning. In 1998, only one HFC MDI product was available for sale in the United States. Several other MDI products are expected to be approved and introduced over the coming years.

² Total net emission of greenhouse gases in 1997 for the United States was listed as 1,605.0 million metric tons of carbon equivalents or 5,885.0 million metric tons of carbon dioxide equivalents as indicated in the Draft 1999 Inventory of U.S. Greenhouse Gas Emissions and Sinks (1990-1997)

11.4 Safety Considerations

As described above in the six individual discussions of propellant applications, safety and other societal concerns, such as VOC emissions, are addressed by the limited use of HFCs as aerosol propellants that occurs today.

Alternatives that might be used in place of HFCs are considerably less cost effective, reduce work place productivity, and impose additional costs of safety and safety risks. Over the diverse range of these uses, it is difficult to quantify the impact, in financial terms or otherwise.

11.5 References

U.S. EPA, Draft *1999 Inventory of U.S. Greenhouse Gas Emissions and Sinks* (1990-1997).

All estimates for the annual usage for each category of aerosol application were based on industry estimates from the HFC and aerosol product producers.

United Nations Environmental Programme (UNEP), Aerosol Technical Options Committee, Montreal Protocol on Substances that Deplete the Ozone Layer, 1998 Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride Technical Options Committee, Nairobi, Kenya 1999.

12. Fire Protection

This section addresses the narrow range of fire protection applications that were served by halons, prior to their phase out under the Montreal Protocol. The range of these specialized fire protection applications includes:

- Building contents fire protection, where high value equipment, data, and artifacts are involved and personal safety needs to be considered. In these situations, water, foam, or dry chemicals could damage or destroy the equipment, while halons and HFCs can effectively suppress the fire without damaging the equipment and endangering personnel. Computer rooms, telecommunications, and data centers are typical examples.
- Suppression of fire/explosion of flammable liquids, for example, in aircraft jet engines
- Hand held fire extinguishers (streaming), where valuable equipment would be damaged by water or dry chemicals

HFCs are important halon substitutes primarily in occupied areas where space and weight are constrained, or speed of suppression is important. HFC emissions from fire fighting are approximately 0.006% of all GHG emissions [source?].

12.1 Technology Alternatives

HFC use for fire fighting represents a very small share of total use. About 50% of the previous halon uses have been replaced with not-in-kind, non-ODP alternatives. These include water-based systems, foam, dry powder, and fire-protection engineering approaches involving risk analysis, prevention steps and early detection systems combined with portable extinguishing equipment. About 25% have been replaced with non-halocarbon gaseous agents such as inert gas mixtures or carbon dioxide. Despite the consumption phaseout in developed countries, there remain some critical halon uses in existing and new applications, such as civil and military aircraft, military vehicles, and other specialized high-risk situations. Critical use halon comprises 3 – 4% of the fire fighting market. Only about 20% of the former halon market has been replaced by HFCs.

12.1.1 Fluorocarbon Alternatives

Several HFCs are currently being sold commercially for fixed fire suppression applications as shown in Table 12-1.

These materials both replace halon 1301 and halon 1211 in fire protection systems.

Table 12-1: HFC Alternatives for Fixed Fire Suppression

Generic Name	Chemical Name
HFC-23	Trifluoromethane
HFC-125	Pentafluoroethane
HFC-227ea	1,1,1,2,3,3,3-heptafluoropropane
HFC236fa	Hexafluoropropane

12.2 Energy Impact

In contrast to the refrigeration and air conditioning equipment discussed in previous sections of this report, fire suppression systems are essentially non-emissive systems that sit idly while awaiting the mishap against which they are intended to protect. The fire detection system consumes a low level of electrical power, and small amounts of energy are consumed during periodic operating tests.

The systems are material intensive, and can include an amount of steel pressure vessels to store the fire suppression agent and steel piping to distribute the fire suppressant. The embodied energy in these materials, as well as the embodied energy in manufacturing and compressing the HFC or inert gas fire suppression material is the most significant energy input over the life cycle.

12.3 LCCP

Emissions of the fire suppressant can be categorized as non-fire and fire emissions, i.e., releases of the fire suppressant to extinguish a fire. Modern fire suppressant systems do not leak and do not require discharge testing. Consequently, non-fire emissions including leakage and accidental discharge are minimal. Current practices hold emissions, both fire and non-fire related, to 1-3% annually of the installed base and even this low figure is falling. Releases to suppress a fire in practice do not occur very frequently and currently are estimated to be approximately 1.5% of the installed bank. Over the 10 to 25 year typical system useful life, most of these systems are never called upon to suppress a fire. At the end of the useful life of a system, the fire suppressant can be recovered for recycling or reclaimed for transformation into non-GWP substances. The UNEP Halon Technical Option Report (1992) concluded: “when used only as fire suppressants there is no likely emissions scenario of these compounds (HFCs) which results in measurable environmental impact.”

12.4 Safety Considerations

HFCs are extremely effective in the basic fire suppression function. Speed of fire suppression using HFCs provides inherent safety benefits.

The acute toxicity of HFC fire suppression agents has been studied extensively and a methodology has been accepted as installation guidance for system installers. The guidance allows the safe usage of HFCs in the fire protection application.

12.5 Ways and Means

- The already small emissions of HFCs from fire protection can be controlled by:
- Selecting HFCs only where careful risk evaluation shows them to be the right choice when safety, speed of suppression, space and weight and cost are taken into account.
- Providing fire suppression systems with high reliability.
- Endorsing rigorous standards in fire suppression system design, installation, commissioning, inspection and maintenance.
- Recommending advanced fire detection that minimizes discharges.
- Minimizing emissions from testing and training.
- Supporting recovery and recycling.

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Appendix A: Embodied Energy and GWP of Fugitive Emissions of Fluorocarbons

In the “cradle-to-grave” accounting of warming impacts that is inherent in the Life Cycle Climate Performance (LCCP) concept, the warming impacts associated with the manufacture of any fluorocarbons must be accounted for. Two basic categories of fluorocarbon manufacturing related warming impact have been identified.

- The warming impact associated with the energy consumed (electric energy and various fuels burned on site) to manufacture both the fluorocarbon and the raw materials used to make the fluorocarbon (the so-called “embodied energy” or “embedded energy”)
- The direct warming impact of any byproduct greenhouse gases that are emitted by the manufacturing process (the so-called “fugitive” emissions).

The total manufacturing related warming impact is summarized in Table A-1 for R-22 and R-134a (the only compounds for which both energy and fugitive emissions data were available). The warming impact of fugitive emissions associated with R-22 production is due primarily to R-23 emissions. The manufacturing warming impact for R-22 is far larger than for any other compound.

Several other HFCs have important applications as refrigerants or refrigerant blend components, blowing agents, solvents, propellants, or fire suppressants – HFC-32, HFC-125, HFC-143a, HFC-43-10 mee, HFC-227ea, HFC-152a, and HFC-245fa, among others – but similar data is not available. Absent such data, HFC-134a has been taken to be representative of the HFC’s as a class, and for LCCP calculations, 9 + 0.3% of GWP has been added to the published GWP values, to account for embodied energy and fugitive emissions, respectively. The resulting values are included in Table A-1.

Table A-1: Estimated Manufacturing Related Warming Impact for R-22 and R-134a

Fluorochemical	CO ₂ Equivalent Warming (100 year ITH for direct warming impact of fugitive emissions) kg CO ₂ equivalent/kg chemical		
	Embodied Energy	Fugitive Emissions	Total
HCFC-22	3	390	393
HFC-134a	9	4	13
HFC-152a	9	1	10
HFC-32	9	2	11
HFC-125	9	8	17
HFC-143a	9	11	20
HFC-245fa	9	3	12
HFC-43-10-mee	9	4	13

A.1 Embodied Energy

Estimates of the embodied energy in the manufacture of several chlorocarbons and fluorocarbons are summarized in Table A-2. When expressed in terms of CO₂ warming equivalent, the estimates for various fluorocarbons range from 3 to 9, an insignificant amount compared to the 100 year ITH direct GWPs. No data was found for the embodied energy in manufacturing other HFCs. In this report, it has been assumed that the embodied energy for manufacturing all HFCs is, in GWP terms, 9 kg/kg HFC.

Table A-2: Estimates of Embodied Energy

Chlorocarbon/ Fluorocarbon	Embodied Energy Gj/Tonne	CO ₂ Equivalent kg CO ₂ /kg chemical	Source Ref. #
HFC-134a (Route A)	64	6	1
HFC-134a (Route B)	105	9	1
R-22	36	3	1
R-12	30	3	1
Ammonia	37	2	1
Isobutane	10	0.5	1
Cyclopentane	24	3	1
Trichloroethylene	32	3	1

A.2 Fugitive Emissions

Fugitive emissions include process emissions due to byproduct venting and leakage and fluorocarbon product losses when transferring into onsite storage vessels at the plant, into transportation containers (primarily truck trailers and ISO containers having a capacity of 35,000 lb. and rail tank cars having a capacity of 180,000 lb.), and into bulk storage containers at customer facilities.

In 1997, AFEAS collected data on fugitive emissions from the manufacturing of four compounds – three HCFC and one HFC – from their members, which was aggregated by a third party auditor. Table A-3, which is reproduced from Reference 2, summarizes the results of this AFEAS exercise.

Table A-3: Fugitive Emission Estimates (Reference 2)

Target Fluorocarbon	HCFC-22	HCFC-141b	HCFC-142b	HFC-134a
Total number of other substances reported to be emitted during production	6	4	4	15
Total process emissions expressed as percent of GWP of the target compound	26	1	2	6
Process emissions excluding HFC-23, expressed as percent of GWP of the target compound	3	1	2	4
100 yr ITH GWP ¹ of the target compound	1500	600	1800	1300
Incremental GWP due to total fugitive emissions	390	6	36	78

Source: Climate Change 95

DuPont and Elf Atochem have provided figures on fugitive emissions, based on their reporting to the U.S. EPA for their North American facilities, that show that the actual values for fugitive emissions are considerably less than the values summarized in Table A-3. The total fugitives for the DuPont and Elf Atochem HFC-134a facilities range between less than 0.1% and 0.3% of HFC-134a output, and consists primarily of minute leaks of the product itself. In both the DuPont and Elf Atochem facilities, unwanted byproduct fluorocarbons are not vented directly to the atmosphere, but are destroyed by a thermal oxidizer. Taking the upper end of this range (0.3%), the effective GWP increment for R134a is $0.3\% \times 1300 = 3.9 \cong 4$ kg CO₂/kg HFC-134a, a rather small level comparison with the +/-20% uncertainty of the GWP value (+/-20% of 1300 is +/-260). DuPont staff plan to present several papers on this topic at the Earth Technologies Forum this fall. For other HFCs, fugitive emissions have not been examined in this level of detail. A reasonable assumption is that total fugitive emissions of 0.3% is readily achieved by good plant design and operating practices, for any HFC. For the LCCP analysis in this report, the GWP of the fugitive emissions have been estimated as 0.3% of the GWP of the particular HFC (or HFCs for blends).

A.3 References

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Appendix B: GWP Values

The Global Warming Potential (GWP) of a gas relates the cumulative (integrated) warming over time caused by the emission of the gas to the cumulative warming caused by the emission of the same mass of CO₂. The two basic factors that drive the GWP value are the “radiative forcing” (the infrared absorption of an incremental amount of the gas in the atmosphere) of the gas and the rate of decay of the gas in the atmosphere, compared to CO₂. There are uncertainties in establishing quantitative values for both radiative forcing and atmospheric decay rate for both the fluorocarbons and CO₂. As a result the IPCC estimated that the accuracy of the GWP values is $\pm 35\%$. As new data has been and continues to be developed, GWP values have been revised and are subject to future revision. A detailed presentation of the methodology for determining GWP is contained in [IPCC [2001]]. The fundamental importance of GWP values to this study is that it permits the warming impact of fluorocarbon emissions to be compared to the warming impact caused by energy consumption (and the associated CO₂ emissions) for the various applications that make use of HFCs.

Values of the 100-year ITH Global Warming Potentials of the fluorocarbons of interest in this study are summarized in Table B-1. Four sets of values are provided:

- Values listed in Appendix B of the TEWI-3 Study.
- Those established by the IPCC in 1995 and documented in *Climate Change 1995*.
- The revised set of values by the World Meteorological Organization (WMO Report No. 44, “Scientific Assessment of Stratospheric Ozone”, WMO Global Ozone Research and Monitoring Project, 1999). These values were not fully peer reviewed by the ICCP, prior to publication.
- The updated values established by the IPCC in 2001 and documented in *Climate Change 2001*.

The GWP values from *Climate Change 1995* have been used for the LCCP calculations in this study, because both the current regime of national greenhouse gas emission accounting and the Kyoto Protocol targets continue to be based on these GWP values. The GWP values for the HFCs of interest to this study that are published in *Climate Change 2001* are typically within 15% of the values published in *Climate Change 1995*. Most values increased, a few decreased or remained the same.

Table B-1: Global Warming Potentials (100 year ITH), Relative to Carbon Dioxide

Fluorochemical	100 Year ITH GWP (kg CO ₂ /kg)			
	TEWI-3 Appendix B	Climate Change 1995	WMO 1999 ³	Climate Change 2001 ⁴
HCFC-22	1,700	1,500 ¹	1,900	1,700
HCFC-123	93	90 ¹	120	120
HCFC-141b	630	600 ¹	700	700
HCFC-142b	2,000	1,800 ¹	2,300	2,400
HFC-23	11,700	11,700 ²	14,800	12,000
HFC-32	650	650 ²	880	550
HFC-125	2,800	2,800 ²	3,800	3,400
HFC-134a	1,300	1,300 ²	1,600	1,300
HFC-143a	3,800	3,800 ²	5,400	4,300
HFC-152a	140	140 ²	190	120
HFC-227ea	2,900	2,900 ²	3,800	3,500
HFC-245fa	820	–	–	950
HFC-365mfc	–	–	910	890
HFC-43-10mee	1,300	1,300 ²	1,700	1,500
HFE-7100	–	–	390	390
HFE-7200	–	–	55	55
R-404A	3,260	3,260	4,544	3,784
R-407A	1,770	1,770	2,336	1,990
R-407C	1,530	1,525	1,984	1,653
R-410A	1,730	1,725	2,340	1,975
R-507	3,300	3,300	4,600	3,850

Source:

¹Climate Change 1995, Table 2.8.

²Climate Change 1995, Technical Summary, Table 4.

³WMO Report No. 44 (1999), Table 10-8

⁴Climate Change 2001, Table 6.7

R-404A: R-125/143a/134a (44/52/4)

R-407A: R-32/125/134a (20/40/40)

R-407C: R-32/125/134a (23/25/52)

R-410A: R-32/125a (50/50)

R-507: R-125/143a (50/50)