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Analysis of Costs to Abate International Ozone-Depleting Substance Substitute Emissions

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Executive Summary

Background

Since the introduction of the *Montreal Protocol on Substances That Deplete the Ozone Layer*, over a decade ago, international use of ozone-depleting substances (ODSs) has declined significantly. The key component of the Montreal Protocol is the stipulation that the production and consumption of all identified compounds that deplete the ozone layer are to be phased out by 2030 in developed countries and 2040 in developing countries. The use of hydrofluorocarbons (HFCs), and to a much lesser extent perfluorocarbons (PFCs), has allowed the rapid phaseout of chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and halons in the U.S. and other countries in applications for which other alternatives are not readily available. HFCs have generally been selected for applications where they provide superior technical (reliability) or safety (low toxicity and flammability) performance. In many cases, HFCs provide equal or better energy efficiency as compared to other available alternatives, thereby reducing long-term environmental impacts. HFCs are expected to replace a significant portion of past and current demand for ODSs in insulating foams, refrigeration and air-conditioning, propellants used in metered dose inhalers, specialized fire protection equipment, and in other applications.

The end-use sectors in which transition away from ODS use and production is occurring include the refrigeration and air-conditioning, aerosols, foams, solvents, and fire-extinguishing industries. An increasing reliance on HFC use in these processes has in turn increased concern over emissions of these gases. Emissions that result from the ODS-substitute sectors contribute to a group of gases known as the high global warming potential (GWP) gases, which includes HFCs, PFCs, and sulfur hexafluoride (SF₆). These gases are many times more effective (on a per ton basis) than CO₂ in trapping heat in the atmosphere. The global warming potentials of the high GWP gases range from 140 to over 23,900 times the global warming capability of CO₂, and in some cases these gases remain in the atmosphere for hundreds or thousands of years. Currently, the most widely used high GWP gas is HFC-134a, which has a shorter lifetime of about 15 years and a GWP of 1300.

Overview

The major focus of most previous analyses regarding GHG emission reduction opportunities has been on energy-related CO₂ emissions. Along with continued efforts on methane and nitrous oxide reductions, reduced emissions of the high GWP gases have the potential to make a significant contribution to cost-effective GHG reductions. This report has been developed, in part, to better characterize the role of the high GWP gases as part of a comprehensive GHG mitigation approach internationally. To that end, this report assembles the costs of reducing quantities of high GWP gas emissions from each of the major ODS-substitute end-use sectors into an international marginal abatement cost (MAC) curve that shows the total emission reductions achievable—at increasing monetary values of carbon—in the year 2020.

The three main objectives of this report—and of the analysis that supports the generation of the MAC curve—are to: (1) present the U.S. EPA’s current forecasts of global high GWP gas emissions from ODS-substitute sectors through 2020 under a “business-as-usual” scenario that assumes no further actions, apart from normal and expected incremental technological improvements, are taken to reduce emissions; (2) use available cost and technical data to describe those technologies and practices that can reduce these emissions from the major emissions sources analyzed (some of which are expected to be voluntarily adopted by industry); and (3) estimate the costs of reducing high GWP gas emissions for each major

source included in this analysis. Forecasts of world emissions are estimated and summarized by region for 2005, 2010, 2015, and 2020. These emissions baselines, when combined with cost, efficiency, and technical data on the specific technologies and practices available to reduce high GWP gas emissions, provide the set of data used to calculate regional, sectoral, and total global MAC curves. Aggregate results of the analysis—conducted by country—are presented (for the purposes of this report) by region in each of the following chapters. The three regions presented include: (1) the United States, (2) non-U.S. Annex I countries (that is, all Annex I countries except for the U.S.), and (3) non-Annex I countries (that is, all countries in the world except for Annex I countries).¹

This report is divided into the following five chapters, each corresponding with one of the ODS-substitute source-categories.

- Chapter 1. HFC Emissions from Refrigeration and Air-Conditioning
- Chapter 2. HFC Emissions from Aerosols
- Chapter 3. HFC Emissions from Foams
- Chapter 4. HFC and PFC Emissions from Fire Extinguishing
- Chapter 5. HFC and PFC/PFPE Emissions from Solvents

For each emission source, this report presents the following information:

- *Baseline Emissions of High GWP Gases.* A section in each chapter discusses the forecasted emissions from that source through 2020 in the three key regional groups (the U.S., Non-U.S. Annex I and Non-Annex I countries). Emissions baselines are estimated based on a “business-as-usual” scenario that assumes no further actions, apart from normal and expected incremental technological improvements, are taken to reduce emissions.
- *High GWP Gas Emission Reduction Options and Associated Costs.* Several available technologies or practices (“options”) have the potential to reduce high GWP gas emissions within each sector. The U.S. EPA uses discounted cash flow analysis to estimate the present and future cost of achieving the reductions associated with each option discussed. Costs are presented in terms of year 2000 United States dollars per metric ton of carbon equivalent (\$/TCE). The costs associated with emissions reductions have been identified and categorized as one-time investments and/or annual operating and maintenance (O&M) costs. In most cases, data on these costs were available; where sufficient data were not available, EPA has presented the options qualitatively.

The framework for this analysis is global in scope, consistent with the intent to develop inputs useful for macroeconomic studies. Given this broad view, this report does not present highly detailed analyses of the individual sources of high GWP gas emissions, nor can it comprehensively evaluate the comparative advantages or technical challenges of alternative technologies in specific industry sectors. It does, however, provide a valuable resource for policy makers internationally in characterizing the role of the high GWP gases as part of a comprehensive greenhouse gas (GHG) mitigation approach. While these gases represent only a small portion of global GHG emissions, they include the most quickly growing sources of emissions. While the focus of most previous work on GHG emission reduction opportunities has been on energy-related CO₂ emissions, reduced high GWP gases can also contribute to cost-effective GHG reductions. This analysis estimates the costs of innovative reduction efforts that can be undertaken by various industries, and is meant to supplement carbon dioxide, nitrous oxide, and methane economic

¹ The term “Annex I” refers to members of the United Nations Framework Convention on Climate Change (UNFCCC) listed under Annex I, which includes developed countries and countries with economies in transition. A comprehensive list of countries and the regions under which they are categorized for the purposes of this report is provided in Appendix B.

analyses in order to provide a broader understanding of the costs of a comprehensive GHG mitigation strategy that covers all of these gases; it will also help to identify opportunities to reduce the costs associated with such a strategy.

Baseline Emission Estimates

Until recently, few countries have made significant efforts to track and project the use and emissions of HFCs and PFCs used as ODS substitutes. However, to the extent that country-specific ODS substitute emission information is available—e.g. from National Communications submitted under the United Nations Framework Convention on Climate Change (UNFCCC)—each country’s data was used as the basis for projecting future emissions.

In the absence of reported data, the following approach was used. First, a “Vintaging Model” of ODS-containing equipment and products was used to estimate the U.S. use and emissions of ODS substitutes. Next, emissions from non-U.S. countries were estimated for each ODS consuming end-use in each country. In developing these estimates, it was initially assumed that the international transitions from ODSs to HFCs and other substitutes follow the same substitution patterns as the United States. These U.S.-based substitution scenarios were then customized to each region or country using adjustment factors that take into consideration differences in historical and projected economic growth,² the timing of the phase-out, and the distribution of ODS and substitute use across end-uses in each region or country. In some sectors, specific adjustments or methodologies were used that were specific only to that sector. The methodology used to estimate and adjust emissions is described further in Appendix A.

Exhibit ES-1 shows the emission estimates of high GWP gases from the ODS and ODS-substitute end use sources in the years 2005, 2010, 2015, and 2020. The exhibit shows a continuing rise in emissions from each of these sectors throughout the forecasted period. This growth in HFC and PFC emissions is expected as substitution in ODS markets reaches maximum market penetration.³

Source of High GWP Gases Used as ODS Substitutes	2005	2010	2015	2020
Refrigeration and Air-Conditioning	59.92	94.50	128.73	158.80
Partially and Fully Fluorinated Solvents	1.07	1.14	1.20	1.26
Aerosols	12.26	14.44	15.92	17.60
Foams	2.94	5.30	7.76	16.38
Fire Extinguishing	2.26	2.26	2.65	3.19
TOTAL	78.45	117.66	156.26	197.23

Notes:

Forecast assumes a “business-as-usual” scenario as described above.

The emissions forecast includes only direct emissions. Indirect emissions—those that result from the production of energy required in the manufacturing and operation of the emitting sources—are not included.

Sums might not add to total due to independent rounding.

Each chapter of this report presents similar tables, each of which present data specific to one of the three key regional groups analyzed: the United States, Non-U.S. Annex I countries, and Non-Annex I countries.

² Economic growth is used as a proxy for the growth in the use of and emissions from products containing ODSs and ODS substitutes. Further research is warranted to assess how closely these two variables have been related in the past and may be related in the future.

³ Although many developed countries are well into the phaseout of ODS production, continued substitution with high GWP gases, especially in developing countries, is expected much further than 2020, as long-lived ODS-containing products, such as air-conditioners and foams, are retired and replaced with ODS substitutes.

At the present time, industry decisions to pursue emission reductions depend greatly on the cost-effectiveness of the available reduction options. A major purpose of this report is therefore to estimate the cost-effectiveness of various emission reduction options and to determine the quantity of future emission reductions that might be achievable across a range of possible market values of carbon-equivalent emission reductions.

Economic Analysis of Options for Reducing Emissions of High GWP Gases

In addition to baseline emission estimates, each source-specific chapter of this report analyzes the technical and economic viability of several emission mitigation options. The cost of implementation and the resulting emission reductions associated with each option provide the bases for the analysis. The reduction options considered in this report were identified from various reports and literature on emission reductions, industry publications, and industry contacts. The most promising options to reduce high GWP gas emissions from ODS substitute sources broadly include: substituting other gases for high GWP gases in a variety of applications, where safety and performance requirements can be met; implementing new technologies that use and/or emit significantly lower amounts of the high GWP gas; and various process and handling options that reduce emissions during the manufacture, use, and disposal of products containing high GWP gases.

Data regarding options that are assumed to have already reached full market penetration or that are assumed not to be feasible in particular countries or regions are not included in the MAC analysis for those countries. Where particular options are deemed applicable, several specific assumptions and data elements contribute to the calculation of the MAC.

Discounting Costs and Benefits

This report uses discounted cash flow analysis to estimate the cost of achieving reductions through instituting each potential mitigation option available to the several sources. All costs are presented in real year 2000 United States dollars. Consistent with the approach EPA has used in developing high GWP gas and methane MAC curves for the United States, the practice of using discounted cash flow analysis reflects the decision-making process that manufacturers use when considering investments in emission reduction practices (see EPA, 1999; EPA, 2001). This decision-making process is typically a cost-benefit analysis, comparing the positive cost (financial burden) to the negative cost (financial and/or emission reduction benefit) associated with each potential mitigation option. Data to support estimates of both costs and benefits of options are available in most cases; where sufficient data are not available, the options are summarized qualitatively, but are not included in the MAC curves presented.

The positive costs are typically categorized as either one-time (capital) investment costs—such as may be incurred when installing new equipment or applying a retrofit option—or as O&M costs—such as are generally applied annually to maintain an option through manual labor, routine repairs, electricity or other fuel use, etc. Mitigation options may have one or both of these types of costs, and both ultimately affect the viability of the option. The costs used in this international analysis improve upon those used in the analysis that supported *U.S. High GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions* (EPA, 2001). International costs are extrapolated from these values using adjustment factors that vary by country and region according to the most pertinent variable (specific to each option or technology). Factors used to adjust these costs include relative labor rates (for labor-intensive options) and relative electricity prices (for energy-intensive options). For some specific

options—specifically those that are considered in the context of an international market in which prices are not highly variable by country—costs are assumed to be the same internationally.

Negative costs, or benefits, include savings that are achieved by reducing or mitigating emissions of a product, sale or recycling of recovered product, or by improving process energy efficiency. The value associated with a particular product may vary by country, and where possible, this variability is taken into account in estimating the benefit.

Together, all of the cost data described here, expressed as costs or savings per metric ton of carbon equivalent emissions reduced, contribute to the calculation of a *break-even price* specific to each mitigation option. This figure represents the point at which an entity (individual, corporation, industry, etc.)—regardless of environmental, legal, or policy concerns—will be financially indifferent in deciding whether to institute an emissions mitigation option. The concept of the break-even price and its implications are discussed briefly in the Marginal Abatement Cost Curves section below, and—along with the general equation used to estimate its value—in greater detail in Appendix D.

Marginal Abatement Cost Curves

The world high GWP gas MAC curve is shown in Exhibits ES-2 and ES-3 at four and twenty percent discount rates, respectively. Exhibit ES-3 also incorporates a forty percent tax rate. Each of these two curves uses the appropriate schedule of emission reductions and costs for all of the high GWP gases as presented in Exhibits ES-4 and ES-5. The MAC curve illustrates emission reductions achievable as the value of carbon increases (\$/TCE).

The MAC curve is derived by rank ordering individual reduction opportunities by \$/TCE and plotting the corresponding emission reductions cumulatively. Each point along the MAC curve shows the cost of abating an additional ton of carbon-equivalent gas at the margin. The break-even price (expressed in dollars per metric ton of carbon equivalent emissions and calculated as described in Appendix D) of each option determines its placement with respect to the y-axis. Moving away from the origin, each point on the curve represents a cumulative sum of emission reductions with respect to the x-axis. Points corresponding to a zero or negative \$/TCE value along the y-axis demonstrate a market in which the benefits of reducing the high GWP gas—represented by avoided costs of HFCs, for example—pay for the emission reduction effort alone. As discussed above, these negative costs imply that it is cost-efficient to adopt the measure (i.e., the option will result in financial savings). Positive break-even values imply financial costs that only the introduction of some external value of emission reductions (determined by an emissions trading market, through taxes or incentives, or through some other externally imposed value) can outweigh, thereby making an investment viable.

As seen in Exhibit ES-2—which is in effect an economic supply curve measuring the quantity of emission reductions supplied by industry to the market at increasing values of carbon—as one follows the curve away from the origin, its elasticity decreases drastically at or around a certain point. At values above this point (roughly \$200/TCE), the curve is relatively inelastic; thus, subsequent or marginal increases in the value of carbon will have a decreased effect on emission reductions. Reductions past this point are unlikely to occur without some external benefit or incentive, neither of which is within the scope of this publication. It is, however, interesting to note the quantifiable emission reductions that are cost-effective barring any type of external variable; these options for which break-even prices fall below zero contribute to a total potential emission reduction of about 18 MMTCE. A total of 65 MMTCE reduction in emissions is achievable at a carbon value less than about \$200/TCE.

Exhibit ES-2: 2020 Marginal Abatement Cost Curve for All ODS Substitutes at Four Percent Discount Rate (No Tax Rate)

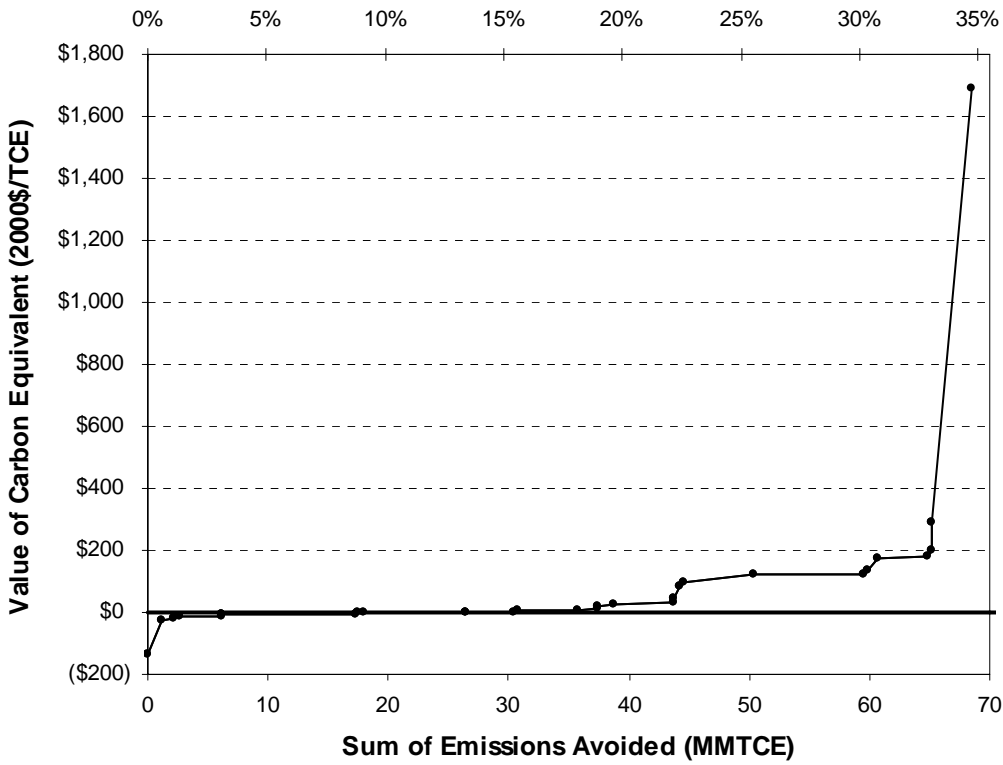


Exhibit ES-3: 2020 Marginal Abatement Cost Curve for All ODS Substitutes at Twenty Percent Discount Rate (40% Tax Rate)

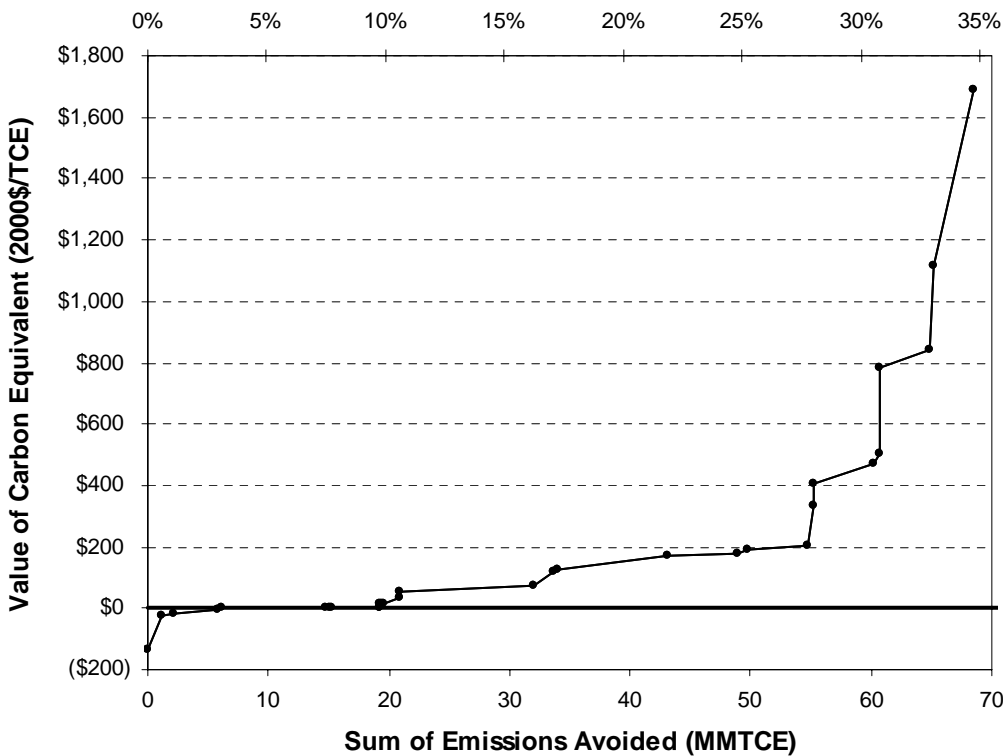


Exhibit ES-4: World Emission Reductions in 2020 and Break-Even Costs for ODS Substitutes (4% Discount Rate / 0% Tax Rate)

SECTOR	Option Name	Break-Even Price (\$/TCE) ^a		Emission Reduction of Option (MMTCE)	Reduction off Baseline of Option (Percent)	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
		Low	High				
Solvents	Retrofit	\$ (134.18)	\$ (134.18)	0.013	0.0%	0.013	0.0%
Aerosols (Non-MDI)	HFC to HC	\$ (22.76)	\$ (22.76)	1.078	0.5%	1.091	0.6%
Aerosols (Non-MDI)	HFC to NIK	\$ (21.37)	\$ (21.37)	1.078	0.5%	2.169	1.1%
Foams	Spray HFC-245fa/CO2 (HFC-227ea/365mfc) to HC	\$ (17.97)	\$ (15.13)	0.457	0.2%	2.626	1.3%
Refrigeration/AC	Leak Repair	\$ (11.74)	\$ (11.74)	3.593	1.8%	6.219	3.2%
Foams	PU One Component HFC-152a to HC	\$ (9.40)	\$ (9.40)	-	0.0%	6.219	3.2%
Foams	XPS: HFC-134a/CO2 to CO2/Alcohol	\$ (8.50)	\$ (8.50)	-	0.0%	6.219	3.2%
Refrigeration/AC	Replace DX with Distributed System	\$ (57.61)	\$ (4.78)	11.108	5.6%	17.327	8.8%
Foams	PU One Component HFC-134a to HC	\$ (0.07)	\$ (0.07)	0.136	0.1%	17.463	8.9%
Solvents	HFC to HFE	\$ -	\$ -	0.426	0.2%	17.889	9.1%
Refrigeration/AC	Recovery	\$ 0.49	\$ 0.49	8.510	4.3%	26.399	13.4%
Solvents	NIK Semi-Aqueous	\$ 0.80	\$ 0.80	0.098	0.0%	26.497	13.4%
Aerosols (Non-MDI)	HFC-134a to 152a	\$ 1.91	\$ 1.91	3.991	2.0%	30.487	15.5%
Solvents	NIK Aqueous	\$ 6.67	\$ 6.67	0.196	0.1%	30.683	15.6%
Refrigeration/AC	Enhanced HFC-134a in MVACs	\$ (275.47)	\$ 7.02	5.029	2.5%	35.712	18.1%
Foams	XPS: HFC-134a/CO2 to CO2	\$ 11.48	\$ 11.48	1.700	0.9%	37.412	19.0%
Foams	Appliance HFC-134a to HC	\$ 17.35	\$ 17.35	0.039	0.0%	37.451	19.0%
Foams	Appliance End-of-Life: Automated Process	\$ 23.82	\$ 23.82	1.336	0.7%	38.787	19.7%
Refrigeration/AC	HFC-152a in MVACs	\$ (73.65)	\$ 30.81	4.921	2.5%	43.708	22.2%
Foams	PU Continuous & Discontinuous Panel HFC to HC	\$ 43.83	\$ 43.83	-	0.0%	43.708	22.2%
Fire Extinguishing	FK-5-1-12	\$ 83.66	\$ 85.22	0.495	0.3%	44.203	22.4%
Foams	Spray HFC-245fa/CO2 (HFC-227ea/365mfc) to CO2	\$ 96.45	\$ 96.45	0.343	0.2%	44.546	22.6%
Refrigeration/AC	Ammonia Secondary Loop	\$ 11.47	\$ 123.84	5.918	3.0%	50.463	25.6%
Refrigeration/AC	HFC Secondary Loop	\$ 9.66	\$ 125.39	8.993	4.6%	59.456	30.1%
Fire Extinguishing	Inert Gases	\$ 71.10	\$ 136.29	0.396	0.2%	59.852	30.3%
Foams	Appliance End-of Life: Manual Process	\$ 175.09	\$ 175.09	0.793	0.4%	60.645	30.7%
Refrigeration/AC	CO2 for New MVACs	\$ (23.44)	\$ 180.72	4.237	2.1%	64.882	32.9%
Foams	Appliance HFC-245fa (HFC-227ea/365mfc) to HC	\$ 201.80	\$ 201.80	0.225	0.1%	65.107	33.0%
Fire Extinguishing	Water Mist	\$ 111.76	\$ 287.80	0.057	0.0%	65.163	33.0%
Aerosols (MDI)	Dry Powder Inhalers	\$ 1,691.25	\$ 1,691.25	3.409	1.7%	68.572	34.8%

^a Costs vary by country/region based on one-time or annual adjustment factors (e.g., electricity price, fuel price, etc.); therefore, the lowest and highest costs are shown.

Exhibit ES-5: World Emission Reductions in 2020 and Break-Even Costs for ODS Substitutes (20% Discount Rate / 40% Tax Rate)

SECTOR	Option Name	Break-Even Price (\$/TCE) ^a		Emission Reduction of Option (MMTCE)	Reduction off Baseline of Option (Percent)	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
		Low	High				
Solvents	Retrofit	\$ (132.14)	\$ (132.14)	0.013	0.0%	0.013	0.0%
Aerosols (Non-MDI)	HFC to HC	\$ (21.95)	\$ (21.95)	1.078	0.5%	1.091	0.6%
Aerosols (Non-MDI)	HFC to NIK	\$ (20.75)	\$ (20.75)	1.078	0.5%	2.169	1.1%
Refrigeration/AC	Leak Repair	\$ (3.78)	\$ (3.78)	3.593	1.8%	5.761	2.9%
Solvents	HFC to HFE	\$ -	\$ -	0.426	0.2%	6.187	3.1%
Refrigeration/AC	Recovery	\$ 0.49	\$ 0.49	8.510	4.3%	14.697	7.5%
Foams	Spray HFC-245fa/CO2 (HFC-227ea/365mfc) to HC	\$ (13.98)	\$ 1.53	0.457	0.2%	15.155	7.7%
Solvents	NIK Semi-Aqueous	\$ 2.14	\$ 2.14	0.098	0.0%	15.253	7.7%
Aerosols (Non-MDI)	HFC-134a to 152a	\$ 2.49	\$ 2.49	3.991	2.0%	19.243	9.8%
Foams	PU One Component HFC-152a to HC	\$ 2.77	\$ 2.77	-	0.0%	19.243	9.8%
Foams	XPS: HFC-134a/CO2 to CO2/Alcohol	\$ 12.82	\$ 12.82	-	0.0%	19.243	9.8%
Foams	PU One Component HFC-134a to HC	\$ 14.08	\$ 14.08	0.136	0.1%	19.379	9.8%
Solvents	NIK Aqueous	\$ 17.89	\$ 17.89	0.196	0.1%	19.575	9.9%
Foams	Appliance End-of-Life: Automated Process	\$ 37.16	\$ 37.16	1.336	0.7%	20.912	10.6%
Foams	PU Continuous and Discontinuous Panel HFC to HC	\$ 56.26	\$ 56.26	-	0.0%	20.912	10.6%
Refrigeration/AC	Replace DX with Distributed System	\$ 15.99	\$ 72.96	11.108	5.6%	32.020	16.2%
Foams	XPS: HFC-134a/CO2 to CO2	\$ 122.09	\$ 122.09	1.700	0.9%	33.719	17.1%
Foams	Spray HFC-245fa/CO2 (HFC-227ea/365mfc) to CO2	\$ 122.55	\$ 122.55	0.343	0.2%	34.062	17.3%
Refrigeration/AC	HFC Secondary Loop	\$ 45.33	\$ 173.22	8.993	4.6%	43.055	21.8%
Refrigeration/AC	Ammonia Secondary Loop	\$ 55.34	\$ 180.96	5.918	3.0%	48.972	24.8%
Foams	Appliance End-of-Life: Manual Process	\$ 191.65	\$ 191.65	0.793	0.4%	49.765	25.2%
Refrigeration/AC	HFC-152a in MVACs	\$ 55.55	\$ 205.42	4.921	2.5%	54.686	27.7%
Fire Extinguishing	FK-5-1-12	\$ 334.91	\$ 336.75	0.495	0.3%	55.181	28.0%
Foams	Appliance HFC-134a to HC	\$ 404.45	\$ 404.45	0.039	0.0%	55.219	28.0%
Refrigeration/AC	Enhanced HFC-134a in MVACs	\$ (35.34)	\$ 468.38	5.029	2.5%	60.248	30.5%
Fire Extinguishing	Inert Gases	\$ 369.25	\$ 505.32	0.396	0.2%	60.645	30.7%
Fire Extinguishing	Water Mist	\$ 467.17	\$ 781.28	0.057	0.0%	60.701	30.8%
Refrigeration/AC	CO2 for New MVACs	\$ 422.48	\$ 839.80	4.237	2.1%	64.938	32.9%
Foams	Appliance HFC-245fa (HFC-227ea/365mfc) to HC	\$ 1,115.58	\$ 1,115.58	0.225	0.1%	65.163	33.0%
Aerosols (MDI)	Dry Powder Inhalers	\$ 1,691.25	\$ 1,691.25	3.409	1.7%	68.572	34.8%

^a Costs vary by country/region based on one-time or annual adjustment factors (e.g., electricity price, fuel price, etc.); therefore, the lowest and highest costs are shown.

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1 Analysis of Costs to Abate International HFC Emissions from Refrigeration and Air-Conditioning

1.1 Introduction

A number of hydrofluorocarbons (HFCs) are used in refrigeration and air-conditioning systems and are emitted to the atmosphere during equipment operation and repair. Specifically, emissions occur during product and equipment manufacturing, during equipment servicing, and from the disposal of equipment and used refrigerant containers. Emissions also occur during equipment operation, as a result of component failure, leaks, and purges. The use of refrigeration and air-conditioning equipment also generates “indirect” emissions of greenhouse gases (primarily carbon dioxide) from the generation of power required to operate the equipment. In many, but not all, refrigeration and air-conditioning applications, these indirect emissions outweigh the direct emissions and, hence, energy efficiency has a major impact on the total greenhouse gas emissions of an application. To the extent possible, both direct and indirect emissions are considered in the refrigeration/air-conditioning analysis; however, options aimed solely at improving energy efficiency rather than abating HFC emissions are not explored in detail. HFCs used in this sector have global warming potentials (GWPs) that range from 140 to 11,700; the majority of HFCs used today in the refrigeration and air-conditioning sector have GWPs from 1,300 (i.e., HFC-134a) to 3,300 (i.e., R-507A).

The refrigeration and air-conditioning sector includes eight major end-uses:

- Household refrigeration;
- Motor vehicle air-conditioning;
- Chillers;
- Retail food refrigeration;
- Cold storage warehouses;
- Refrigerated transport;
- Industrial process refrigeration; and
- Residential and small commercial air-conditioning/heat pumps.

Each end-use is composed of a variety of different equipment types that have historically used ozone-depleting substances (ODSs) such as chlorofluorocarbons (CFCs) or hydrochlorofluorocarbons (HCFCs). As the ODS phase-out is taking effect under the Montreal Protocol, equipment is being retrofitted or replaced to use HFC-based substitutes or intermediate substitutes—HCFCs—that will eventually need to be replaced by non-ozone depleting alternatives. In time, HCFCs are expected to be replaced with HFCs or other alternative refrigerants. These end-uses are explained in more detail below.

Household Refrigeration

The household refrigeration end-use consists of household refrigerators and freezers. HFC-134a is the primary substitute for CFC-12 in domestic refrigeration units in most developing countries, with hydrocarbon refrigerant, especially isobutane (HC-600a), dominating much of the European market and continuing to grow in market share. HC-600a is also gaining market share in Japan (Kuijpers, 2002).

The charge size of a typical household refrigeration unit has decreased over the past 15 years to about 0.17 kilograms for new HFC-134a units (with HC-600a systems being about 40 percent smaller), and the equipment has an expected lifetime of about 20 years. This end-use is one of the largest in terms of the number of units in use; however, because the charge sizes are small and the units are hermetically sealed (and, therefore, rarely require recharging), emissions are relatively low. Thus, the potential for reducing emissions through leak repair is small. In most Annex I countries, where regulations are in place that require the recovery of refrigerant from appliances prior to disposal, the retirement of old refrigerators is not expected to result in significant refrigerant emissions. Refrigerant emissions at disposal from developing countries, where refrigerant recovery is not generally required, are expected to be greater. Emissions from the insulating foam in household refrigerators/freezers are discussed in a separate chapter of this report.

Motor Vehicle Air-Conditioning

Motor vehicle air-conditioners (MVACs) refer to the air-conditioning systems contained in motor vehicles (e.g., cars, trucks, and buses). Currently, the quantity of refrigerant contained in a typical car air-conditioner is approximately 1 kilogram (typically from 1 to 1.2 kilograms for vehicles containing CFC-12 systems, and an average of 0.8 kilograms for vehicles containing HFC-134a systems) (Atkinson, 2000). Due to concerns over the environmental impact of refrigerants, the average charge size of MVACs—as well as associated leak rates—have been reduced over time, and this trend is expected to continue. The expected lifetime of MVACs is about 12 years. Refrigerant use in this sector is significant because there are more than 700 million motor vehicles registered globally (Ward's, 2001). In developed countries, CFC-12 was the refrigerant used in MVACs until it was phased out of new cars from 1992 to 1994, after which all air-conditioners installed in new automobiles used HFC-134a. HFC-134a is also used as a retrofit chemical for existing CFC-12 systems (UNEP, 1998). CFC-12 is still used in MVACs in developing countries and its availability in some developed countries (e.g., the United States) has resulted in its use for servicing older MVACs that were originally manufactured as CFC-12 systems. A variety of HCFC/hydrocarbon refrigerant blends are approved for use in the United States by the U.S. EPA as replacements for CFC-12 in MVACs, although these blends have not been endorsed by vehicle or system manufacturers for such use. Globally, HCFC/hydrocarbon blends have captured only a small and declining share of the retrofit market. Climate change concerns associated with the use of HFC-134a resulted in the research and development into other MVAC alternatives. Possible alternatives to HFC-134a systems include transcritical carbon dioxide systems, hydrocarbons, and HFC-152a systems, all of which are under study and development (SAE, 2000).

Chillers

Chillers are used to regulate the temperature and reduce humidity in offices, hotels, shopping centers, and other large buildings, as well as in specialty applications on ships, submarines, and nuclear power plants and other industrial applications. The four primary types of chillers are centrifugal, reciprocating, scroll, and screw—each of which is named for the type of compressor employed. Chillers are long-lasting relative to most air-conditioning and refrigeration equipment. Most operating chillers will remain in service for more than 20 years, and some will last 30 years or more. A wide variety of chillers are offered, with cooling capacities from 7 kW to over 30,000 kW (RTOC, 2003). The charge size of a chiller depends mostly on cooling capacity, and ranges from less than 25 kilograms (reciprocating) to over 2,000 kilograms (centrifugal). HCFC-123 has been the refrigerant of choice as a retrofit option for newer existing CFC-11 units and HFC-134a has been the refrigerant of choice as a retrofit option for newer existing CFC-12 units. The replacement market for CFC-12 high-pressure chillers and CFC-11 low-pressure chillers is dominated by both HCFC-123 chillers and HFC-134a chillers in developed and developing countries. Following the phase-out of the production of HCFCs (in 2030 for developed

countries and 2040 for developing countries),¹ recycled, recovered, and reclaimed HCFCs will continue to be used in most countries. This trend is not the case, however, in the EU, where restrictions on the use of HCFCs in new equipment exist, where the production of HCFCs is not permitted beyond 2010, and where recycled HCFCs may not be reused beyond 2015. In the EU, HFC-134a will be an important option for chillers, but because of its global warming impact, it is being targeted for phase-out there. Ammonia chillers are, therefore, being used as an HFC alternative in some EU countries (Kuijpers, 2002).

Additionally, HFC-245fa is a potential refrigerant for use in new design low-pressure chillers to replace the market currently dominated by HCFC-123 (in low-pressure chillers), and HFC-134a (in high-pressure chillers). However, due to a variety of reasons, the commercialization of this chiller technology is not likely to occur in the next ten years or so, if at all. High-pressure chillers that currently use HCFC-22 will ultimately be replaced by several HFC refrigerant blends and HFC-134a chillers. Likewise, most existing CFC-114 chillers will be replaced with HFC-236fa or HFC-134a chillers, for use primarily in specialty applications (e.g., on ships, submarines, and nuclear power plants).

Retail Food Refrigeration

Retail food refrigeration includes refrigerated equipment found in supermarkets, convenience stores, restaurants, and other food service establishments. This equipment includes small reach-in refrigerators and freezers, refrigerated display cases, walk-in coolers and freezers, and large parallel systems. Charge sizes range from 6 to 1,800 kilograms, with a lifetime of 15 to 20 years. Convenience stores and restaurants typically use stand-alone refrigerators, freezers, and walk-in coolers. In contrast, supermarkets usually employ large parallel systems that connect many display cases to a central condensing unit by means of extensive piping. Because the piping required for connection of all the cases can be miles long, these systems contain very large refrigerant charges and often experience high leak rates.

During the earlier phases of the CFC phase-out in developed countries, the use of HCFC-22 in retail food refrigeration was expanded considerably. Retail food equipment is being retrofitted with HCFC-based blends, although HFC blends are also used as a retrofit refrigerant. The HFC blend R-404A is the preferred refrigerant being used in new retail food equipment in developed countries, while R-507A is also used extensively in the market (Kuijpers, 2002). In developing countries, distributed systems as well as centralized systems that use HFCs, hydrocarbons, ammonia, and carbon dioxide are being developed (both with and without secondary loops) (Kuijpers, 2002).

Cold Storage Warehouses

Cold storage warehouses are used to store meat, produce, dairy products, and other perishable goods. The expected lifetime of a cold storage warehouse is 20 to 25 years, and while charge sizes vary widely with system size and design, a rough average is about 4,000 kilograms. Warehouses in developed countries have historically used CFC-12 and R-502 refrigerants, and use HCFC-22 and HFC-134a as replacements in new equipment. Once HCFCs are phased out, R-404A and R-507A are expected to replace HCFC-22 in new warehouses. Retrofits are also possible; for example, existing CFC-12 cold storage warehouses can be retrofitted with R-401A, and existing R-502 warehouses can be retrofitted with R-402A. Not all

¹ Several scientific studies have found that HCFC-123 in chillers can bring environmental benefits compared to other refrigerants as a result of its low ODP, very low direct GWP, very short atmospheric lifetime, and the fact that its design allows for both extremely low emissions (documented at less than 0.5 percent annually [Calm et al., 1999; Smithart, 2003]) and the highest full-load efficiency (RTOC, 2003). Nonetheless, the emission projections developed for this analysis assume full compliance with the current HCFC phase-out schedule.

cold storage warehouses currently use halocarbon refrigerants. Many facilities, for example, use ammonia in secondary loop brine systems.

Refrigerated Transport

The refrigerated transport end-use includes refrigerated ship holds, truck trailers, railway freight cars, and other shipping containers. The average charge sizes are relatively small (7 to 8 kilograms). The expected lifetime of a refrigerated transport system is 12 years. Trailers, railway cars, and shipping containers using CFC substitute refrigerants are commonly charged with HFC-134a, R-404A, and HCFC-22 (UNEP, 1999a). Ship holds, on the other hand, rely on HCFC-22 (UNEP, 1999a) and ammonia. In addition to HFC-134a, R-404A can also be used in new equipment. Existing equipment can be retrofitted with R-401A, R-402A, R-404A, R-507A, and other refrigerants. In addition, refrigerated transport equipment includes systems that operate based on the evaporation and expansion of liquid carbon dioxide or nitrogen.

Industrial Process Refrigeration

Industrial process refrigeration includes complex, often custom-designed, refrigeration systems used within the chemical industry, petrochemical industry, pharmaceutical industry, oil and gas industry, metallurgical industry, sports and leisure facilities, and many other applications. Charge sizes typically range from 650 to 9,100 kilograms (although charge sizes for some applications can fall outside this range), and the average lifetime is approximately 25 years. Ammonia, hydrocarbons, HCFC-123, and HFC-134a are expected to be the most widely used substitute refrigerants for new equipment in the near future (UNEP, 1999a). Assuming no changes to the requirements of the Montreal Protocol and no additional restrictions on refrigerant choice, upon completion of the HCFC phase-out, HFC-134a, R-404A and R-507A are expected to be the primary refrigerants used in this end-use.

Residential and Small Commercial Air-Conditioning/Heat Pumps

Residential and small commercial air-conditioning (window units, unitary air-conditioners, packaged terminal air-conditioners) and heat pumps are another source of HFC emissions. Most of these units are window and through-the-wall units, ducted central air-conditioners, and non-ducted split systems. The charge sizes of the equipment in this sector range based on cooling capacity requirements, and are on the order of 0.5 to 10 kilograms for residential systems, and about 10 to 180 kilograms for commercial systems. The average lifetime of equipment is 15 years. Residential and commercial air-conditioning has been relying almost exclusively on HCFC-22 refrigerant. R-410A, R-407C, and HFC-134a are currently being used to replace HCFC-22 in some new equipment for most end-uses, and this trend is expected to continue as HCFC-22 is phased out. In particular, R-410A is expected to dominate the U.S. residential market in the future, while R-407C is expected to replace HCFC-22 mainly in retrofit applications and some new residential equipment. Other countries may experience different patterns of R-410A and R-407C use.

1.2 Baseline Emission Estimates

1.2.1 Emission Estimating Methodology

Description of Methodology

A full description of the emission model used to calculate ODS substitute emissions from all sectors is provided in Appendix A. Specific information on how the model calculates refrigeration and air-conditioning emissions is described below.

The U.S. EPA's Vintaging Model and data from industry are used to simulate the aggregate impacts of the ODS phase-out on the use and emissions of various fluorocarbons and their substitutes in the United States (see Appendix A). Emission estimates for non-U.S. countries incorporate estimates of the consumption of ODSs by country, as provided by the United Nations Environment Programme (UNEP, 1999b). The estimates for the European Union (EU) were provided in aggregate and each country's gross domestic product (GDP) was used as a proxy to divide the consumption of the individual member nations from the EU total. Estimates of country-specific ODS consumption as reported under the Montreal Protocol were then used in conjunction with Vintaging Model output for each ODS-consuming sector. In the absence of country level data, preliminary estimates of emissions were calculated by assuming that the transition from ODSs to HFCs and other substitutes follow the same general substitution patterns internationally as observed in the United States. From this preliminary assumption, emission estimates were then tailored to individual countries or regions by applying adjustment factors to U.S. substitution scenarios, based on relative differences in (1) economic growth; (2) rates of ODS phase-out; and (3) the distribution of ODS use across end-uses in each region or country, as explained below and in further detail in Appendix A.

Emission Equations

For refrigeration and air-conditioning products, emission calculations are split into two categories: emissions during equipment lifetime, which arise from annual leakage and service losses, and disposal emissions, which occur at the time of discard. The first equation calculates the emissions from leakage and service, and the second equation calculates the emissions resulting from disposal of the equipment. These service/leakage emissions and disposal emissions are summed to calculate the total emissions from refrigeration and air-conditioning. As new technologies replace older ones, improvements in their leak, service, and disposal emission rates are assumed to occur.

Emissions from any piece of equipment include both the amount of chemical leaked during equipment operation and the amount emitted during service. Emissions from leakage and servicing can be expressed as follows:

$$ES_j = (I_a + I_s) \times \sum QC_{j-i+1} \quad \text{for } i=1 \rightarrow k$$

Where:

ES_j = *Emissions from Equipment Serviced*. Emissions in year j from normal leakage and servicing of equipment.

I_a = *Annual Leak Rate*. Average annual leak rate during normal equipment operation (expressed as a percentage of total chemical charge).

l_s = *Service Leak Rate*. Average annual leakage from equipment servicing (expressed as a percentage of total chemical charge).

Q_c = *Quantity of Chemical in New Equipment*. Total amount of a specific chemical used to charge new equipment in a given year by weight.

j = *Year of emissions*.

i = *Counter*. From 1 to lifetime (k).

k = *Lifetime*. The average lifetime of the equipment.

Note: It is recognized that leakage rates are not a function of the total system, but change with system pressure and temperature. For instance, when equipment charges are diminished due to refrigerant losses (leakage), system pressures are also reduced somewhat and the leakage rate changes. This becomes appreciable once the entire liquid refrigerant is gone. The average leak rates used in the equation above account for this effect. They also account for the range of equipment types (from those that do not leak at all to those with high leaks) and service practices (i.e., proper refrigerant recovery and refrigerant venting).

Emissions also result at equipment disposal. The disposal emission equations assume that a certain percentage of the chemical charge will be emitted to the atmosphere when that vintage is discarded. Disposal emissions are thus a function of the quantity of chemical contained in the retiring equipment fleet and the proportion of chemical released at disposal:

$$Ed_j = Q_{c_{j-k+1}} \times [1 - (rm \times rc)]$$

Where:

Ed = *Emissions from Equipment Disposed*. Emissions in year j from the disposal of equipment.

Q_c = *Quantity of Chemical in New Equipment*. Total amount of a specific chemical used to charge new equipment in year $j-k+1$, by weight.

rm = *Chemical Remaining*. Amount of chemical remaining in equipment at the time of disposal (expressed as a percentage of total chemical charge).

rc = *Chemical Recovery Rate*. Amount of chemical that is recovered just prior to disposal (expressed as a percentage of chemical remaining at disposal (rm)).

j = *Year of emissions*.

i = *Counter*. From 1 to lifetime (k).

k = *Lifetime*. The average lifetime of the equipment.

Finally, lifetime and disposal emissions are summed to provide an estimate of total emissions.

$$E_j = Es_j + Ed_j$$

Where:

E = *Total Emissions*. Emissions from refrigeration and air-conditioning equipment in year j .

Es = *Emissions from Equipment Serviced*. Emissions in year j from normal leakage and servicing (recharging) of equipment.

Ed = *Emissions from Equipment Disposed*. Emissions in year j from the disposal of equipment.

j = *Year of emissions*.

Regional Variations/Adjustments

From the general methodology described in Appendix A, the following regional assumptions were applied:

- **Adjustment for EC-Regulation No. 2037/2000.** Countries in the European Union are assumed to be in full compliance with EC-Regulation No. 2037/2000, which stipulates that no new

refrigeration and air-conditioning equipment be manufactured with HCFCs as of January 1, 2002. The EC regulation also bans the use of HCFCs in all equipment after January 1, 2015. Compliance with these regulations will likely lead to increased use of HFCs to replace HCFCs, and is assumed to correspond to increased emissions of 20 percent in 2005, 15 percent in 2010, and 15 percent in 2020, relative to what the EU baseline otherwise would be (see Appendix A for an explanation of how these baseline refrigeration and air-conditioning emissions are calculated before applying this adjustment). These relative emission increases were determined by running a Vintaging Model scenario wherein the uses of HCFCs were assumed to comply with the regulation.

- **Recovery/recycling adjustments.** The emissions from developing (or “non-Annex I”) countries, Countries with Economies in Transition (CEITs) and Turkey were increased by approximately 20 percent over initial estimates to reflect the assumed low levels of recovery and recycling of refrigerants from small end-uses (i.e., MVACs, commercial/residential air-conditioning, refrigerated transport, and other appliances), relative to the United States. This assumed increase in emissions from lower levels of recovery/recycling was derived based on Vintaging Model test runs, wherein emissions were first projected assuming an 80-percent baseline recovery rate (to reflect the assumed status quo in developed countries) and then projected again assuming a 30-percent baseline recovery rate (to reflect the assumed status quo in developing countries). The GWP-weighted emissions in the latter low-recovery scenario were determined to be approximately 20 percent higher than the former high-recovery scenario (ICF Consulting, 2002a).
- **Market adjustments.** The baseline assumes that hydrocarbon and ammonia refrigerants and other non-HFC or low-emitting options will penetrate international markets more than in the United States, because of more relaxed safety standards, greater acceptance of non-HFC choices by industry, end-users, regulators, and insurance companies, and increased public and regulatory scrutiny to reduce HFC emissions. To reflect this, baseline emission estimates of non-U.S. countries were reduced by the following amounts:
 - European Union: 30%
 - Japan: 30%
 - Non-EU Europe: 25%
 - CEITs: 20%
 - Australia/New Zealand: 10%
 - All Other Countries: 20%

These assumptions were based solely on qualitative information on current and future global market penetration of low-GWP refrigerants, as well as low-emission technologies and practices. For example, hydrocarbon technology is believed to now dominate the domestic refrigeration market in Western Europe, particularly in Germany and Scandinavia. Hydrocarbon domestic refrigerators are produced by major manufacturers in Germany, Denmark, Italy, Japan, UK, France, Spain, and Sweden. Some of the largest manufacturers in China, India, Indonesia, Australia, Korea, and Cuba are also producing domestic refrigerators that use hydrocarbons (Greenpeace, 2001; Japan Times, 2002). To reflect this and many other trends, baseline emissions from non-U.S. countries are adjusted downwards as shown above.

- **Redistribution of emissions by end-use, based on MVAC analysis.** Based on a variety of available data on international motor vehicle sales, air-conditioning usage, and MVAC emissions, a separate analysis was conducted to estimate total MVAC emissions by region. These MVAC emission estimates by region were then used to determine the relative share of refrigeration/air-

conditioning emissions attributable to MVACs, and to reapportion emissions from all other end-uses accordingly, relative to the end-use breakout calculated for the United States. The methodology used to perform this analysis is explained in detail below.

MVAC Analysis

Because MVACs are expected to account for a much higher proportion of total refrigeration/AC emissions in the United States compared to most other developed and, especially, developing countries (due to the number of air-conditioned automobiles on the road), this end-use has been modeled separately to achieve a higher degree of accuracy in emission estimates.

Specifically, for all countries for which data on historical vehicle sales were available in Ward’s World Motor Vehicle Data (2001), country-specific models were developed to estimate emissions from MVACs. To populate this model, the number of operational MVACs was estimated based on annual historical sales of passenger cars and light trucks (as provided in Ward’s (2001)) and on estimates of the percentage of the vehicle fleet equipped with air-conditioning units. Based on quantitative and qualitative data provided in EC (2003a), Hill and Atkinson (2003), OPROZ (2001) and Barbusse et al. (1998), Table 1-1 shows the percent of current and future vehicle fleets assumed to be equipped with operational air-conditioning units:

Table 1-1: Percent of On-Road Vehicle Fleet Assumed to Have Operational Air-Conditioning Units

Country/Region	2000	2005	2010	2015	2020
United States & Japan	95.0%	98.0%	99.0%	99.0%	99.0%
All Other Annex I countries	58.0%	65.5%	70.0%	80.5%	95.0%
Latin America & Caribbean	45.0%	50.0%	55.0%	60.0%	65.0%
All Other Non-Annex I countries, Russia, CEITs	18.0%	23.0%	28.0%	33.0%	38.0%

As shown above, MVACs in Japan are assumed to have reached the same degree of market penetration within the vehicle fleet as in the United States. In all other countries, MVACs are assumed to increasingly penetrate the vehicle fleet over time. In developing countries, this rate of increase is assumed to be one percent each year, while in all other Annex I countries, the rate of increase is assumed to be more rapid, reaching 95 percent of the vehicle fleet in 2020 (EC, 2003a; Hill and Atkinson, 2003).

Based on historical estimates of vehicle fleet size and assumptions about the percent of vehicle fleets with operational air-conditioners (Baker, 2002), current and future MVAC fleets were calculated for each country. From these estimates, MVAC emissions were calculated by assuming that, as a result of low levels of refrigerant recovery and recycling, MVAC emissions in developing countries are approximately 20 percent greater than emission rates in the United States (where annual average emissions for this analysis are assumed to be 10.9 percent² and emissions at disposal are assumed to be 42.5 percent of the total MVAC charge).³ MVAC charge size and loss rates were decreased in later years, as it is assumed that MVAC systems become tighter and require less refrigerant over time. All systems are assumed to be HFC-134a in the baseline.

Once MVAC emissions were estimated for those countries for which Ward’s data were available, the proportion of MVAC emissions as a percent of the total refrigeration/AC emissions (developed using the methodology described above) was calculated. These percentages were then averaged by region. The

² This emission rate includes emissions released during routine equipment operation from leaks, as well as those released during the servicing of equipment by both professionals and do-it-yourselfers.

³ While these emission rates differ slightly from those reported in recent studies conducted for the European Commission (EC, 2003a; 2003b), overall MVAC emissions based on U.S. EPA and EC estimates are comparable.

average estimated percentage of refrigeration/air-conditioning GWP-weighted emissions that are attributable to MVACs by regional grouping are presented in Table 1-2.

Table 1-2: Estimated Percent of Refrigeration/Air-Conditioning HFC Emissions Attributable to MVACs

Country/Region	2005	2010	2015	2020
United States & Japan	37.0%	28.5%	22.7%	19.5%
All Other Annex I Countries	48.7%	40.4%	20.5%	15.9%
Latin America & Caribbean	18.7%	16.2%	10.7%	7.8%
Russia, CEITs & All Other Non-Annex I Countries	9.5%	10.7%	10.9%	13.6%

Based on the above percent of sector baseline emissions assumed to come from MVACs for each region, the U.S. baseline emissions breakout by end-use was used to proportionally redistribute the remaining emissions of a particular country/region. Thus, for example, because MVACs contribute only 4.0 percent of total sector emissions in Latin American countries in 2005, the balance of emissions in Latin America was distributed across all other end-uses, in proportion to the U.S. end-use breakout. Therefore, if the emissions in Latin America in 2005 were estimated to be 10 MMTCE, this analysis assumes that 0.4 MMTCE are from MVACs and the remaining 9.6 MMTCE are from other sector end-uses. The resulting breakout of baseline GWP-weighted HFC emissions by end-use and region are summarized in Table 1-3. These emission breakouts by end-use help determine the maximum amount of emissions that can be avoided by any given abatement option (since each option is applicable only to specific end-uses).

Table 1-3: Distribution of Refrigeration and Air-Conditioning Sector HFC Emissions by End-use, Region, and Year

End-use	United States & Japan	All Other Annex I	Latin America &	All Other Non-Annex I,
			Caribbean	Russia, CEITs
2005				
Chillers	3.2%	2.6%	4.1%	4.6%
Retail Food	38.5%	31.3%	49.6%	55.3%
Cold Storage	1.2%	1.0%	1.6%	1.7%
Industrial Process	4.5%	3.7%	5.8%	6.5%
Commercial A/C	0.7%	0.6%	0.9%	1.0%
Residential A/C	0.6%	0.5%	0.8%	0.9%
Refrigerated Transport	13.8%	11.3%	17.9%	19.9%
Other Appliances	0.5%	0.4%	0.6%	0.7%
MVACs	37.0%	48.7%	18.7%	9.5%
2010				
Chillers	2.3%	1.9%	2.7%	2.9%
Retail Food	42.1%	35.1%	49.4%	52.6%
Cold Storage	1.4%	1.2%	1.7%	1.8%
Industrial Process	6.1%	5.1%	7.1%	7.6%
Commercial A/C	3.7%	3.1%	4.4%	4.6%
Residential A/C	5.6%	4.7%	6.5%	7.0%
Refrigerated Transport	9.8%	8.2%	11.5%	12.2%
Other Appliances	0.4%	0.4%	0.5%	0.5%
MVACs	28.5%	40.4%	16.2%	10.7%
2015				
Chillers	1.8%	1.9%	2.1%	2.1%
Retail Food	42.6%	43.9%	49.3%	49.2%
Cold Storage	1.5%	1.5%	1.7%	1.7%
Industrial Process	6.6%	6.8%	7.6%	7.6%

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End-use	United States & Japan	All Other Annex I	Latin America & Caribbean	All Other Non-Annex I, Russia, CEITs
Commercial A/C	6.4%	6.5%	7.3%	7.3%
Residential A/C	9.9%	10.2%	11.5%	11.4%
Refrigerated Transport	7.4%	7.6%	8.6%	8.5%
Other Appliances	1.0%	1.1%	1.2%	1.2%
MVACs	22.7%	20.5%	10.7%	10.9%
2020				
Chillers	1.6%	1.6%	1.8%	1.7%
Retail Food	41.6%	43.5%	47.7%	44.7%
Cold Storage	1.5%	1.6%	1.8%	1.6%
Industrial Process	7.0%	7.4%	8.1%	7.6%
Commercial A/C	8.3%	8.7%	9.6%	8.9%
Residential A/C	13.0%	13.6%	14.9%	14.0%
Refrigerated Transport	6.5%	6.8%	7.5%	7.0%
Other Appliances	0.8%	0.9%	1.0%	0.9%
MVACs	19.5%	15.9%	7.8%	13.6%

Note: Totals may not sum to 100% due to independent rounding.

1.2.2 Baseline Emissions

The amount of HFC emissions from MVAC units is expected to rise, since HFC-134a has been the primary refrigerant used in the growing automobile industry, and because it is the primary refrigerant used to replace older CFC-12 systems. The baseline for MVACs assumes a mix of professionally serviced systems and those serviced by unskilled people without recovery equipment (i.e., “do-it-yourselfers”). Since commercial unitary and residential air-conditioning equipment has yet to transition fully into HFCs, the emissions of HFCs from these end-uses in 2005 are estimated to be relatively insignificant, but will increase substantially over time. Retail food systems are expected to transition at least in part to HFC-134a and HFC-containing blends, and because of certain equipment characteristics, such as their large number of fittings, often have higher refrigerant emission rates. Because of the relatively high cost of refrigerant and the large charges associated with retail food equipment, the baseline assumes that an inherently strong economic incentive exists to closely monitor refrigerant leakage in these types of equipment. Cold storage systems also have large charge sizes, but their emissions relative to other refrigeration and air-conditioning end-uses are not expected to increase significantly. HFC emissions from chillers are relatively low as a result of the continued use of HCFC-123 in this application,⁴ as well as the low leak rates of new HFC-134a units. The baseline emission projections assume that the recovery and recycling of refrigerants during service and disposal in Annex I countries will curtail emissions across all of the end-uses.

The resulting baseline estimates of HFC emissions are summarized in Table 1-4.

Table 1-4: Baseline HFC Emission Estimates from Refrigeration and Air-Conditioning (MMTCE)

Region	2005	2010	2015	2020
United States	26.87	40.08	53.95	67.84

⁴ Note the emissions of all CFC and HCFC refrigerants, including HCFC-123, are not included in the baseline emission estimates.

Region	2005	2010	2015	2020
Non-U.S. Annex I	18.11	25.66	35.70	38.11
Non-Annex I	14.94	28.77	39.08	52.86
Total	59.92	94.50	128.73	158.80

Note: Totals may not sum due to independent rounding.

1.3 Costs of HFC Emission Reduction from Refrigeration/AC

This section presents a cost analysis for achieving HFC emission reductions from the emission baselines presented above. Each abatement option is described below, but only those options not assumed to occur in the baseline and for which adequate cost data are available are included in the cost analysis. To the extent possible, this analysis considered total equivalent warming impacts (TEWI), to account for the climate and cost impacts associated with energy consumption (i.e., indirect emissions). Due to data limitations, a full life cycle analysis was not possible. For example, the cost and emission impacts associated with (a) the manufacture of refrigerant and all system components, (b) the energy required for reclamation, and (c) the recycling of all system components at the end of equipment life were not assessed in this analysis.

The remainder of this section provides a description of the economic assumptions for these abatement options.

1.3.1 Description and Cost Analysis of Abatement Options

HFC emissions from refrigeration and air-conditioning equipment can be reduced through a variety of practice and technology options. Many of the options considered in this report would entail voluntary action by the private sector and/or further government regulation. For example, national governments can regulate maximum allowable leak rates for refrigeration and air-conditioning equipment, or require the recovery of refrigerant and the proper disposal of non-reclaimable refrigerant. Many Annex I countries have already implemented a variety of such regulatory actions to reduce ODS emissions. Some of the most widely recognized options to reduce refrigerant emissions include the following (UNEP, 1998; UNEP, 1999a; Crawford, 1999; U.S. EPA, 2001a):

Practice Options:

- Leak repair;
- Refrigerant recovery and recycling;
- Proper refrigerant disposal; and
- Technician certification/HFC sales restriction

Alternative Refrigerant Options:

- Ammonia;
- Hydrocarbons;
- Low-GWP refrigerants; and
- Carbon dioxide.

Technology Options:

- Distributed systems⁵ for stationary commercial refrigeration equipment;
- Secondary loop systems for stationary equipment;
 - HFC secondary loop systems
 - Ammonia secondary loop systems
- Enhanced HFC-134a systems in MVACs;
- HFC-152a refrigerant in MVACs (direct expansion or secondary loop systems);
- Carbon dioxide systems in MVACs;
- Oil-free compressors;
- Geothermal (in lieu of air-to-air) cooling systems;
- Desiccant cooling systems; and
- Absorption systems.

Table 1-5 summarizes the duration and applicability of the process and technology emission reduction options across all end-use applications considered in this analysis. The applicability of the alternative refrigerant options depends on the technology used; hence, some are explored in more detail in the analysis of technology options.

⁵ The term “distributed system” as used in this report refers to commercial refrigeration equipment applicable to the retail food and cold storage end-uses, although the term could also be used to refer to technology applicable to other uses, such as residential and small commercial air-conditioning.

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Table 1-5: Assumptions on Duration and Applicability of Emission Reduction Options

Option Description	Duration of Emission Reduction (years)	Potential Applicability to End-use Equipment								
		Chillers	Retail Food	Cold Storage Warehouses	Refrigerated Transport	Industrial Process Refrigeration	Commercial Unitary A/C	MVACs	Residential A/C	Household Refrigeration and Small Appliances
Practice Options										
Leak Repair	5	+	+	+	▪	+	▪	▪	▪	▪
Refrigerant Recovery	1	▪	▪	▪	+	▪	+	+	+	+
Proper Refrigerant Disposal	NA	▪	▪	▪	▪	▪	▪	▪	▪	▪
Technician Certification	NA	▪	▪	▪	▪	▪	▪	▪	▪	▪
Alternative Refrigerants										
Ammonia	Lifetime of equipment	▪	+	+	▪	▪	▪	▪	▪	▪
Hydrocarbons	Lifetime of equipment	▪	▪	▪	▪	▪	▪	▪	▪	▪
Low-GWP Refrigerants	Lifetime of equipment	▪	▪	▪	▪	▪	▪	+	▪	▪
Carbon Dioxide	Lifetime of equipment	▪	▪	▪	▪	▪	▪	+	▪	▪
Technology Options										
Distributed Systems for Stationary Commercial Refrigeration Equipment	Lifetime of equipment		+	+						
Secondary Loop Systems for Stationary Equipment—HFC Primary Refrigerant	Lifetime of equipment		+	+		▪				
Secondary Loops Systems for Stationary Equipment—Ammonia Primary Refrigerant	Lifetime of equipment		+	+		▪				
Enhanced HFC-134a Systems in MVACs	Lifetime of equipment							+		
HFC-152a in MVACs (direct expansion or secondary loop)	Lifetime of equipment							+		
CO ₂ in MVACs	Lifetime of equipment							+		
Oil-Free Compressors	Lifetime of equipment	▪	▪	▪	▪	▪	▪	▪	▪	▪
Geothermal (in lieu of air-to-air) Cooling Systems	Lifetime of equipment						▪		▪	
Desiccant Cooling Systems	Lifetime of equipment	▪					▪		▪	
Absorption Systems	Lifetime of equipment	▪					▪		▪	

+ Option is technically feasible and is addressed in the cost analysis of this report.

▪ Option is potentially feasible but is not addressed in the cost analysis of this report.

The following section describes all of these options in greater detail and presents a cost analysis for those options not assumed to occur in the baseline and for which adequate cost data are available. The resulting emission abatement potentials and costs of each option explored in the cost analysis are summarized in Section 1.4. The technology options explored in this chapter do not include retrofit costs and, therefore, are assumed to penetrate only the markets of new (not existing) equipment. “New” equipment is defined as air-conditioning/refrigeration equipment manufactured in 2005 or later.

Practice Options

Leak Repair for Large Equipment

Reducing leak rates can reduce HFC emissions to a significant degree, especially in large systems such as chillers, cold storage warehouses, and retail food systems that could leak large amounts of refrigerant. Although some of the options available for existing equipment may be impractical for in-place equipment, given the difficulty and expense of retrofitting, there are still many options available that are economically feasible. Some of the leak repair options used in current industry practice include (U.S. EPA, 1997; U.S. EPA, 1998; Calm, 1999):

- Use of preventive maintenance, including scheduling inspection and repairs;
- Monitoring of leaks using stationary leak monitors or other new technologies, such as early warning signals,⁶ remote monitoring, and diagnostics;
- Use of new, more durable gasket materials that provide tighter seals and absorb less refrigerant;
- Augmentation of threaded joints with O-ring seals;
- Augmentation or replacement of gaskets and O-rings with adhesive sealants;
- Broader use and improvement of brazing techniques rather than threaded or snap fittings (e.g., use of sufficient silver content,⁷ and use of dry nitrogen or other inert gas to avoid oxidation);
- Focus on ensuring accessibility to field joints and use of isolation valves, which allow for greater ease of repair;
- Focus on proper securing to reduce vibration fractures in the pipe and connections from the compressor and other moving parts of the system;
- Repair or retrofit of high-emitting systems through targeted component upgrades;⁸ and
- Performance of major modifications to the systems.⁹

⁶ Technologies in the final stages of development expect to be able to generate early warning signals at less than five percent charge loss in commercial refrigeration and air-conditioning systems (Gaslok, 2002).

⁷ For solder, a 15-percent silver content is recommended (U.S. EPA, 1997).

⁸ This option may include replacing the purge unit or other component upgrades that typically require the removal of refrigerant from the machine, two full days of two technicians’ time, and several thousand dollars worth of materials (U.S. EPA, 1998).

⁹ This option may include modifications that are not strictly leak repair, but would result in greatly reduced leak rates. For example, combining the installation of a new purge system, the replacement of flare joints, and other containment options, or combining the replacement of gaskets and seals, the replacement of the motor, and the installation of new refrigerant metering.

As suggested by the above list, leak reduction options range from simple repairs to major system upgrades. Even in countries where maximum allowable leak rates are regulated by law, further leak reduction improvements, such as the replacement or upgrade of a major system component, are still possible. For example, preliminary data gathered from U.S. industry indicate that leak rates for certain types of existing equipment in the United States range from 8 to 40 percent, whereas achievable leak rates for new or modified equipment can be between 4 to 15 percent. Furthermore, through additional design and practice changes, leakage could be reduced to as low as 0.25 to 5 percent in the future (Amrane, 2001). Already, some retail food equipment has reached leak rates of less than 10 percent, and even lower for new chiller equipment (Crawford, 2002; Amrane, 2001).

Since the lower cost leak reduction options represent significant cost savings, this analysis assumes that they occur under the baseline. The cost analysis therefore focuses only on the more extensive and costly options. This option is assumed to be technically applicable to all equipment with large charge sizes (i.e., chillers, retail food, cold storage, and industrial process refrigeration).¹⁰ This analysis assumes that 50 percent of emissions occur as a result of equipment leakage during routine operation, while the other 50 percent of emissions are released during equipment servicing and disposal. Thus, the maximum technical applicability of this option is assumed to be 50 percent of emissions from large equipment (see Table 1-6). Furthermore, because equipment will still leak a marginal amount once repairs are made, it is assumed that the reduction efficiency of this option is 95 percent. The project lifetime is estimated to be five years. Regional technical applicability and reduction efficiency for 2010 and 2020 are presented in Table 1-6. Assumptions on maximum market penetration for each region and year are presented in Table 1-16.

Table 1-6: Summary of Assumptions for Leak Repair for Large Equipment

Country/Region	Applicable End-Uses ^a	Reduction Efficiency ^a	Technical Applicability ^b	
			2010	2020
U.S. & Japan	Chillers	95%	26.0%	25.9%
Other Annex I	Retail food		21.7%	27.0%
Latin America & Caribbean	Cold storage		30.5%	29.7%
Other Non-Annex I, Russia, CEITs	Industrial process		32.5%	27.8%

^a End-Uses and Reduction Efficiency apply to all regions.

^b Technical applicability is shown as a percent of total refrigeration/air-conditioning sector emissions, and equals 50 percent of total refrigeration/air-conditioning emissions from chillers, retail food, cold storage, and industrial process refrigeration.

Cost and Emission Reduction Analysis

The following bullets describe the cost and emission inputs used to derive the final \$/TCE for the leak repair option, the results of which are presented in Section 1.4:

- **One-Time Costs.** A one-time cost of \$1,450 is assumed for performing more significant minor repairs on larger systems, such as maintenance of the purge system or replacement of a gasket or O-ring, etc. This cost is based on an estimate provided in U.S. EPA (1998), adjusted to 2000 dollars, which assumes that \$200 in parts and 16 hours of labor is required to perform the repair.
- **Annual Costs.** No annual costs are associated with this option.

¹⁰ In this report, the term *technically applicable* refers to the emissions to which an option can be applied. The Leak Repair option is assumed to be technically applicable to all emissions from leaks (but not servicing and disposal) from the four end-uses listed in Table 1-6. See Appendix I for a glossary of terminology.

- **Cost Savings.** An annual cost savings is associated with reduced refrigerant loss. The cost of refrigerant (assumed to be R-404A) is estimated to be \$18.41/kg,¹¹ and 43 kg of refrigerant per unit are assumed to be saved each year, resulting in an annual cost savings of approximately \$791.63 per unit.
- **Emission Reductions.** Under the leak repair option described above, approximately 43 kg of R-404A refrigerant can be avoided each year for five years, resulting in an annual emission reduction of approximately 36 TCE per job (i.e., 43 kg or 0.043 metric tons of refrigerant, multiplied by the GWP of 3260, the reduction efficiency of 0.95, and the conversion factor of carbon to carbon dioxide equivalents of 12/44).

Refrigerant Recovery and Recycling from Small Equipment

Recovery and recycling of HFCs help to decrease HFC emissions during equipment service and disposal. The approach involves the use of a refrigerant recovery device that transfers refrigerant into an external storage container prior to servicing of the equipment. Once the recovery process and source operations are complete, the refrigerant contained in the storage container may be recharged back into the equipment, cleaned through the use of recycling devices, sent to a reclamation facility to be purified,¹² or disposed through the use of incineration technologies. Refrigerant recovery may also be an important way to reduce emissions from near-empty refrigerant containers (i.e., can heels). Refrigerant recovery is assumed to be widely practiced in Annex I countries in the baseline, as it is typically required by law.

This analysis assesses the recovery of refrigerant above that which is already practiced (e.g., due to regulations in many developed countries or for economic reasons) at service and disposal only for small equipment—i.e., MVACs, refrigerated transport, household and other small appliances, and unitary equipment—because it is assumed that recovery from large equipment is already widely practiced in the baseline.¹³ Recovery for large equipment is assumed to be practiced in the baseline because of the significant cost savings associated with recovery of large quantities of refrigerant from this equipment. Because emission reductions and costs vary by scenario and end-use, emission reductions and costs associated with four recovery scenarios were averaged to obtain one break-even cost. The four scenarios studied are recovery/recycling of (1) MVACs at service, (2) MVACs at disposal, (3) small appliances at service, and (4) small appliances at disposal.

This analysis assumes that 50 percent of emissions are released during equipment servicing and disposal, while the remaining 50 percent occur as a result of leakage during normal operations. Thus, the technical applicability of this option is 50 percent of emissions from small equipment (see Table 1-7). Furthermore, because in the United States small appliances are considered completely recovered when 90 percent of the refrigerant is removed from units with running compressors, or when 80 percent of the refrigerant is removed from units with non-operating compressors, this analysis assumes that the reduction efficiency of this option is 85 percent (Contracting Business Interactive, 2003; U.S. EPA, 1993). The project lifetime is assumed to be one year. Regional technical applicability and reduction

¹¹ Cost of R-404A is based on the list price quoted by DuPont Customer Service (2004).

¹² Recycling cleans, and reclamation purifies, recovered refrigerant; reclamation is more thorough and involves repeated precision distillation, filtering, and contaminant removal. Recycling is used for onsite servicing of MVACs and other equipment and reclamation requires sending the refrigerant offsite to a reclaimer.

¹³ While the Society of Automotive Engineers (SAE) has issued industry standards on equipment and technician procedures that apply to MVACs and provide for on-site recovery/recycling of HFC-134a from MVAC systems for reuse in the serviced system, recovery from these and other small systems is still not believed to be widely practiced in most developing countries, as a result of a lack of infrastructure (i.e., recovery/recycling equipment) (World Bank, 2002).

efficiency for 2010 and 2020 are presented in Table 1-7. Recovery of small appliances and MVACs is assumed to be practiced at 80 percent in the baseline in developed countries and at 30 percent in the baseline in developing countries. Assumptions on maximum market penetration for each region and year are presented in Table 1-16.

Table 1-7: Summary of Assumptions for Recovery/Recycling from Small Equipment

Country/Region	Applicable End-Uses ^a	Reduction Efficiency ^a	Technical Applicability ^b	
			2010	2020
U.S. & Japan	MVACs	85%	24.0%	24.1%
Other Annex I	Refrigerated transport		28.3%	23.0%
Latin America & Caribbean	Household/ other small appliances		19.5%	20.3%
Other Non-Annex I, Russia, CEITs	Commercial unitary AC Residential AC		17.5%	22.2%

^a End-Uses and Reduction Efficiency apply to all regions.

^b Technical applicability is shown as a percent of total refrigeration/air-conditioning sector emissions, and equals 50 percent of total refrigeration/air-conditioning emissions from MVACs, refrigerated transport, household/other small appliances, and commercial unitary and residential air-conditioning.

Cost and Emission Reduction Analysis

The following bullets describe the cost and emission inputs used to derive the final \$/TCE for the refrigerant recovery option, the results of which are presented in Section 1.4:

- **One-Time Costs.** The one-time cost associated with this option is the cost of recovery and/or recovery/recycling equipment, which ranges based on the equipment type. While all costs were expressed in terms of cost per job (see below), the cost of a high-pressure recovery unit is assumed to be approximately \$815, based on the average cost of four recovery scenarios: (1) recovery from MVACs at service; (2) recovery from MVACs at disposal; (3) recovery from stationary equipment at service; and (4) recovery from stationary equipment at disposal (U.S. EPA, 1998; 2001b).
- **Annual Costs.** All costs associated with this option, including capital costs, were expressed in terms of cost per job. The cost per job was calculated by multiplying the average additional labor required by the technician to recover the refrigerant charge (from five to 10 minutes, depending on recovery scenario) by the average labor rate (\$50/hr) and the average operating costs (which incorporates both the annualized costs of equipment and energy use). Based on this methodology, the average job is estimated to cost approximately \$9.50 (U.S. EPA, 1998; 2001b).
- **Cost Savings.** As a result of the average cost of recovered refrigerant (R-134a, R-404A, and R-407C)—calculated to be \$11.32/kg (the average for the four scenarios described above, considering the likely refrigerants involved)—and an average recoverable charge of 0.83 kg (the average of the four recovery scenarios described above, considering the 85-percent reduction efficiency), this option is associated with a cost savings of approximately \$9.40 per job.
- **Emission Reductions.** Under the refrigerant recovery option described above, the emission of 0.83 kg of refrigerant can be avoided from small equipment, resulting in the reduction of approximately 0.38 TCE per recovery job (assuming an average GWP of 1,664).¹⁴

¹⁴ This GWP value is based on an average GWP for MVACs and stationary equipment, where the average GWP for MVACs is assumed to be 1,300 (R-134a), and the average GWP for stationary equipment is assumed to be 2,028.5 (R-134a, R-404A, and R-407C). Therefore, the calculation is: $[1300 + (1300 + 3260 + 1525.5)/3]/2 = 1664.25$

Proper Refrigerant Disposal

One potential source of emissions from the refrigeration and air-conditioning sector is the accidental or deliberate venting of refrigerant. The venting of refrigerant can be reduced by increasing the reclamation of used refrigerant (discussed in more detail below) and properly disposing of refrigerant that cannot be reclaimed (such as highly contaminated refrigerant or mixed refrigerant). Disposal costs vary by country and region, as do transportation costs, storage costs, and access to refrigerant disposal facilities (e.g., high temperature incinerators that handle refrigerants). Global average ODS destruction costs are estimated to vary between \$1.80 and \$2.70 per pound (approximately \$4 to \$6 per kilogram) (ICF Consulting, 2002b). This option was not explored in the cost analysis as a result of the uncertainty associated with access to disposal facilities and cost disparities within regions.

Technician Certification/HFC Sales Restriction

By ensuring that refrigeration/air-conditioning technicians receive training in proper refrigerant handling, including recovery/recycling practices, and/or by restricting the sale of HFC refrigerants to certified technicians only, refrigerant emissions can be reduced. In some countries, such as the United States, technicians must be certified in accordance with national regulations to purchase CFC and HCFC refrigerants and service refrigeration and air-conditioning equipment. Restricting the use of HFC refrigerants to certified technicians would similarly reduce emissions. The costs of promulgating regulations in individual countries are uncertain and highly variable, and hence, this option was not explored further.

Alternative Refrigerant Options

Ammonia

Ammonia, primarily used in water-cooled chillers, has excellent thermodynamic properties and can be used in many types of systems. In addition, it has the advantage of having a strong odor, which makes refrigerant leaks easier to detect, and is lighter than air, facilitating dispersion in the event of a release (UNEP, 1999a). However, it must be used carefully, because it is toxic and slightly flammable. Ammonia is an explosion hazard at 16 to 25 percent in air, which creates a problem in confined spaces. Chillers that use ammonia as a refrigerant are commercially available in Europe and elsewhere, and they have efficiencies that are comparable to those of HFC-134a chillers in some instances. Building and fire codes, however, restrict the use of ammonia in the urban areas of the United States and many other countries. These safety concerns and institutional barriers effectively limit the potential for expanded use of ammonia chillers (Sand et al., 1997).

While the use of ammonia within public spaces such as supermarkets is limited in some countries by building codes and ordinances, it is a potential alternative for supermarkets if safety concerns can be adequately addressed through engineering design such as secondary loops and isolation. Indeed, modern ammonia systems manufactured in the United States are fully contained closed-loop systems with fully integrated controls that regulate pressures throughout the system. Also, all systems are required to have an emergency diffusion system and a series of safety relief valves to protect the system and its pressure vessels from over-pressurization and possible failure (ASHRAE, 2002). Systems with ammonia are being built and used in Europe (Sand et al., 1997). However, the further use of ammonia as a supermarket primary refrigerant may be unlikely in the near future in the United Kingdom and other countries because of the capital costs and issues of compliance with standards and safety regulations (Cooper, 1997). Ammonia would also be an option in some industrial process refrigeration and cold storage applications, contingent upon addressing all of the relevant concerns regarding flammability and toxicity. For

example, ammonia is used in about 80 percent of current installations of large-size refrigeration plants, as well as many indirect commercial refrigeration systems (RTOC, 2003).

The chemical properties of ammonia make it incompatible with current designs of residential light commercial unitary air-conditioning systems, which use copper for the refrigerant tubing, in the heat exchangers and in other components. Ammonia in the presence of water cannot be used with copper or zinc (UNEP, 1999a); however, ammonia can be used in aluminum and steel systems. Compatible components would have to be developed to use ammonia. As a result of these technical and cost barriers, as well as ammonia's flammability and toxicity, ammonia is considered an unlikely candidate for use in commercial and residential unitary equipment (Sand et al., 1997).

Many of the existing uses of ammonia are included in the baseline analysis. One additional option—using ammonia secondary loop systems in retail food and cold storage end-uses—is analyzed in more detail below, in the section on Technology Options.

Hydrocarbons

Hydrocarbons have thermodynamic properties comparable to fluorocarbons that make them good refrigerants; however, their high flammability causes safety concerns. Considering technical requirements apart from safety, there is potential for use of hydrocarbons in retail food refrigeration, refrigerated transport, household refrigeration, residential air-conditioning, MVACs, and commercial unitary systems. Currently used refrigerants include HC-600a, HC-290, and HC-1270 (UNEP, 1999a). In addition to good thermodynamic properties, hydrocarbons also have other advantages such as energy efficiencies comparable to fluorocarbons, zero ODP, and very low direct GWP.

The primary disadvantage of hydrocarbons is flammability, resulting in significant safety and liability issues. This causes increased costs for safety precautions in factories and can necessitate design changes in every application, such as relocation of electrical components to reduce the likelihood of accidents from potential leaks (Kruse, 1996; Paul, 1996). This also entails additional hardware costs for many applications (ADL, 1999; Crawford, 2000). Hydrocarbon refrigerant use is generally restricted by U.S. safety codes, and with the exception of industrial refrigeration, the U.S. EPA has not listed hydrocarbons as acceptable substitutes to ODS refrigerants (per Section 612 of the Clean Air Act Amendments of 1990). Even if systems that are designed to use hydrocarbon refrigerants were listed, liability concerns would remain. Systems using flammable refrigerants will require additional engineering and testing, development of standards and service procedures, and training of manufacturing and service technicians before commercialization.

Hydrocarbon domestic refrigerators have been available in Western Europe since the early 1990s, and have now fully penetrated some of the new domestic refrigeration markets, such as that in Germany. Hydrocarbon domestic refrigerators are also available in Argentina, Australia, Brazil, China, Cuba, India, Indonesia, Japan and elsewhere. Similarly, hydrocarbon refrigerants are available in other products, although little information is readily available regarding their market success to date (Hydro Cool Online, 2002; Calor Gas Refrigeration website, 2004; CARE Web site, 2004).

In addition, hydrocarbons have been used in MVACs for the last several years. Some have estimated that, in certain parts of Australia, 280,000 vehicles contain hydrocarbon refrigerants (Greenhill website, 2000), although independent data have not been supplied to confirm that estimate. The use of hydrocarbon refrigerants in direct expansion systems not designed for a flammable refrigerant can pose safety concerns and is not considered acceptable by much of the global MVAC industry. The Society of Automotive Engineers' (SAE) Alternate Refrigerant Cooperative Research Program has demonstrated a

secondary loop system using hydrocarbon refrigerant that minimizes the possible release of flammable refrigerant into the passenger compartment (Hill and Atkinson, 2003).

Proponents of hydrocarbon systems claim that these systems bring numerous benefits, including increased energy efficiency, lower refrigerant cost, lower capital cost, and less noise (HyChill website, 2004; Greenchill website, 2000), although little independent research exists to confirm the veracity of these claims. In many parts of the world, however, safety issues, public perception, and manufacturer acceptance impedes further penetration of this option.

This analysis does not consider the use of hydrocarbons in household refrigeration because it is assumed that this option is reaching maximum market penetration in the baseline. In those regions where hydrocarbons have not successfully penetrated markets (e.g., North America), it is assumed that the perceived risk and lack of acceptance of hydrocarbon refrigerants, which has prevented adoption to date, will continue to serve as a barrier in the foreseeable future. The use of hydrocarbons in other refrigeration end-uses was not considered further due to uncertainty concerning price and likely market penetration.

Low-GWP Refrigerants

The use of low-GWP refrigerants (e.g., HFC-152a with a GWP of 140) in place of higher GWP refrigerants (e.g., HFC-134a with a GWP of 1,300) is another option for reducing greenhouse gas emissions to the atmosphere. The use of HFC-152a in MVACs is explored in this cost analysis, as described in detail on page 28.

Several other low-GWP refrigerants exist. For example, carbon dioxide, discussed further below, has a GWP of 1. In addition, HCFC-123 and HCFC-124, which are not considered alternatives to HFCs, have low direct GWPs, complicated by factors including their contribution to stratospheric ozone depletion. While some studies (Calm et al., 1999; Wuebbles and Calm, 1997; U.S. EPA, 2002; RTOC, 2003) suggest the extended use of HCFC-123 in large tonnage chillers may offer a means to reduce direct GWP-weighted refrigerant emissions, and in some instances may reduce overall greenhouse gas emissions, this option is not examined in this analysis, as full compliance with the current HCFC phase-out schedule is assumed.

Carbon Dioxide

Another option is to use carbon dioxide as a refrigerant. Prototype carbon dioxide systems have been developed for numerous types of systems, including MVACs, industrial processing, refrigerated transport, and retail food systems. Carbon dioxide has zero ODP and a GWP of 1, and is claimed by its proponents to be advantageous for use as a refrigerant. However, carbon dioxide is associated with potential safety risks and other technical/economic disadvantages. Above certain concentrations, exposure to carbon dioxide may result in adverse health consequences. At very high concentrations, even for short periods of time, carbon dioxide affects the central nervous system and is an asphyxiant. To protect against adverse health effects from workplace exposure, the Occupational Safety and Health Administration's (OSHA) recommended 8-hour time-weighted average exposure limit is 5,000 ppm (ACGIH, 1999). Also, carbon dioxide systems operate at high pressure, which presents a potential hazard and may increase the cost of designing and purchasing equipment. In addition, potential loss of operational efficiency and associated increases in energy use and indirect emissions, refrigerant containment issues, long-term reliability, and compressor performance are other potential problems (Environment Canada, 1998).

For this analysis, carbon dioxide systems are only evaluated as options for MVACs. Carbon dioxide is being investigated for use in other end-uses but, due to the early stage of development and a lack of available information, those end-uses are not explored in this analysis. The MVAC option is described in detail in the section on Technology Options.

Technology Options

Distributed Systems for Stationary Commercial Refrigeration Equipment

A distributed system consists of multiple compressors that are distributed throughout the store near the display cases they serve and are connected by a water loop to a single cooling unit that is located on the roof or elsewhere outside of the store. Refrigerant charges for distributed systems can be smaller than the refrigerant charge used in a comparable traditional centralized direct expansion (DX) system. Significant reductions in total global warming impact from current levels may be possible with distributed systems that use HFC refrigerants (Sand et al., 1997). Reduced refrigerant charge sizes, in addition to increased energy efficiency associated with such systems, could effectively decrease global warming impacts, even with the use of fluorocarbon refrigerants.

Using HFC distributed systems in lieu of HFC centralized DX systems in retail food settings offers the potential to reduce HFC emissions. Distributed systems have smaller refrigeration units distributed among the refrigerated and frozen food display cases, with each unit sending heat to a central water cooling system. A distributed system would significantly reduce the refrigerant inventory and minimize the length of refrigerant tubing and the number of fittings that are installed in direct expansion systems, thereby reducing leaks of HFCs (ADL, 2002).

This technology option is assumed to be applicable to the retail food and cold storage end-uses. The project lifetime is assumed to be 20 years, and the emission reduction efficiency is calculated to be approximately 93 percent (i.e., the reduced leakage from use of a distributed system divided by the leakage of the baseline system, or $(0.15 - 0.04 \times 0.25)/0.15$). This calculation is based on an assumed annual leak rate of 4 percent (compared to 15 percent for centralized direct expansion [DX] systems), and a charge size that is 75 percent less than centralized DX systems (ADL, 2002). Regional technical applicability and reduction efficiency for 2010 and 2020 are presented in Table 1-8. Assumptions on maximum market penetration for each region and year are presented in Table 1-16 and Table 1-17. Because the cost analysis for this option does not address the costs to retrofit existing DX systems, this option is assumed to penetrate only new (post-2004) retail food and cold storage installations (i.e., those installed in 2005 or beyond).

Table 1-8: Summary of Assumptions for Distributed Systems for New Stationary Equipment

Country/Region	Applicable End-Use Sector(s) ^a	Reduction Efficiency ^a	Technical Applicability ^b	
			2010	2020
U.S. & Japan	Retail food Cold storage	93%	43.6%	43.1%
Other Annex I			36.3%	45.1%
Latin America & Caribbean			51.0%	49.4%
Other Non-Annex I, Russia, CEITs			54.4%	46.3%

^a End-Uses and Reduction Efficiency apply to all regions.

^b Technical applicability is shown as a percent of total refrigeration/air-conditioning sector emissions, and equals the percent of total refrigeration/air-conditioning emissions that are assumed to come from retail food and cold storage end-uses.

Cost and Emission Reduction Analysis

The following bullets describe the cost and emission inputs used to derive the final \$/TCE for distributed systems, the results of which are presented in Section 1.4. For more information on the calculation of costs and emission savings of this alternative refrigeration technology, see Section 1.3.2 on “Calculation of Indirect Emissions and Costs for Options Applicable to Stationary Equipment.”

- **One-Time Costs.** HFC distributed systems are assumed to cost approximately \$300 per ton of cooling capacity to install, or \$100 more per ton of cooling capacity than conventional HFC centralized DX systems (U.S. EPA, 2001a).
- **Annual Costs.** There are no annual costs associated with this option.
- **Cost Savings.** Based on average electricity prices in the United States from 1994-1999 (EIA, 2000), this option is associated with an annual cost savings of \$5.72 per ton of cooling capacity in the United States, as a result of an approximately 8 percent increase in energy efficiency relative to centralized DX systems (ADL, 2002). In all other countries, this annual cost savings was adjusted by average electricity prices (average of 1994-1999) based on EIA (2000). In addition, this system will prevent the annual emission of nearly 0.32 kg of refrigerant per ton of cooling capacity, as a result of reduced leakage. Assuming an average cost of (R-404A) refrigerant of \$18.41/kg (DuPont Customer Service, 2004), this translates into annual cost savings of approximately \$5.85 per ton of cooling capacity. Combined, the annual cost savings associated with this option is \$11.56 per ton of cooling capacity.
- **Emission Reductions.** Because the distributed system described above use less energy than a typical DX system, less carbon dioxide is produced in generating electricity to run it. This indirect energy benefit is calculated to be approximately 0.02 TCE per ton of cooling capacity each year, using average power plant emission rates in the United States. In all other countries, the indirect emission benefit was calculated by multiplying the 0.02 TCE emission reduction calculated for the United States by a ratio of U.S. to regional or national average CO₂ emission rates for electricity production, based on Sand et al. (1997). The reduction of direct emissions of approximately 0.32 kg of refrigerant equates to approximately 0.28 TCE per ton of cooling capacity per year. Therefore, in the United States, total annual emission reduction associated with this option is estimated to be 0.31 TCE per ton of cooling capacity. Furthermore, as a result of avoided losses at disposal (assumed to be 56 percent of original charge), a further 0.89 kg of refrigerant emissions could be avoided per ton of cooling capacity, equal to a one-time emission reduction of 0.79 TCE per ton of cooling capacity.

Secondary Loop Systems for Stationary Equipment

Secondary loop systems pump cold fluid to remove heat from equipment (e.g., refrigerated food display cases) or areas to be cooled. The fluid, often a brine solution, passes through a heat exchanger to be cooled by a refrigerant isolated from the equipment or areas cooled. These systems require a significantly lower refrigerant charge, have lower leak rates, and can allow the use of flammable or toxic refrigerants.

Secondary loops may be used in commercial and industrial refrigeration applications, for example, to cool supermarket display cases without circulating toxic or flammable refrigerants throughout the store or to reduce the needed charge of HFC refrigerants. The primary disadvantages of the secondary loop system can be a loss of energy efficiency and higher capital costs. Potential benefits of secondary cooling systems, however, include decreased charge sizes, decreased leak rates, faster defrost, lower maintenance needs, and longer shelf lives, which can result in significant cost-savings over time (Bennett, 2000; Baxter, 2003; Faramarzi and Walker, 2003). Indeed, the reduction in size and leak rate of the refrigerant charge could result in a reduced global warming impact, even with the use of fluorocarbon refrigerants.

The use of zero GWP refrigerants could result in even lower global warming impacts (Sand et al., 1997). Furthermore, secondary loop systems have improved temperature control compared to conventional direct expansion systems, which can represent an important advantage in countries like the United States, where recent regulations on temperature control for refrigerated products such as meat, poultry, and fish have become more stringent. Moreover, recent technological improvements to secondary cooling systems, such as high-efficiency evaporative condensers and display cases with high temperature brines, have increased system efficiency (Baxter, 2003; Faramarzi and Walker, 2003). Two types of secondary loop systems, for use in retail refrigeration and cold storage warehouses, are analyzed in more detail below.

Secondary loops could mitigate some but not all of the risks of using flammable refrigerants in residential and commercial unitary end-uses. In addition, secondary loops also have potential applications in motor vehicle air-conditioning, discussed further under the option of “HFC-152a Refrigerant in MVACs.” Due to the lack of technical and cost information on secondary loop systems in these other applications, they are not included as options in this analysis.

HFC Secondary Loop Systems for Stationary Commercial Refrigeration Equipment

Designing new retail food and cold storage systems to operate using secondary loops with HFCs can also reduce HFC emissions. As discussed above, secondary loop systems circulate a secondary coolant or brine from the central refrigeration system to the display cases (UNEP, 1999a; ADL, 1999). These systems have lower leak rates and operate at reduced charges. Additionally, pipes used in these systems are now pre-manufactured and can be made of pre-insulated plastic instead of copper. This reduces material costs and, by eliminating the need for brazing, allows for faster installation. In the United States, installation costs have been reduced by more than 25 percent in recent years. With continued research and development, it is expected that this technology will soon be as cost-effective to purchase, install, and operate as centralized DX systems (Bennett, 2000). This technology option is assumed to be applicable to the retail food and cold storage end-use sectors. This option is assumed to reduce emissions from appropriate end-uses by up to 98.5 percent, based on an assumed charge of only 11 percent of the base case (centralized DX systems) and an annual leak rate of 2 percent compared to 15 percent for an “optimal installation” of a centralized DX system (ADL, 2002). The project lifetime is assumed to be 20 years. The regional technical applicabilities and reduction efficiencies for 2010 and 2020 are presented in Table 1-9. Assumptions on maximum market penetration for each region and year are presented in Table 1-16 and Table 1-17. Because the cost analysis for this option does not address the costs to retrofit existing DX systems, this option is assumed to penetrate only new (post-2004) retail food and cold storage installations (i.e., those installed in 2005 or beyond).

Table 1-9: Summary of Assumptions for HFC Secondary Loop Systems for New Stationary Equipment

Country/Region	Applicable End-Use Sector(s) ^a	Reduction Efficiency ^a	Technical Applicability ^b	
			2010	2020
U.S. & Japan	Retail food, Cold storage	98.5%	43.6%	43.1%
Other Annex I			36.3%	45.1%
Latin America & Caribbean			51.0%	49.4%
Other Non-Annex I, Russia, CEITs			54.4%	46.3%

^a End-Uses and Reduction Efficiency apply to all regions.

^b Technical Applicability is shown as a percent of total refrigeration/air-conditioning sector emissions, and equals the percent of total refrigeration/air-conditioning emissions that are assumed to come from equipment in the retail food and cold storage end-uses.

Cost and Emission Reduction Analysis

The following bullets describe the cost and emission inputs used to derive the final \$/TCE for HFC secondary loop systems, the results of which are presented in Section 1.4. For more information on the

calculation of costs and emission savings of this alternative refrigeration technology, see Section 1.3.2 on “Calculation of Indirect Emissions and Costs for Options Applicable to Stationary Equipment.”

- **One-Time Costs.** This option is assumed to cost approximately \$240 per ton of cooling capacity to install, or \$40 (20 percent) more than conventional centralized HFC direct expansion systems (Bennet, 2000; Smithart, 2000; ADL, 1999). Improved secondary loop systems now being manufactured may be associated with even lower cost premiums—ranging from 0 to 10 percent more expensive than conventional centralized DX systems (Kazachki, 2004). Such systems may be considered in future analyses.
- **Annual Costs.** Based on average electricity prices in the United States from 1994-1999 (EIA, 2000), this option is associated with an annual cost of \$11.43 per-ton of cooling capacity, as a result of an approximately 15 percent increase in energy consumption relative to centralized DX systems (ADL, 2002). In all other countries, this annual cost was adjusted by average electricity prices (1994-1999) based on EIA (2000). Annual energy costs may actually be much lower if energy saving features are applied. Indeed, new secondary loop systems with improved design features (e.g., use of evaporative condensing) may result in annual energy requirements that are roughly the same as those for conventional DX systems, or even lower (Kazachki, 2003; Baxter, 2003). Such systems may be considered in future analyses.
- **Cost Savings.** On a per-ton of cooling capacity basis, this system will prevent nearly 0.34 kg of refrigerant emissions each year in the United States, as a result of reduced leakage. Assuming an average cost of (R-404A) refrigerant of \$18.41/kg (DuPont Customer Service, 2004), this translates into an annual cost savings of \$6.17 per ton of cooling capacity.
- **Emission Reductions.** Under the HFC secondary loop system described above, the annual direct emission of nearly 0.34 kg (0.30 TCE) of refrigerant can be avoided annually per ton of cooling capacity. However, indirect emission (energy) penalties lower total emission benefits by more than 15 percent (approximately 0.05 TCE per ton of cooling capacity) in the United States. In all other countries, the indirect emission penalty was calculated by multiplying the 0.05 TCE emission penalty assumed for the United States by a ratio of U.S. to regional or national average CO₂ emission rates for electricity production, based on Sand et al. (1997). Additional emission benefits are also associated with this option as a result of avoided (R-404A) refrigerant losses at equipment disposal. Assuming an emission rate of 56 percent at disposal, a further 1.11 kg of refrigerant emissions could be avoided per ton of cooling capacity, equal to a one-time emission reduction of 0.99 TCE per ton of cooling capacity.

Ammonia Secondary Loop Systems for Stationary Commercial Refrigeration Equipment

The use of ammonia is very common in certain countries while strongly restricted in others. For example, for many decades ammonia has been used in almost all dairies, breweries, slaughterhouses, and large freezing plants nearly all over Europe, while its use is heavily regulated in North America (ACHR News, 2000). Ammonia refrigeration has historically been used in large, low-temperature industrial refrigeration, as well as medium and large chillers, generally in food processing (Crawford, 1999). However, the use of ammonia refrigerant is beginning to expand into retail food and smaller-sized chillers in some countries, particularly those in the European Union.

Because of ammonia’s toxicity and flammability, major design modifications would be required for the majority of traditional HFC systems. Furthermore, since different countries have different sets of building codes, fire codes, and other safety standards relating to the use of ammonia in building equipment, some countries (e.g., the United States) would need to revise those codes to allow for the expanded use of ammonia in new equipment types.

Ammonia can be used as the primary refrigerant in secondary loop systems in place of HFCs. Because ammonia secondary loop systems avoid running the primary refrigerant through miles of piping to and from food storage cases, they have lower leak rates than conventional centralized DX systems, and operate at reduced charges. In these types of systems, ammonia is kept out of public contact (e.g., outside of buildings), and non-toxic fluids are used as secondary coolants. Incremental one-time costs for ammonia systems are assumed to include expenditures for equipment needed to ensure safety. The annual operating costs also include net energy requirements, but, because of a lack of information, do not cover costs associated with training of technicians and development and updating of safety protocols to handle more hazardous refrigerants such as ammonia. This technology option is assumed to be applicable to the retail food and cold storage end-uses. The project lifetime is assumed to be 20 years. The reduction efficiency of this option is 100 percent, as the ammonia completely replaces the HFC. Because the cost analysis for this option does not address the costs to retrofit existing DX systems, this option is assumed to be technically applicable in only new (post-2004) retail food and cold storage installations.

Table 1-10 presents regional technical applicabilities and the reduction efficiency for 2010 and 2020.

Table 1-10: Summary of Assumptions for Ammonia Secondary Loop Systems for New Stationary Equipment

Country/Region	Applicable End-Use Sector(s) ^a	Reduction Efficiency ^a	Technical Applicability ^b	
			2010	2020
U.S. & Japan	Retail food Cold storage	100%	43.6%	43.1%
Other Annex I			36.3%	45.1%
Latin America & Caribbean			51.0%	49.4%
Other Non-Annex I, Russia, CEITs			54.4%	46.3%

^a End-Uses and Reduction Efficiency apply to all regions.

^b Technical Applicability is shown as a percent of total refrigeration/air-conditioning sector emissions, and equals the percent of total refrigeration/air-conditioning emissions that are assumed to come from equipment in the retail food and cold storage end-uses.

Ammonia systems are assumed to penetrate a greater percentage of non-U.S. markets, as a result of more relaxed safety standards and greater acceptance by industry, end-users, regulators, and insurance companies in those countries. Assumptions on maximum market penetration for each region and year are presented in Table 1-16 and Table 1-17.

Cost and Emission Reduction Analysis

The following bullets describe the cost and emission inputs used to derive the final \$/TCE for ammonia secondary loop systems, the results of which are presented in Section 1.4. For more information on the calculation of costs and emission savings of this alternative refrigeration technology, see Section 1.3.2 on “Calculation of Indirect Emissions and Costs for Options Applicable to Stationary Equipment.”

- **One-Time Costs.** Ammonia secondary loop systems are assumed to cost approximately \$250 per ton of cooling capacity to install, or \$50 (25 percent) more than conventional centralized HFC direct expansion systems (Anderson, 2001).
- **Annual Costs.** Based on average electricity prices in the United States from 1994-1999 (EIA, 2000), this option is associated with an annual cost of \$11.43 per ton of cooling capacity, as a result of an approximately 15 percent increase in energy consumption relative to centralized DX systems (ADL, 2002). In all other countries, this annual cost was adjusted by average electricity prices (1994-1999) based on EIA (2000). Note that next generation ammonia secondary loop systems may adopt energy saving features that yield lower annual energy costs, as discussed above for HFC secondary loop systems.

- **Cost Savings.** On a per-ton of cooling capacity basis, this system will prevent 0.34 kg of refrigerant emissions each year in the United States, as a result of reduced leakage. Assuming an average cost of (R-404A) refrigerant of \$18.41/kg (DuPont Customer Service, 2004), this translates into an annual cost savings of \$6.26 per ton of cooling capacity.
- **Emission Reductions.** Under the ammonia secondary loop system described above, the annual emission of 0.34 kg (0.30 TCE) of refrigerant can be avoided annually in the United States per ton of cooling capacity. However, indirect emission (energy) penalties lower total emission benefits by more than 15 percent (approximately 0.05 TCE per ton of cooling capacity) in the United States. In all other countries, the indirect emission penalty was calculated by multiplying the 0.05 TCE emission penalty assumed for the United States by a ratio of U.S. to regional or national average CO2 emission rates for electricity production, based on Sand et al. (1997). Additional emission benefits are also associated with this option as a result of avoided (R-404A) refrigerant losses at equipment disposal. Assuming an emission rate of 56 percent at disposal, a further 1.27 kg of refrigerant emissions could be avoided per ton of cooling capacity, equal to a one-time emission reduction of 1.13 TCE per ton of cooling capacity.

Enhanced HFC-134a Systems in MVACs

Various options exist to reduce emissions of HFC-134a in MVACs by reducing charge size, leak rates, and/or system efficiency (i.e., reducing system power consumption). Specifically, reducing the volume of the system components, such as the condenser and refrigerant lines, can reduce charge size. Similarly, leak rates can be lowered and system efficiency improved by using better system components, such as improved system sealing, lower permeation hoses, improved fittings, and higher evaporator temperatures (Lundberg, 2002; Xu and Amin, 2000). Additional savings of indirect emissions can be obtained by improving system efficiency, for example through the use of oil separators and externally controlled swashplate compressors.

Based on the latest science and industry estimates available at publication, enhanced HFC-134a systems can reduce baseline direct emissions by 50 percent (SAE, 2003a). This technology is expected to become commercial between 2004 and 2006 (SAE, 2003a). This analysis assumes a project lifetime (i.e., MVAC lifetime) of 12 years. Regional technical applicabilities and the reduction efficiency are presented in Table 1-11.

Table 1-11: Summary of Assumptions for Enhanced HFC-134a Systems for New MVACs

Country/Region	Applicable End-Use Sector(s)	Reduction Efficiency ^a	Technical Applicability ^b	
			2010	2020
U.S. & Japan	MVACs	50%	28.5%	19.5%
Other Annex I			40.4%	15.9%
Latin America & Caribbean			16.2%	7.8%
Other Non-Annex I, Russia, CEITs			10.7%	13.6%

^a Reduction Efficiency applies to all regions, and represents the reduction in direct emissions (compared to conventional HFC-134a systems) as a result of reduced leakage.

^b Technical Applicability is shown as a percent of total refrigeration/air-conditioning sector emissions, and equals the percent of total refrigeration/air-conditioning sector emissions that are assumed to come from MVACs.

Acceptance of this substitute would likely vary by region, based on consumer and industry attitudes, economic variables, and availability of competing options. Enhanced HFC-134a systems are expected to become commercially available several years before other alternatives (e.g., carbon dioxide, HFC-152a). Therefore, this analysis assumes that initially enhanced HFC-134a systems will most deeply penetrate the markets of Europe, Australia and Japan, where regulations, policy, and/or voluntary initiatives are moving

fastest to reduce HFC use and emissions. Beyond 2010, however, Europe¹⁵ and Japan are expected to move away from HFC-134a use in MVACs, so this option is assumed to gain the greatest market penetration in other developed countries, such as the United States and Canada, where industry is resistant to switching from using HFC-134a. In developing countries, capital cost is expected to prevent this option from penetrating the market at all. The cost analysis for this option does not include any costs associated with retrofitting existing HFC-134a systems. Therefore, this option is assumed to penetrate only new MVACs produced after 2004. Assumptions on maximum market penetration for each region and year are presented in Table 1-16 and Table 1-17.

Cost and Emission Reduction Analysis

The following bullets describe the cost and emission inputs used to derive the final \$/TCE for enhanced HFC-134a systems for MVACs, the results of which are presented in Section 1.4:

- **One-Time Costs.** While enhanced HFC-134a MVACs are yet to be fully developed and commercialized, the additional capital cost of this option is assumed to be 40 Euros, or \$45 USD,¹⁶ per system, based on the latest available industry estimates (SAE, 2003a).
- **Annual Costs.** No annual costs are associated with this option.
- **Cost Savings.** Enhanced HFC-134a systems will potentially reduce energy consumption by as much as 25 to 30 percent (SAE, 2003a). For calculation purposes, 27.5 percent is assumed. In the United States, this gain in energy efficiency is estimated to translate into a savings of 10.2 gallons of gasoline per vehicle per year (Rugh and Hovland, 2003). Assuming an average gasoline price of \$1.51/gallon (EIA, 2001), this results in an annual cost savings of approximately \$15.46 per year in the United States.¹⁷ For all other countries, this annual cost savings is adjusted by the estimated amount of gasoline saved per vehicle per year¹⁸ and by average regional costs of unleaded gasoline in 2000.¹⁹ Additional savings due to less maintenance are not analyzed or included here.

In addition, small cost savings are also associated with saved HFC-134a refrigerant, assumed to cost \$7.94/kg (DuPont Customer Service, 2004). On an annual basis, these savings are estimated

¹⁵ The proposed EC Regulation on fluorinated gases, presented by the Commission on August 11, 2003, prohibits the use of fluorinated gases with a GWP higher than 150 in new MVACs placed on the market beginning in 2009, with the exception of manufacturers that successfully apply for a quota allocation (EC, 2003b). It is currently undergoing review and revision.

¹⁶ This cost conversion is based on an exchange rate of \$112.5/€100 (Universal Currency Converter Web site, 2003).

¹⁷ Average gasoline price is based on the reported average retail price of regular unleaded gasoline in 2000 in the United States (EIA, 2001).

¹⁸ The estimated quantity of gasoline saved per vehicle per year varies by the percent of fuel consumed by MVACs (as a percent of total fuel consumption), which in turn varies by MVAC usage. Based on available data, the estimated annual savings of gasoline per vehicle per year associated with a 27.5-percent increase in MVAC efficiency is 2.3 gallons in Europe and 2.0 gallons in Japan (Rugh and Hovland, 2003). For the purpose of this report, the MVAC efficiency value for Europe was used as a proxy for the remaining countries.

¹⁹ EIA (2001) provides average 2000 prices of regular unleaded gasoline for select countries, which are used as proxies for adjusting the annual cost savings for non-U.S. countries by region. Specifically, the average price in Germany (\$3.45/gallon) is used as a proxy for all European countries; the average price in Australia and Canada (\$1.90/gallon) is used as a proxy for all other developed countries except Japan; and the average price in Mexico and Taiwan (\$2.09/gallon) is used as a proxy for all developing countries. The average gasoline price for Japan is \$3.74/gallon.

to total approximately \$0.35 per MVAC—assuming that conventional HFC-134a MVACs contain an average charge of 0.8 kg, that they emit 10.9 percent of this charge each year, and that 50 percent of these emissions could be avoided through this option.

- Emission Reductions.** Under the enhanced HFC-134a system described above, the annual emission of approximately 0.04 kg (i.e., 0.8 kg charge multiplied by the emission rate of 10.9%/year and the reduction efficiency of 50%) of HFC-134a refrigerant could be avoided from reduced leakage, resulting in the annual reduction of 0.015 TCE per MVAC. Furthermore, based on U.S. emission factors for motor gasoline (U.S. EPA, 2003), indirect emission benefits associated with a 27.5-percent system efficiency improvement could lead to the annual reduction of an additional 0.025 TCE per MVAC in the United States. Overall, this option could, therefore, reduce 0.040 TCE per MVAC each year in the United States. For all non-U.S. countries, the annual indirect emission benefit estimated for the United States (0.025 TCE) was adjusted by the estimated amount of gasoline saved per vehicle per year (Rugh and Hovland, 2003) and by the global average emission factor for motor gasoline (IPCC, 1996).

HFC-152a Refrigerant in MVACs

Replacing HFC-134a refrigerant in MVACs with HFC-152a represents a significant opportunity to reduce HFC emissions, since the GWP of HFC-152a is 140, 89 percent less than that of HFC-134a, whose GWP is 1300. HFC-152a is a flammable refrigerant but is less flammable than hydrocarbons. HFC-152a can be used in both direct expansion (DX) and secondary loop MVAC systems. Because there is still great uncertainty associated with the future costs of HFC-152a secondary loop systems for MVACs, this cost analysis only considers the DX option. Likewise, because there is still great uncertainty associated with future costs of “improved” HFC-152a MVACs—which will use improved system components to further reduce refrigerant leak rates, as well as externally-controlled variable displacement compressors and refrigerant system controls to further increase system efficiency—only the conventional DX systems are considered in this costs analysis.

In addition to direct emission reductions associated with a lower GWP, HFC-152a DX systems in MVACs also reduce indirect emissions by improving system efficiency by about 10 percent (SAE, 2003a). This analysis assumes a project lifetime (i.e., MVAC lifetime) of 12 years. Regional technical applicabilities and the reduction efficiency are presented in Table 1-12.

Table 1-12: Summary of Assumptions for HFC-152a DX Systems in New MVACs

Country/Region	Applicable End-Use Sector(s)	Reduction Efficiency ^a	Technical Applicability ^b	
			2010	2020
U.S. & Japan	MVACs	89%	28.5%	19.5%
Other Annex I			40.4%	15.9%
Latin America & Caribbean			16.2%	7.8%
Other Non-Annex I, Russia, CEITs			10.7%	13.6%

^a Reduction Efficiency applies to all regions, and represents the reduction in direct emissions (compared to conventional HFC-134a systems) as a result of lower GWP.

^b Technical Applicability is shown as a percent of total refrigeration/air-conditioning sector emissions, and equals the percent of total refrigeration/air-conditioning sector emissions that are assumed to come from MVACs.

The use of HFC-152a DX systems in MVACs would not require any significant changes to existing HFC-134a system components apart from a safety mitigation system (e.g., a refrigerant detector and a valve to isolate the remaining charge from the passenger compartment), thereby rendering this option easy to introduce into the market. Furthermore, compared to baseline HFC-134a systems, HFC-152a systems are

expected to be more efficient and may operate at reduced refrigerant charges and leakage rates.²⁰ However, because HFC-152a is a slightly flammable gas, safety systems are needed. Thus, personnel training would be needed to enable the safe and effective recovery and recycling of refrigerant at service and disposal, and additional safety systems to minimize the potential for large leaks into the passenger compartment may be required. New fire-safe service equipment for refrigerant recovery/charging and leak detection may also be required.

While the MVAC industry has demonstrated the use of HFC-152a in prototype DX (and secondary loop) MVAC systems, the technology is still in the research and development phase. HFC-152a systems are expected to become commercially available between 2006 and 2008 (SAE, 2003a). Once available, it is assumed that initially HFC-152a systems will have the greatest market share in Europe, Australia and Japan, where policies and regulations are being developed that will aim aggressively at reducing HFC-134a emissions from MVACs. Once the technical and economic barriers associated with carbon dioxide systems are resolved and such systems become more widely used, it is expected that HFC-152a popularity will then decline in the European market and later in other nations like Japan and Australia. In comparison, because other developed countries (e.g., the United States and Canada) are less open to using non-HFC alternatives, this option is expected to gain market share slowly in those regions. In addition, because HFC-152a has the lowest capital cost of all MVAC options considered in this analysis, it is expected to be the primary alternative for MVAC markets in developing countries in later years. Retrofitting HFC-134a systems to HFC-152a systems is not considered technically or economically feasible because it is assumed that additional safety systems to reduce potential passenger exposure must be incorporated into the system. Thus, costs associated with retrofit were not assessed, and this option is assumed to penetrate only new (post-2004) MVACs. Assumptions on maximum market penetration for each region and year are presented in Table 1-16 and Table 1-17.

Cost and Emission Reduction Analysis

The following bullets describe the cost and emission inputs used to derive the final \$/TCE for HFC-152a systems for MVACs, the results of which are presented in Section 1.4:

- **One-Time Costs.** While research and development is still ongoing on HFC-152a systems, based on the latest available industry estimates, the capital cost of this option is assumed to be 20 to 25 Euros per system more than a standard HFC-134a system (SAE, 2003a). For calculation purposes, 22.50 Euros, or \$25.31 USD,²¹ is used.
- **Annual Costs.** No annual costs are associated with this option.
- **Cost Savings.** Based on industry consensus, HFC-152a systems are estimated to reduce energy consumption by 10 percent (SAE, 2003a), although these gains may not be realized in all weather conditions (Hill and Atkinson, 2003). This gain in energy efficiency is estimated to result in a savings of approximately 3.9 gallons of gasoline per vehicle per year in the United States, which translates into an annual cost savings of \$5.92, based on average U.S. prices of regular unleaded gasoline in 2000 (Rugh and Hovland, 2003; EIA, 2001). For all non-U.S. countries, this cost savings is adjusted by the estimated amount of gasoline saved per vehicle per year²² and by the average regional costs of unleaded gasoline in 2000.²³

²⁰ Because these systems are still under development, this cost analysis does not consider the possible reduction in charge and leakage rates, although efficiency improvement predictions based on SAE (2003a) are included.

²¹ This cost conversion is based on an exchange rate of \$112.5/€100 (Universal Currency Converter Web site, 2003).

²² It assumed that a 10 percent increase in MVAC efficiency results in the annual savings of 0.8 gallons of gasoline

Because this analysis assumes that HFC-152a would be the same price as HFC-134a, and because HFC-152a systems are assumed to leak at the same rate as conventional HFC-134a, (although the associated emissions are less damaging to the environment due to the lower GWP), no cost savings are associated with saved refrigerant.

- **Emission Reductions.** Under the HFC-152a system described above, the annual emission of approximately 0.09 kg of HFC-134a refrigerant could be avoided in place of annual emissions of 0.09 kg of HFC-152a—which results in the net annual reduction of 0.028 TCE per MVAC. In addition, based on U.S. emission factors for motor gasoline (U.S. EPA, 2003), indirect emission benefits associated with a 10-percent system efficiency improvement could lead to the reduction of an annual additional 0.009 TCE per MVAC in the United States. Overall, this option could, therefore, reduce approximately 0.037 TCE per MVAC each year in the United States. For all non-U.S. countries, the annual indirect emission benefit estimated for the United States (0.009 TCE) was adjusted by the estimated amount of gasoline saved per vehicle per year (Rugh and Hovland, 2003) and by the global average emission factor for motor gasoline (IPCC, 1996). Emission benefits are also achieved by this option at MVAC disposal, as the emission of HFC-134a could be substituted by emission of lower-GWP HFC-152a. Assuming that on average 42.5 percent of the original MVAC charge is lost at disposal, the one-time loss of 0.34 kg of HFC-134a refrigerant could be replaced by HFC-152a, resulting in the net reduction of approximately 0.11 TCE per MVAC.

Carbon Dioxide in MVACs

Systems using carbon dioxide as the refrigerant in MVACs represent a potential opportunity for emission reduction. This technology uses a transcritical vapor cycle which differs from conventional MVAC systems and requires innovative design and engineering. The arrangement of components in carbon dioxide systems is generally consistent with conventional systems; however, a suction line heat exchanger is added and a low side accumulator is used (in place of a high side receiver, as used in most conventional HFC-134a systems). In addition, the individual system components are designed to reflect the extremely high pressure levels of supercritical carbon dioxide (about 2,000 psig).

Because carbon dioxide has a GWP of 1, it would virtually eliminate the climate impacts of direct refrigerant emissions from MVACs. Carbon dioxide systems perform most efficiently in areas, like northern Europe, that require air conditioners for cooling and other purposes, but generally have mild ambient temperatures.²⁴ In addition, heat pump technology for vehicles is under development (VDA, 2003), which may allow CO₂ systems to be used for supplemental heating of the passenger compartment (SAE, 2003a). This may be an important function in cars with very efficient engines where minimal waste heat is available to warm the passenger compartment.

While CO₂ has the advantage of being non-flammable, its system operating pressure is five to 10 times that of HFC-134a; therefore, appropriate safety features and new system/component designs are required before this option can be brought to market. In addition, an internal heat exchanger, which would further cool the high-temperature CO₂ from the gas cooler and heat the low-temperature CO₂ from the accumulator, would be needed to increase cooling capacity and energy efficiency to acceptable levels.

in Europe and 0.7 gallons of gasoline in Japan (Rugh and Hovland, 2003). For the purpose of this report, the MVAC efficiency value for Europe was used as a proxy for the remaining countries.

²³ Annual cost savings are adjusted by average gasoline prices as explained in footnote 19.

²⁴ Compared to other refrigerant technologies, prototype carbon dioxide MVAC systems are not as efficient in warmer climate conditions. The MVAC industry is actively pursuing research and development activities to improve system efficiency in warmer weather conditions (SAE, 2003b).

Also, in the event of a large leak, passengers could be exposed to potentially dangerous levels of CO₂; therefore, it is assumed that safety systems designed to minimize passenger exposure would be incorporated into the system design.

Several engineering constraints must still be overcome, including those associated with flexible lines, increased system weight, and system leakage/leak detection methods. In addition, because these systems will be designed and built differently than current MVACs, and because the high pressure presents additional risks, technicians will need to be trained on how to service and maintain these new systems safely and correctly. New service equipment for refrigerant charging and leak detection may also be required. Moreover, because of the high pressure of these systems, MVAC servicing and maintenance would need to be performed by skilled technicians, in order to prevent safety hazards and maintain system performance.

The efficiency gains associated with CO₂ systems (between 20 and 25 percent [SAE, 2003a]) are considered in this cost analysis, using 22.5 percent for calculation purposes. While efforts are ongoing to develop “improved” CO₂ systems for MVACs—which experts predict would exceed this 20 to 25 percent energy efficiency gain—much uncertainty remains regarding the investment costs required to manufacture these systems. Therefore, these “improved” CO₂ systems are not considered further in this analysis. This analysis assumes a project lifetime (i.e., MVAC lifetime) of 12 years. Regional technical applicabilities and the reduction efficiency for the CO₂ option considered are presented in Table 1-13.

Table 1-13: Summary of Assumptions for CO₂ Systems in New MVACs

Country/Region	Applicable End-Use Sector(s)	Reduction Efficiency ^a	Technical Applicability ^b	
			2010	2020
U.S. & Japan	MVACs	100%	28.5%	19.5%
Other Annex I			40.4%	15.9%
Latin America & Caribbean			16.2%	7.8%
Other Non-Annex I, Russia, CEITs			10.7%	13.6%

^a Reduction Efficiency applies to all regions, and represents the reduction in direct emissions (compared to conventional HFC-134a systems).

^b Technical Applicability is shown as a percent of total refrigeration/air-conditioning sector emissions and equals the percent of total refrigeration/air-conditioning sector emissions that are assumed to come from MVACs.

Carbon dioxide systems may be available on the market in the next four to six years (SAE, 2003a). Because European and Japanese manufacturers are most aggressively pursuing CO₂, this option is expected to eventually (by 2020) become the dominant market player in these world markets. In other developed countries such as the U.S. and Canada, industry is not aggressively developing this technology and it is assumed that this option will not be widely adopted in these markets in the near future. Finally, because of the high capital costs associated with this option (see details below), it is also not expected to be adopted in developing countries until later years, assuming a projected global market shift to non-GWP alternatives. The project lifetime is assumed to be 12 years, and assumptions on maximum market penetration for each region and year are presented in Table 1-16 and Table 1-17. Retrofitting HFC-134a systems to carbon dioxide is not considered technically or economically feasible because of the high operating pressures and because it is assumed that additional safety systems to reduce potential passenger exposure must be incorporated into the systems. Thus, costs to retrofit were not assessed, and this option is assumed to penetrate only new (post-2004) MVACs.

Cost and Emission Reduction Analysis

The following bullets describe the cost and emission inputs used to derive the final \$/TCE for CO₂ systems for MVACs, the results of which are presented in Section 1.4:

- **One-Time Costs.** Based on the latest available industry estimates, the capital cost of this option is assumed to be 80 to 120 Euros on a per system basis (SAE, 2003a). For calculation purposes, 100 Euros, or \$112.50 USD,²⁵ was used.
- **Annual Costs.** No annual costs are associated with this option.
- **Cost Savings.** Based on industry consensus, it is estimated that enhanced CO₂ systems may reduce energy consumption, compared to a baseline HFC-134a system, by 20 to 25 percent (an average of 22.5 percent is used for calculation purposes), although these gains may not be realized at all ambient temperatures (SAE, 2003a). This gain in energy efficiency results in the savings of approximately 8.4 gallons of gasoline per vehicle per year in the United States, which translates roughly into an annual cost savings of \$12.67 (Rugh and Hovland, 2003; EIA, 2001). For all non-U.S. countries, this cost savings was adjusted by the estimated amount of gasoline saved per vehicle per year²⁶ and by average cost of unleaded gasoline in 2000 (Rugh and Hovland, 2003; EIA, 2001).²⁷

In addition, small cost savings are associated with saved (HFC-134a) refrigerant, assumed to cost \$7.94/kg (DuPont Customer Service, 2004). On an annual basis, these savings are estimated to total \$0.69 per MVAC—assuming that conventional HFC-134a MVACs contain an average charge of 0.8 kg, that they emit 10.9 percent of this charge each year, and that 100 percent of these emissions could be avoided through this option. The additional cost of CO₂ refrigerant is assumed to be small and is not included in the analysis.

- **Emission Reductions.** Under the CO₂ system described above, the annual emission of approximately 0.09 kg of HFC-134a refrigerant could be avoided, resulting in the reduction of 0.031 TCE per MVAC. In addition, based on U.S. emission factors for motor gasoline (U.S. EPA, 2003), indirect emission benefits associated with a 22.5-percent system efficiency improvement could lead to the reduction of an additional 0.020 TCE per MVAC in the United States. Overall, this option could, therefore, reduce approximately 0.051 TCE per MVAC each year in the United States. For all non-U.S. countries, the annual indirect emission benefit estimated for the United States (0.020 TCE) was adjusted by the estimated amount of gasoline saved per vehicle per year (Rugh and Hovland, 2003) and by the global average emission factor for motor gasoline (IPCC, 1996). Furthermore, a one-time disposal loss of 0.34 kg of HFC-134a refrigerant can also be avoided (assuming a disposal loss rate of 42.5 percent), which would result in a further one-time reduction of 0.12 TCE per MVAC.

Oil-Free Compressors

Oil-free compressors are available for chillers, industrial process applications, and other applications where compressors are used. The elimination of oil in refrigeration/air-conditioning compressors has been achieved through various innovative designs, including the incorporation of magnetic or hybrid ceramic bearings (SKF, 2003; Smithart, 2003). In some systems, oil may decrease heat transfer and reduce operating efficiency; therefore, removing oil may increase the ability to sustain system efficiency over the life of the equipment—thereby lowering indirect emissions of CO₂ associated with producing electricity. Eliminating the use of oil in compressors can reduce the number of equipment components (e.g., oil separators and sealing, fittings and connections), allowing equipment to be made tighter, and resulting in lower leak rates. In addition, oil-free compressors remove the need for oil changes and the

²⁵ This cost conversion is based on an exchange rate of \$112.5/€100 (Universal Currency Converter Web site, 2003).

²⁶ A 22.5-percent increase in MVAC efficiency is assumed to result in the annual savings of 1.9 gallons of gasoline in Europe and 1.7 gallons of gasoline in Japan (Rugh and Hovland, 2003). For the purpose of this report, the MVAC efficiency value for Europe was used as a proxy for the remaining countries.

²⁷ Annual cost savings are adjusted by average gasoline prices as explained in footnote 19.

associated refrigerant emissions that may be experienced either through the service practices used or from refrigerant dissolved in the oil. This potential emission reduction may be offset however by an increased frequency of compressor/bearing inspection or replacement (Digmanese, 2004), although an increasing history of operation may prove that unnecessary. This option was not included in the cost analysis, however, as a result of limited data available on this new technology and its applicability in future markets.

Geothermal Cooling Systems

In some locations, geothermal cooling systems for residential and commercial spaces are popular and economically sound as an alternative to conventional air-conditioning systems. Geothermal technology transfers heat between the system and the earth and can provide both space heating and cooling. Though installation costs are typically 30 to 50 percent higher than conventional systems, annual costs are reduced by 20 to 40 percent, due in large part to increased energy efficiency. Economic paybacks can accrue in as little as three to five years. Geothermal systems may save homeowners 20 to 50 percent in cooling costs (Geoexchange, 2000; Rawlings, 2000). This technology has also been used in ice skating rinks. Because of a lack of cost and market penetration data, this technology is not considered further in this analysis.

Desiccant Cooling Systems

Desiccant cooling is produced by removing moisture from an air stream using a desiccant, and then separately cooling the dry air. The desiccant is thermally regenerated, typically by burning natural gas or alternatively, by capturing excess heat. Desiccant cooling may replace the latent cooling done by some end-uses, such as unitary systems. Integrated desiccant cooling systems that combine a desiccant system with a vapor compression or other cooling system have been successfully installed in some commercial buildings (Fisher et al., 1994).

However, current designs are used primarily in niche markets that require precisely-controlled and/or low humidity, such as hospital operating rooms and certain industrial processes. For desiccant-based systems to be considered widely feasible options in the commercial air-conditioning market, improvements in efficiency, cost, size, reliability, and life expectancy must be made (Sand et al., 1997).

Desiccant systems have also been tried in MVAC systems, but found not to be technically or economically feasible. These systems require an intermittent source of heat; however, because new automobiles produce very little waste heat, not enough heat is produced for a desiccant system to function. Desiccant systems may therefore only be feasible where there is a large heat source, as in a large truck or bus (Environment Canada, 1998). Furthermore, in order for desiccant air-conditioners to become viable options for MVACs, the varying heat source must be controlled during normal driving conditions, when vehicle speed is continually changing. Current prototypes are large and heavy, and the systems have not been shown to be cost-effective or durable enough to justify the initial investment (U.S. EPA, 2001a).

Because of the technical barriers and insufficient cost information associated with the feasibility of this option in potentially applicable end-uses, this option was not explored further in this analysis.

Absorption Systems

Absorption systems refrigerate/cool through the use of two fluids and some quantity of heat input, rather than electrical input as in the more familiar vapor compression cycle. Specifically, absorption systems use a secondary fluid or absorbent to circulate the refrigerant (Rafferty, 2003). These systems can be

used in residential refrigeration and chiller applications and, potentially, heat pumps in residential and light commercial applications, as described below.

Refrigeration Systems: In the late 1990s, more than one million of an estimated 62 million refrigerators sold annually were thermally-activated ammonia/water absorption systems (Sand et al., 1997). The refrigerants used for absorption refrigeration have negligible GWPs. Absorption refrigeration is commonly used in hotel rooms and for recreational vehicles because it operates quietly and has the ability to use bottled gas as an energy source. Absorption refrigerators are limited in size because of design constraints. The thermal coefficient of performance (COP) of these refrigerators can be increased by as much as 50 percent (from a COP of 0.2 to 0.3) through design improvements without degrading cooling capacity (Sand et al., 1997). However, the low efficiency of absorption equipment means that the indirect emissions must be carefully analyzed. Inherent design limitations make it unlikely that absorption refrigeration will become a significant replacement for vapor compression refrigerators. However, absorption refrigeration has great capacity and operating attributes that permit it to fill niche markets (Sand et al., 1997).

Chillers: Gas-fired (as opposed to electrically-powered) absorption water chillers are sold in the United States and are common in Japan. These systems are used mostly where there is a relatively short cooling season, where electricity costs (especially demand charges) are high, and/or where fairly high-grade waste heat is available. Although absorption chillers are far less efficient than competitive systems if waste heat is not available, the technology is feasible and, under some economic circumstances, compares favorably with vapor compression chillers using fluorocarbon refrigerants. Market success will be determined by factors such as the relative costs of natural gas and electricity, peak load charges, and purchase costs. In addition, absorption chillers currently have higher capital costs than vapor compression equipment, such that significant operating cost savings would be necessary to make their purchase economically competitive.

Heat Pumps: Research and development efforts are attempting to create absorption heat pumps that would be used for heating and cooling in residential and light commercial applications. Several years ago, in Europe and the United States, generator absorber heat exchange (GAX) ammonia-water absorption heat pumps were being developed, while field test units had been built in Japan. Absorption heat pumps could be used to reduce global warming impacts in areas where heating load dominates, although they would have the opposite effect in areas where cooling dominates (Sand et al., 1997).

Because these options are either still under development or are currently optimal primarily in niche markets, sufficient information was not available to include their costs and reduction potential in this analysis.

1.3.2 Calculation of Indirect Emissions and Costs for Options Applicable to Stationary Equipment

For three of the technology options assessed for stationary equipment²⁸—distributed systems, HFC secondary loop systems, and ammonia secondary loop systems—a TEWI analysis was conducted to account for “indirect” emissions and costs associated with changes in energy consumption relative to centralized direct expansion systems, the conventional HFC technology assumed to be replaced.

²⁸ Three other technology options analyzed quantitatively in this report apply only to MVACs. For those options, the net costs and emissions associated with changes in energy efficiency (i.e., reduced fuel consumption) are considered in the analysis, as explained under each of the option descriptions.

Analysis of Costs to Abate International ODS Substitute Emissions

Calculations of indirect emissions and costs are based on data from ADL (2002) and EIA (2000), as presented in Table 1-14.

Based on Table 1-14, net energy consumption and costs in the United States were factored into the annual costs/cost savings of each of the three technology options. For all non-U.S. countries, net indirect emissions were adjusted based on country-specific information on average CO₂ emission rates (kg/kWh) associated with national electricity generation (Sand et al., 1997). Likewise, for all non-U.S. countries, annual costs or cost savings associated with changes in energy consumption were also adjusted based on country-specific electricity prices for industry (average 1994-1999) (EIA, 2000).

Table 1-14: Net Annual Emissions and Energy Costs of Replacement Options in the United States in a 600,000 Square Foot Supermarket^{a,b}

	Centralized Direct Expansion System (Base)	Distributed System	Ammonia Secondary Loop System	HFC Secondary Loop System
Charge Size (kg) ^c	1,633	408	180	180
HFC Leak Rate (% of charge/yr) ^c	15%	4%	0%	2%
Direct Emissions (kg/yr)	245	16	0	4
Change in Direct Emissions (kg/yr)	N/A	(229)	(245)	(241)
Change in Direct Emissions (kg/yr) per ton of cooling capacity ^d	N/A	(0.32)	(0.34)	(0.34)
Change in Direct Emissions (TCE/yr) ^e	N/A	(204)	(218)	(214)
Energy Consumption (kWh/yr) ^c	1,200,000	1,100,000	1,400,000 ^f	1,400,000 ^f
Indirect Emissions (TCE/yr) ^g	198	182	231	231
Change in Indirect Emissions (TCE/yr)	N/A	(17)	33	33
Change in Indirect Emissions (TCE/yr) per ton of cooling capacity ^d	N/A	(0.02)	0.05	0.05
Change in Net Emissions (TCE/yr)	N/A	(221)	(185)	(181)
Net Electricity Cost (\$/yr) ^h	N/A	(\$4,000)	\$8,000	\$8,000
Annual Change in Energy Consumption (kWh/yr) per ton of cooling capacity ⁱ	N/A	(139)	278	278
Estimated Net Electricity Cost (\$/ton of cooling capacity)^j	N/A	(\$5.72)	\$11.43	\$11.43

Note: Totals may not sum due to independent rounding.

N/A = not applicable.

^a 600,000-sq. ft. is the typical size of a supermarket in the United States (ADL, 2002).

^b To apply this U.S. analysis to the rest of the world, adjustments by relative energy emission factors (kg CO₂/kWh) and electricity costs for individual countries, based on Sand et al. (1997) and EIA (2000), were made.

^c Based on ADL (2000).

^d Assumes that conventional direct expansion systems require 5 pounds (or 2.27 kg) of refrigerant per ton of cooling capacity (Smithart, 2000). For a 600,000 sq. ft. store using 3,600 lb. refrigerant (ADL, 2002), this translates to 720 tons of cooling capacity.

^e Assumes the refrigerant is R-404A (ADL, 2002).

^f Recent technological advances on secondary loop refrigeration systems for supermarkets suggest that, with the use of improved technological features and design/manufacturing/contractor experience, these systems can lead to significant reductions in energy consumption (Walker, 2000; Baxter, 2003; Kazachki, 2003); however, these reductions are not assumed in this analysis.

^g Assumes a national average emissions factor of 0.606 kg CO₂/kWh (EIA, 2004).

^h Assumes average energy costs for U.S. between 1994-1999 (of approximately \$0.04/kWh) based on EIA (2000).

ⁱ Calculated by dividing the change in energy consumption (kWh/yr) by the charge size of direct expansion systems(kg) and multiplying by the quantity of refrigerant needed on a per ton of cooling capacity basis for conventional direct expansion systems (see footnote e). E.g., for secondary loop systems: (1,400,000 – 1,200,000) kWh/yr ÷ 1,633 kg charge × 2.27 kg/ton of cooling capacity = 278 kWh/ton of cooling capacity.

^J Calculated by multiplying annual change in energy consumption per ton of cooling capacity by average energy costs (assumed to be approximately \$0.04/kWh, as explained in footnote h).

Thus, for HFC and ammonia secondary loop systems, which are associated with decreased energy efficiency relative to centralized HFC direct expansion systems and, therefore, increased indirect emissions, the net increase in indirect emissions was subtracted from the estimated savings in direct emissions, and annual energy costs were accounted for in the analysis. Conversely, for distributed systems, which are associated with increased energy efficiency compared to centralized HFC direct expansion systems, the net savings in indirect emissions were added to the savings of direct emissions, and annual cost savings associated with lower electricity costs were accounted for in the analysis. Therefore, overall, the calculation of indirect emissions and costs resulted in slightly lower emission benefits and higher annual costs for HFC and ammonia secondary loop systems, and in a slightly greater emission benefit and lower annual costs for direct expansion systems.

1.3.3 Summary of Technical Applicability and Market Penetration of Abatement Options

Table 1-15 summarizes the percent of total refrigeration/air-conditioning sector emissions that may be technically abated by each of the options explored in this analysis, based on the percent of sector emissions from each end-use (which varies by region), as provided in Table 1-3. Market penetration values for each abatement option were developed for each region when possible, to best reflect qualitative information available on region-specific realities and possible future action. The commercial refrigeration and MVAC technology options explored in this chapter are assumed to penetrate only new (not existing) equipment, where “new” equipment is defined as equipment manufactured in 2005 or later. Table 1-16 presents the assumed maximum market penetration for the technology options into equipment manufactured in 2005, 2010, 2015 and 2020. Table 1-17 presents the final maximum penetration into the installed base of equipment, taking into account the percent of each market that is new (i.e., manufactured in 2005 or beyond) in all preceding years. Values from Table 1-17 are multiplied by technical applicabilities (Table 1-15) and the reduction efficiency to generate the percent reduction off baseline emissions for each option, as presented in Table 1-18. The text box provided in Section 1.4 provides further explanation on how the results (percent reduction off baseline emissions) are calculated.

Table 1-15: Summary of Technical Applicability of Abatement Options by Region, Percent^a

Abatement Option	U.S. & Japan				Europe, Australia, New Zealand, & All Other Developed Countries				Latin America & Caribbean				Russia, CEITs, & All Other Developing Countries			
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
Refrigerant Recovery from Small Equipment	26.3	24.0	23.7	24.1	30.7	28.3	23.0	23.0	19.4	19.5	19.6	20.3	16.0	17.5	19.7	22.2
Leak Repair for Large Equipment	23.7	26.0	26.3	25.9	19.3	21.7	27.0	27.0	30.6	30.5	30.4	29.7	34.0	32.5	30.3	27.8
Ammonia Secondary Loop	39.7	43.6	44.1	43.1	32.3	36.3	45.4	45.1	51.2	51.0	51.0	49.4	57.0	54.4	50.9	46.3
Distributed System	39.7	43.6	44.1	43.1	32.3	36.3	45.4	45.1	51.2	51.0	51.0	49.4	57.0	54.4	50.9	46.3
HFC Secondary Loop System	39.7	43.6	44.1	43.1	32.3	36.3	45.4	45.1	51.2	51.0	51.0	49.4	57.0	54.4	50.9	46.3
Enhanced HFC-134a in MVACs	37.0	28.5	22.7	19.5	48.7	40.4	20.5	15.9	18.7	16.2	10.7	7.8	9.5	10.7	10.9	13.6
HFC-152a in MVACs	37.0	28.5	22.7	19.5	48.7	40.4	20.5	15.9	18.7	16.2	10.7	7.8	9.5	10.7	10.9	13.6
CO ₂ in MVACs	37.0	28.5	22.7	19.5	48.7	40.4	20.5	15.9	18.7	16.2	10.7	7.8	9.5	10.7	10.9	13.6

^a Expressed as a percent of total refrigeration and air-conditioning emissions.

Table 1-16: Incremental Maximum Market Penetration of Technology Options into New Equipment by Region, Expressed as a Percent of Emissions from New Refrigeration/Air-Conditioning Equipment^a

Abatement Option	U.S.				Europe				Japan, Australia & New Zealand				All Other Developed Countries				Latin America & Caribbean, Russia, CEITs, & All Other Developing Countries			
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
Ammonia																				
Secondary Loop	3	5	13	20	5	10	13	15	5	10	13	15	5	10	13	15	5	10	10	10
Distributed System	8	15	23	30	10	20	30	40	10	20	30	40	10	20	30	40	8	15	20	25
HFC Secondary Loop System	8	15	23	30	5	10	18	25	5	10	18	25	5	10	18	25	8	10	13	10
Enhanced HFC-134a in MVACs	10	65	75	65	40	20	10	0	40	25	10	0	10	65	75	65	0	0	0	0
HFC-152a in MVACs	0	5	15	25	0	25	15	0	0	25	40	25	0	5	15	25	0	20	35	50
CO ₂ in MVACs	0	5	10	10	0	30	75	100	0	25	50	75	0	5	10	10	0	0	5	10

^a Expressed as a percentage of new equipment for the given year. The baseline market penetration of all technology options is assumed to be zero so that only incremental market penetration is analyzed.

Table 1-17: Incremental Maximum Market Penetration of All Abatement Options by Region, Expressed as a Percent of Total Refrigeration/Air-Conditioning Emissions^a

Abatement Option	U.S.				Europe				Japan, Australia & New Zealand				All Other Developed Countries				Latin America & Caribbean, Russia, CEITs, & All Other Developing Countries			
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
Refrigerant Recovery from Small Equipment ^b	5.0	10.0	10.0	15.0	5.0	10.0	10.0	15.0	5.0	10.0	10.0	15.0	5.0	10.0	10.0	15.0	20.0	30.0	40.0	50.0
Leak Repair for Large Equipment	3.0	3.0	5.0	5.0	3.0	3.0	5.0	5.0	3.0	3.0	5.0	5.0	3.0	3.0	5.0	5.0	5.0	10.0	12.0	15.0
Ammonia Secondary Loop	0.2	1.4	4.3	9.4	0.3	2.6	6.1	8.8	0.3	2.6	6.1	8.8	0.3	2.6	6.1	8.8	0.3	2.6	5.6	7.0
Distributed System	0.5	4.1	9.9	17.9	0.6	5.3	12.9	20.5	0.6	5.3	12.9	20.5	0.6	5.3	12.9	20.5	0.5	4.1	9.4	13.7
HFC Secondary Loop System	0.5	4.1	9.9	17.9	0.3	2.6	7.0	12.0	0.3	2.6	7.0	12.0	0.3	2.6	7.0	12.0	0.5	3.2	6.6	7.9
Enhanced HFC-134a in MVACs	0.8	18.8	48.3	68.3	3.3	15.0	20.8	11.2	3.3	16.3	22.9	12.8	0.8	18.8	48.3	68.3	0.0	0.0	0.0	0.0
HFC-152a in MVACs	0.0	1.3	5.8	14.1	0.0	6.3	14.2	14.2	0.0	6.3	20.4	30.8	0.0	1.3	5.8	14.1	0.0	5.0	17.1	33.4
CO ₂ in MVACs	0.0	1.3	4.6	8.3	0.0	7.5	31.3	65.8	0.0	6.3	22.9	47.5	0.0	1.3	4.6	8.3	0.0	0.0	1.3	4.6

^a Expressed as a percentage of entire installed base. The baseline market penetration is assumed to be zero, unless otherwise noted.

^b Shown percentage values are incremental relative to the baseline market penetration, which is assumed to be 80 percent in developed countries and 30 percent in developing countries.

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Table 1-18: Percent Reduction off Baseline Emissions of All Abatement Options by Region

Abatement Option	U.S.				Europe				Japan				Australia & New Zealand				All Other Developed Countries				Latin America & Caribbean				Russia, CEITs, & All Other Developing Countries						
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015
Refrigerant Recovery from Small Equipment	1.1	2.0	2.0	3.1	1.3	2.4	2.0	2.9	1.1	2.0	2.0	3.1	1.3	2.4	2.0	2.9	1.3	2.4	2.0	2.9	3.3	5.0	6.7	8.6	2.7	4.5	6.7	9.4			
Leak Repair for Large Equipment	0.7	0.7	1.2	1.2	0.5	0.6	1.3	1.3	0.7	0.7	1.2	1.2	0.5	0.6	1.3	1.3	0.5	0.6	1.3	1.3	1.5	2.9	3.5	4.2	1.6	3.1	3.5	4.0			
Ammonia Secondary Loop	0.1	0.6	1.9	4.0	0.1	1.0	2.8	4.0	0.1	1.2	2.7	3.8	0.1	1.0	2.8	4.0	0.1	1.0	2.8	4.0	0.2	1.4	2.8	3.5	0.2	1.4	2.8	3.2			
Distributed System	0.2	1.6	4.1	7.2	0.2	1.8	5.5	8.6	0.2	2.1	5.3	8.2	0.2	1.8	5.5	8.6	0.2	1.8	5.5	8.6	0.2	1.9	4.4	6.3	0.2	2.1	4.4	5.9			
HFC Secondary Loop System	0.2	1.7	4.3	7.6	0.1	0.9	3.1	5.3	0.1	1.1	3.0	5.1	0.1	0.9	3.1	5.3	0.1	0.9	3.1	5.3	0.2	1.6	3.3	3.9	0.3	1.7	3.3	3.6			
Enhanced HFC-134a in MVACs	0.2	2.7	5.5	6.7	0.8	3.0	2.1	0.9	0.6	2.3	2.6	1.2	0.8	3.3	2.3	1.0	0.2	3.8	5.0	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			
HFC-152a in MVACs	0.0	0.3	1.2	2.4	0.0	2.2	2.6	2.0	0.0	1.6	4.1	5.3	0.0	2.2	3.7	4.4	0.0	0.4	1.1	2.0	0.0	0.7	1.6	2.3	0.0	0.5	1.7	4.0			
CO ₂ in MVACs	0.0	0.4	1.0	1.6	0.0	3.0	6.4	10.4	0.0	1.8	5.2	9.3	0.0	2.5	4.7	7.5	0.0	0.5	0.9	1.3	0.0	0.0	0.1	0.4	0.0	0.0	0.1	0.6			

1.4 Results

Emission reduction potential for abatement options varies by region based on assumed end-use breakouts (provided in Table 1-3) and on qualitative information regarding current and future likelihood of market penetration by region. The percent reduction from the baseline associated with each abatement option is calculated by multiplying the technical applicability (from Table 1-15) by both the incremental maximum market penetration (from Table 1-16) and the reduction efficiency. For more information on how emission reductions are calculated for each option, please see the Text Box below, which presents an illustrative example of the emission reduction methodology.

Table 1-19 through Table 1-21 provide a summary of the potential emission reduction opportunities and associated annualized costs for the United States, Non-U.S. Annex I and Non-Annex I countries in 2020. The annualized costs to reduce one ton of carbon equivalent (TCE) are presented for two different discount rate scenarios: 4 percent and 20 percent. The tax rate associated with each cost scenario is 0 percent and 40 percent, respectively. The results are ordered by increasing costs per TCE, using the highest cost in the region under the 4 percent discount rate. The emissions reduced by the option and a cumulative total of emissions reduced, in MMTCE and percent of the regional refrigeration and air-conditioning baseline, are presented.

Table 1-19: United States Emission Reductions in 2020 and Break-Even Costs for Refrigeration and Air-Conditioning

Reduction Option	Cost (2000\$/TCE)		Emission Reduction of Option (MMTCE)	Percent Reduction from 2020 Baseline	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
	Discount/Tax Rate 4%/0%	20%/40%				
Enhanced HFC-134a in MVACs	(\$275.47)	(\$35.34)	4.51	6.7%	4.51	6.7%
HFC-152a in MVACs	(\$73.65)	\$55.55	1.66	2.4%	6.17	9.1%
CO ₂ in MVACs	(\$23.44)	\$422.48	1.09	1.6%	7.26	10.7%
Distributed Systems	(\$12.70)	\$62.60	4.87	7.2%	12.13	17.9%
Leak Repair for Large Equipment	(\$11.74)	(\$3.78)	0.83	1.2%	12.96	19.1%
Refrigerant Recovery from Small Equipment	\$0.49	\$0.49	2.09	3.1%	15.05	22.2%
HFC Secondary Loop	\$28.87	\$68.66	5.16	7.6%	20.20	29.8%
Ammonia Secondary Loop	\$30.19	\$78.79	2.74	4.0%	22.94	33.8%

Table 1-20: Non-U.S. Annex I Emission Reductions in 2020 and Break-Even Costs for Refrigeration and Air-Conditioning

Reduction Option	Break-Even Cost (2000\$/TCE) ^a				Emission Reduction of Option (MMTCE)	Percent Reduction from 2020 Baseline	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
	Discount/Tax Rate		Discount/Tax Rate					
	4%/0%	20%/40%	4%/0%	20%/40%				
Leak Repair for Large Equipment	(\$11.74)	(\$11.74)	(\$3.78)	(\$3.78)	0.64	1.7%	0.64	1.7%
Distributed Systems	(\$57.61)	(\$8.08)	\$15.99	\$69.97	3.07	8.0%	3.71	9.7%
Refrigerant Recovery from Small Equipment	\$0.49	\$0.49	\$0.49	\$0.49	1.52	4.0%	5.24	13.7%
Enhanced HFC-134a in MVACs	(\$161.67)	\$7.02	\$299.69	\$468.38	0.51	1.3%	5.74	15.1%
HFC-152a in MVACs	(\$4.59)	\$30.81	\$164.88	\$205.42	1.31	3.4%	7.05	18.5%
Ammonia Secondary Loop	\$18.59	\$123.84	\$62.61	\$180.96	1.44	3.8%	8.50	22.3%
HFC Secondary Loop	\$16.97	\$125.39	\$53.67	\$173.22	1.90	5.0%	10.40	27.3%
CO ₂ in MVACs	\$113.91	\$180.72	\$763.86	\$839.80	2.84	7.5%	13.24	34.7%

^a Costs vary by country/region based on one-time or annual adjustment factors (e.g., electricity price, fuel price, etc.); therefore, the lowest and highest costs for the region are shown.

Table 1-21: Non Annex I Emission Reductions in 2020 and Break-Even Costs for Refrigeration and Air-Conditioning

Reduction Option	Break-Even Cost (2000\$/TCE) ^a				Emission Reduction of Option (MMTCE)	Percent Reduction from 2020 Baseline	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
	Discount/Tax Rate		Discount/Tax Rate					
	4%/0%	20%/40%	4%/0%	20%/40%				
Enhanced HFC-134a in MVACs	(\$13.12)	(\$13.12)	\$448.24	\$448.24	-	0.0%	-	0.0%
Leak Repair for Large Equipment	(\$11.74)	(\$11.74)	(\$3.78)	(\$3.78)	2.12	4.0%	2.12	4.0%
Distributed Systems	(\$25.88)	(\$4.60)	\$48.87	\$70.09	3.17	6.0%	5.29	10.0%
Refrigerant Recovery from Small Equipment	\$0.49	\$0.49	\$0.49	\$0.49	4.91	9.3%	10.20	19.3%
HFC-152a in MVACs	\$26.58	\$26.58	\$200.58	\$200.58	1.96	3.7%	12.16	23.0%
HFC Secondary Loop	\$10.53	\$59.19	\$49.87	\$104.49	1.93	3.7%	14.09	26.7%
Ammonia Secondary Loop	\$12.47	\$59.61	\$60.78	\$114.41	1.74	3.3%	15.83	29.9%
CO ₂ in MVACs	\$172.75	\$172.75	\$830.74	\$830.74	0.30	0.6%	16.13	30.5%

^a Costs vary by country/region based on one-time or annual adjustment factors (e.g., electricity price, fuel price, etc.); therefore, the lowest and highest costs for the region are shown.

1.5 Summary

Baseline HFC emissions from refrigeration/AC are expected to grow significantly between the years 2005 and 2020 as HFCs become increasingly used throughout the world to replace gases phased out under the Montreal Protocol. The highest percentage emissions growth is expected to occur in developing countries.

This analysis considers the costs and emission reduction potential of eight practice and technology emissions mitigation options: (1) Leak Repair for Large Equipment; (2) Refrigerant Recovery/Recycling from Small Equipment; (3) Distributed System; (4) HFC Secondary Loop; (5) Ammonia Secondary Loop; (6) Enhanced HFC-134a Systems in MVACs; (7) HFC-152a Systems in MVACs; and (8) CO₂ Systems in MVACs. The costs and emission reduction benefits of each option were compared in each region. Overall, enhanced HFC-134a systems in MVACs represent the most cost-effective option for

reducing emissions in all regions at a 4 percent discount rate. Distributed systems represent the most promising option for reducing the greatest amount of emissions worldwide, at a negative or low cost. In developing countries, the low-cost option of refrigerant recovery is also promising for significantly reducing emissions.

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2 Analysis of Costs to Abate International HFC Emissions from Aerosols

2.1 Introduction

Aerosol propellants are used in metered dose inhalers (MDIs), as well as a variety of consumer products. Historically, the majority of aerosol applications have used chlorofluorocarbons (CFCs) as propellants; however, efforts have been taken to transition away from CFC propellants. As a result of initiatives under the Montreal Protocol, many pharmaceutical companies that produce MDIs have committed to develop alternatives to CFC-based MDIs. Furthermore, many consumer products, such as spray deodorants and hair sprays and specialty aerosol uses, such as freeze spray and dust removal products, have successfully been reformulated with hydrocarbon propellants or replaced with Not-in-Kind (NIK) substitutes such as pump sprays or solid and roll-on deodorants. Such transitions occurred in the United States as far back as 1977, when the country placed a ban on CFC propellants in non-MDI aerosols for non-essential uses.

Various hydrofluorocarbons (HFCs) have also been introduced as alternative propellants in aerosol applications. These HFCs include HFC-134a, HFC-152a, and HFC-227ea, and are associated, respectively, with 100-year global warming potentials (GWPs) of 1,300, 140, and 2,900 times that of carbon dioxide. Aerosol HFCs are emitted from pharmaceutical products (primarily MDIs)²⁹ and consumer products (primarily specialty aerosols).

The pharmaceutical aerosol industry is actively working to develop HFC-propellant MDIs, a type of inhaled therapy used to treat asthma and chronic obstructive pulmonary disease (COPD). The earliest non-CFC substitute products used HFC-134a, but eventually the industry expects products to utilize HFC-227ea as well. In addition to MDIs that use propellants, dry powder inhalers (DPIs) can be used as a substitute for some MDIs. Because MDIs are medical devices, substitute propellants must meet far stricter performance and toxicology specifications than would be required in most other products. For example, prior to entering the United States market, the Food and Drug Administration must approve reformulated MDIs with an alternative propellant.

Chemical manufacturers are also marketing HFCs, especially HFC-152a and HFC-134a, as aerosol propellants in consumer products, primarily for use in specialty applications. This use is particularly true for applications where flammability or volatile organic compound (VOC) emissions and their impact on urban air quality are a concern. If HFC use is accelerated, increased public concern will likely facilitate the aerosol industry's responsible use of these chemicals (UNEP, 1999).

²⁹ Note that this analysis does not include non-MDI aerosols produced by the pharmaceutical industry such as bandage sprays.

2.2 Baseline Emission Estimates

2.2.1 Emission Estimating Methodology

Description of Methodology

A full description of the emission model used to calculate ODS substitute emissions from all sectors is provided in Appendix A. Specific information on how the model calculates aerosol emissions is described below.

EPA uses a detailed Vintaging Model of ODS-containing equipment and products to estimate the use and emissions of various ODS substitutes in the United States, including HFCs. Emission baselines from non-U.S. countries were derived using country-specific ODS consumption estimates as reported under the Montreal Protocol in conjunction with Vintaging Model output for each ODS-consuming end-use sector. For sectors where detailed information was available, these data were incorporated into country-specific versions of the Vintaging Model to customize emission estimates. In the absence of country level data, these preliminary estimates were calculated by assuming that the transition from ODSs to HFCs and other substitutes follows the same general substitution patterns internationally as observed in the United States. From this preliminary assumption, emission estimates were then tailored to individual countries or regions by applying adjustment factors to U.S. substitution scenarios, based on relative differences in (1) economic growth; (2) rates of ODS phaseout; and (3) the distribution of ODS use across end uses in each region or country.

Emission Equations

All HFCs used in aerosols are assumed to be emitted in the year of manufacture. Since there is currently no aerosol recycling, all of the annual production of aerosol propellants is assumed to be released to the atmosphere. The following equation describes the emissions from the aerosols sector:

$$E_j = Qc_j$$

Where:

E_j = *Emissions*. Total emissions of a specific chemical in a year j from use in aerosol products, by weight.

Qc_j = *Quantity of Chemical*. Total quantity of a specific chemical contained in aerosol products sold in the year j , by weight

j = *Year of emissions*.

For aerosols, two separate baseline emissions were created; one baseline tracks HFC emissions from the MDI industry, while the other estimates HFC emissions from consumer and specialty products (i.e., non-MDI aerosols).

Regional Adjustments

The adjustment factor assumptions used in the global aerosol emissions estimating methodology, which are described in more detail in Appendix A, include both economic and timing adjustment factors. The timing factors reflect that some nations are not moving at the same pace out of the use of CFCs and into

the use of HFCs as other nations are. For all ODS end-uses, by 2005, it is assumed that Non-Annex I (i.e., developing) countries are 75 percent through the CFC transition, and by 2010, the CFC transition is complete. These timing factors are partially offset by generally higher growth rates in developing countries.

In addition, the methodology used to estimate global aerosol emissions includes an adjustment specific to non-MDI aerosols. This adjustment was necessary because the ban on CFC use in aerosols caused the United States to transition out of CFCs earlier than other countries. Therefore, the unweighted U.S. consumption of non-MDI ODS substitutes (including a large market segment that transitioned into NIK or hydrocarbon substitutes) was used as a proxy for U.S. 1990 non-MDI ODS consumption (see Step 3 in Appendix A). For countries other than the United States, it was then assumed that 15 percent of the non-MDI aerosols ODS consumption transitioned to HFCs, while the remainder is assumed to transition to NIK or hydrocarbon alternatives.

2.2.2 Baseline Emissions

Table 2-1 and Table 2-2 display total HFC emission estimates in million metric tons of carbon equivalent (MMTCE) for the MDI and non-MDI aerosols sectors, respectively. Both HFC-134a and HFC-227ea are expected to be emitted from the use of MDIs in the future as substitutes for CFCs. The MDI emissions baseline accounts for all emissions of HFC-227ea from the aerosols sector. Non-MDI emissions are responsible for the majority (approximately 60 percent) of the HFC-134a emissions from the aerosols sector (mainly for specialty applications) and all of the HFC-152a emissions (mostly formulated consumer products).

Table 2-1: Baseline HFC Emission Estimates from MDI Aerosols (MMTCE)

Region	2005	2010	2015	2020
United States	1.58	1.70	1.84	1.98
Non-U.S. Annex I	2.12	2.35	2.48	2.63
Non-Annex I	0.90	1.47	1.79	2.21
Total	4.60	5.52	6.12	6.82

Note: Totals may not sum due to independent rounding.

Table 2-2: Baseline HFC Emission Estimates from Non-MDI Aerosols (MMTCE)

Region	2005	2010	2015	2020
United States	3.00	3.31	3.65	4.03
Non-U.S. Annex I	4.65	5.59	6.12	6.71
Non-Annex I	0.02	0.03	0.03	0.04
Total	7.66	8.92	9.80	10.78

Note: Totals may not sum due to independent rounding.

2.3 Costs of HFC Emission Reductions for Aerosols

This section presents a cost analysis for achieving HFC emission reductions from the emission baselines presented in Table 2-1 and Table 2-2 above. All cost analyses for the non-MDI emission reduction options assume a 10-year project lifetime; the cost analysis for the MDI option assumes a 15-year project lifetime. Each abatement option is described below.

2.3.1 Description and Cost Analysis of Abatement Options

Four potential mitigation options are analyzed in this report. The first mitigation option has the potential to abate emissions from the MDI baseline (Table 2-1), while the other three options have the potential to abate emissions from the non-MDI baseline (Table 2-2). The options are:

- MDI replacement with dry powder inhalers (DPIs);
- Non-MDI replacement with lower GWP HFCs;
- Non-MDI replacement with Not-In-Kind (NIK) alternatives; and
- Non-MDI replacement with hydrocarbon aerosol propellants.

DPIs have been authorized as a substitute for some HFC-propellant MDIs. The non-MDI baseline includes emissions from specialty aerosol uses such as tire inflators, electronics cleaning products, dust removal, freeze spray, signaling devices, and mold release agents as well as consumer products such as hairsprays, mousse, deodorants and anti-perspirants, household products, and spray paints (ADL, 1999). HFCs are currently used when flammability issues cannot easily be overcome, such as tire inflators and air signaling horns that use HFC-134a to avoid potential explosivity associated with highly flammable propellants like propane or butane (ADL, 1999). HFC-152a has been used in dusters since 1993 (UNEP, 1999), and continued substitution of HFC-134a with HFC-152a, or a lower GWP gas in general aerosol applications, is a reduction strategy that has had significant success thus far, and is expected to continue. The other options to reduce HFC emissions from non-MDI aerosol applications include NIK replacement and hydrocarbon aerosol propellants.

The remainder of this section provides a description of the economic assumptions for these four abatement options.

MDI Replacement with Dry Powdered Inhalers (DPIs)

As MDIs transition away from CFC use, alternatives such as HFC propellants, DPIs, and oral medications are being developed. Although hydrocarbons have replaced CFCs as propellants in many commercial aerosols, they have been found to be unacceptable for use in MDIs (IPAC, 1999). Given the unique medical requirements for developing MDIs, and the fact that the industry has been investing heavily in the development of HFC technologies, an aerosol replacement for HFC-based MDIs is unlikely to be developed within the time frame of this analysis. Globally, the number of HFC MDIs used has grown to more than 100 million in 2001 (UNEP, 2002). Rather than developing new alternatives that use HFCs, some MDI manufacturers may turn to DPIs, oral medication, or other NIK alternatives. In 2001, the number of multi-dose DPIs used world-wide was estimated at 65 million (UNEP, 2002).³⁰ This analysis examines the option of further replacing HFC-based MDIs with DPIs because of its technical feasibility and demonstrated success in the MDI market.

DPIs are a viable option with most anti-asthma drugs, although they are not successful with all patients or all drugs. Micronised dry powder can be inhaled and deposited in the lungs from DPIs as with MDIs, but only in patients who are able to inhale robustly enough to transport the powder to the lungs. DPIs are not suitable for persons with severe asthma or for young children. Unlike MDIs, powdered drug particles contained in DPIs tend to aggregate and may cause problems in areas with hot and humid climates (March Consulting Group, 1999; UNEP, 2002). Other issues that doctors and patients consider when

³⁰ Multiple-dose DPIs contain pre-measured doses that provide treatment for a day or up to one month. Single-dose DPIs are also available where only one dose can be loaded at a time (UNEP, 2002).

choosing a treatment device include the patient's manual dexterity, ability to adapt to a new device, and their perception of the effectiveness of the medicine and taste of any added ingredients (Price et al., 2004). It is important to note that the choice of treatment, including the type of propellant used in MDIs, is a medical decision involving the pharmaceutical industry, the FDA or other regulatory authority, and ultimately doctors and their patients. Doctors and their patients will be involved in selecting the method of therapy, treatment regimen, and which type of device(s) and active ingredients(s) to prescribe that will prove most effective for particular individuals (IPAC, 1999).

In 1998, DPI usage was estimated to represent 17 percent of all inhaled medication (i.e., inhaler units) world-wide and has increased to 27 percent in 2002 (UNEP, 2002). DPIs may represent a viable alternative, as suggested by their increased use in Europe; for example, in Holland they account for more than 65 percent of inhaled medication (UNEP, 2002). The use of newly available DPIs is on the rise in the United States, where DPIs made up 14 percent of the total U.S. market share as of mid-2002 (UNEP, 2002). There is also a trend toward the development of a broad range of oral treatments that would be swallowed, rather than inhaled, and may be introduced over the next 10 to 20 years. These new medications may impact MDI use, although will likely not replace inhaled MDI therapy entirely.

This analysis assumes that DPIs are technically applicable³¹ to all HFC emissions from MDIs. However, due to the limitations in their use for severe asthma patients and young children, and the difficulties experienced in hot and humid climates, this analysis assumes a global incremental maximum market penetration into the HFC-based MDI market of 0 percent in 2005, increasing up to 50 percent in 2020 (see Table 2-3). Also assumed is a 100 percent reduction efficiency. To the extent that health and technical concerns are adequately met, a transition in inhalation therapy away from propellant MDIs and toward NIK alternatives may occur over the next 10 to 20 years. The rapidity at which these changes will occur is dependent upon product development cycles (generally about 10 years), cost-effectiveness, and manufacturing capacity (UNEP, 1999).

Cost and Emission Reduction Analysis

Cost assumptions for this option were taken directly from Ecofys (2000).³² The following bullets describe the cost and emission inputs used to derive the final \$/TCE for the DPI option, the results of which are presented in Section 2.4:

- **One-time Costs.** No one-time costs are assumed for implementing DPIs.
- **Annual Costs.** The annual cost associated with using DPIs was estimated to be approximately €33,000 (in 1999 euros) per metric ton of substance (Enviros March, 2000), which translates to an annual cost of \$599,625 dollars based on an exchange rate of \$112.5/€100 (Universal Currency Converter Web site, 2003). According to the source cited by Ecofys (2000), this annual cost incurred by the industry takes into account the increase in cost of DPI treatment, the cost to market the new treatment, and the cost to retrain the patients in using the DPI (Enviros March, 2000).

³¹ In this report, the term *technically applicable* refers to the emissions to which an option can be applied. Because DPIs can eliminate emissions from MDIs, they are technically applicable to all MDI emissions but are not technically applicable to non-MDI emissions. Other factors will affect their application and the market penetration assumed in this analysis. See Appendix I for a glossary of terminology.

³² The Ecofys (2000) report cites Enviro March (2000) costs, which were developed assuming a conversion to DPIs from an MDI containing HFC-134a (Enviros March, 2000). For this analysis, these costs and the associated emission reductions were applied to the total baseline MDI market, which consists of MDIs that use HFC-134a and HFC-227ea.

- **Cost Savings.** No cost savings are assumed for this option.
- **Emission Reductions.** This option is assumed to avoid 1,000 kilograms of HFC emissions under the cost scenario as provided by Ecofys (2000). This reduction equates to 354.55 TCE, calculated using the GWP of HFC-134a.

Non-MDI Replacement with Lower GWP HFCs

Replacement of higher GWP HFCs, such as HFC-134a, with a lower GWP HFC, such as HFC-152a, has the potential to greatly reduce emissions from the non-MDI aerosols sector. HFC-134a is the primary non-flammable propellant in certain industrial products. HFC-152a possesses only moderate flammability hazards and might therefore be acceptable for some applications (UNEP, 2002). This analysis assumes that converting to HFC-152a is technically applicable to all emissions of HFC-134a from the non-MDI baseline. Non-MDI emissions of HFC-134a are calculated by the Vintaging Model to be 83 percent of total GWP-weighted non-MDI aerosol emissions. As shown in Table 2-3, the incremental maximum market penetration of this alternative is assumed to increase from 10 percent in 2005 up to 50 percent in 2020. Because HFC-152a has a GWP of 140 (versus a GWP of 1,300 for HFC-134a), this substitution has an emission reduction efficiency of 89.2 percent (i.e., the difference of the GWPs divided by the GWP of HFC-134a).

Cost and Emission Reduction Analysis

The following bullets describe the cost and emission inputs used to derive the final \$/TCE for converting to a lower GWP aerosol propellant, the results of which are presented in Section 2.4:

- **One-time Costs.** Costs of converting a filling facility to accept HFC-152a may range from \$400,000 to \$500,000 (Dupont, 2000). To be conservative, this analysis assumes that a one-time cost of \$500,000 dollars is required to achieve the assumed reduction scenario.
- **Annual Costs.** The cost per pound of HFC-134a (\$1.70 per pound) is slightly lower than the cost per pound of HFC-152a (\$1.93 per pound) (Atofina, 2003; Atofina 2004). Thus, filling a can that requires 2 ounces of propellant with HFC-134a costs \$0.21, versus \$0.24 with HFC-152a; therefore, the difference in chemical costs is an additional \$0.03 per can. An annual cost of \$281,250 was calculated by assuming that a filling facility produces 10 million units per year, each requiring two ounces of aerosol propellant.
- **Cost Savings.** No costs savings are realized with this alternative since the HFC-152a is estimated to cost slightly more than HFC-134a.
- **Emission Reductions.** Assuming that 10 million eight ounce cans are converted from HFC-134a to HFC-152a, and the typical quantity of propellant required per unit is two ounces (or 0.0567 kilograms), the potential quantity of HFC-134a avoided by the facility in one year is estimated to be 567,000 kilograms. Accounting for the reduction efficiency of 89.2 percent, this facility could avoid 0.18 MMTCE per year (i.e., 567 metric tons of HFC-134a multiplied by the GWP of 1300, the reduction efficiency of 0.892, and the conversion factor of carbon to carbon dioxide equivalents of 12/44).

Non-MDI Replacement with NIK Technology

Not-in-Kind (NIK) aerosol propellants include finger/trigger pumps, powder formulations, sticks, rollers, brushes, nebulizers, and bag-in-can/piston-can systems. These systems often prove to be a better and more cost-effective option than HFC-propelled aerosols, particularly in areas where a unique HFC property is not specifically needed for a certain end-use. NIKs already occupy a sizable share of markets

where they were introduced during the initial CFC phaseout. Since NIK products have already assumed much of the available non-MDI HFC aerosol market share, an incremental maximum market penetration of 5 percent was assumed in 2005 and 10 percent for years 2010, 2015, and 2020 (see Table 2-3). The analysis assumes that this option is technically applicable to all non-MDI emissions and has a reduction efficiency of 100 percent. The GWP of 538 was used to represent both HFCs being abated and was calculated using the weighted average of the HFC-134a and HFC-152a baseline emissions.

Cost and Emission Reduction Analysis

The following bullets describe the cost and emission inputs used to derive the final \$/TCE for NIK aerosol propellants, the results of which are presented in Section 2.4:

- **One-time Costs.** Significant variability exists in financial components of projects targeting NIK replacements for HFC-containing aerosol products. This variability is attributable to the wide range of potential aerosol and NIK product types. For this analysis, an incremental capital cost of \$250,000 per facility was used.
- **Annual Costs.** In the case of liquid pumps and solid applicators, capital investments are generally lower, but material costs will be higher than for HFCs (UNEP, 1999). To account for higher material costs of the particular sticks, rollers, and pumps being used, the analysis assumes an estimated \$500,000 in annual costs for a facility that produces 10 million units (e.g., cans, pumps).
- **Cost Savings.** Despite the costs of this option, overall savings can be significant, due primarily to the avoidance of HFC costs. Filling a can that requires two ounces of propellant with an HFC was estimated to cost approximately \$0.23 (based on the average price per pound of HFC-134a and HFC-152a weighted by the mass percent of the baseline emissions comprised by each gas) versus no costs of chemical for an NIK formulated can, resulting in a savings of \$2,309,703 per year for a filling facility that produces 10 million total cans in one year. This cost savings is offset by the annual cost of \$500,000, resulting in an annual savings of \$1,809,703 for this option.
- **Emission Reductions.** Assuming that 10 million eight ounce units are converted from an HFC to an NIK process, each unit using approximately two ounces of propellant, the quantity of HFC avoided in one year was estimated at 567,000 kilograms, or 0.08 MMTCE using the weighted average GWP of 538.

Non MDI Replacement with Hydrocarbon Aerosol Propellants

Hydrocarbon (HC) aerosol propellants are usually mixtures of propane, butane, and isobutane. Their primary advantage lies in their affordability; the price of HC propellants are less than one-tenth that of HFCs. The main disadvantages of hydrocarbon aerosol propellants are flammability and VOC emission concerns. Hydrocarbons contribute to ground level ozone and smog and therefore may be regulated in some areas. In markets where flammability and/or VOC emissions are less of a concern, hydrocarbons already hold a sizable share. Since hydrocarbon aerosol propellants have already penetrated a significant amount of the market; further penetration is limited due to flammability and VOC concerns. Hence, this analysis assumes an incremental maximum market penetration of 5 percent in 2005, expanding to 10 percent in later years. The analysis also assumes that converting to hydrocarbons is technically applicable to all non-MDI emissions, but that various factors including the flammability of hydrocarbons will limit the market penetration of this option. The reduction efficiency of this abatement option is taken to be 100 percent, since the HFC is completely replaced by a hydrocarbon propellant with a very low GWP. The GWP of 538 was used to represent both HFCs being abated and was calculated using the weighted average of the HFC-134a and HFC-152a baseline emissions.

Cost and Emission Reduction Analysis

The following bullets describe the cost and emission inputs used to derive the final \$/TCE for converting to a hydrocarbon aerosol propellant, the results of which are presented in Section 2.4:

- One-time Costs.** The one-time cost of converting a filling facility to accept hydrocarbon propellants can range from \$10,000 to \$1.2 million, including the costs of installing safety control features (Nardini, 2002). The high conversion cost accounts for the fact that hydrocarbons are highly flammable gases that require stringent safety precautions in manufacturing, storage, handling, transport, and customer use. The range in one-time cost varies based on the need for investments in new equipment and the need to relocate to regions where the use of HCs is considered safe (Nardini, 2002). One-time costs are expected to be lower, for instance, for a facility converting from HFC-152a to a hydrocarbon propellant where flammability controls are likely to already be in place. This report assumes that a facility producing 10 million cans per year must invest \$325,000 for this option.
- Annual Costs.** Annual costs may be incurred to ensure good handling practices of hydrocarbons that are considered hazardous air pollutants (HAPs), regular maintenance on fire prevention devices such as fire detection systems, sprinklers, and shut-off valves, and proper safety training for employees (UNEP, 2002). Such costs have not been quantified for this analysis; however, future work may be performed to investigate estimated annual costs.
- Cost Savings.** Hydrocarbon prices are generally lower than those of HFCs, which lowers overall production costs and contributes to cost savings. To represent savings for this option, filling a can that requires two ounces of and HFC propellant was estimated to cost \$0.23 (based on the average price per pound of HFC-134a and HFC-152a weighted by the mass percent of the baseline emissions comprised by each gas) versus \$0.04 for the cost of a HC (based on the price of a propane/isobutane blend of \$0.30 per pound, Diversified CPC, 2004), which yields a cost savings of approximately \$1,934,700 per year experienced by a filling facility that produces 10 million cans in one year.
- Emission Reductions.** As with the scenario used for the NIK option, the quantity of HFC avoided in one year by transitioning to hydrocarbons was estimated at 567,000 kilograms, or 0.08 MMTCE.

2.3.2 Summary of Technical Applicability and Market Penetration of Abatement Options

Table 2-3 summarizes the technical applicability and incremental maximum market penetration of the aerosol options presented in the discussions above.

Table 2-3: Technical Applicability and Incremental Maximum Market Penetration of Aerosol Options (Percent)^a

Option	Technical Applicability (All Years)	Maximum Market Penetration			
		2005	2010	2015	2020
DPI (MDI) ^b	100%	0%	5%	20%	50%
HFC to HC (Non-MDI)	100%	5%	10%	10%	10%
HFC to NIK (Non-MDI)	100%	5%	10%	10%	10%
HFC-134a to HFC-152a (Non-MDI)	83% ^c	10%	25%	35%	50%

^aAssumed maximum market penetration of options is presented as a percentage of total sector emissions for which the options are applicable. The baseline market penetration is assumed to be zero to assess the emission reductions possible due to increased use of each option.

^bAssumptions are separated by the line to reflect that the MDI option addresses different baseline emissions than the non-MDI options.

^cBased on percent of non-MDI aerosol emissions as determined by the Vintaging Model.

To calculate the percent of emission reductions off the applicable (i.e., MDI or non-MDI) aerosols baseline for each abatement option, the technical applicability (Table 2-3) is multiplied by the market penetration value (Table 2-3), and by the reduction efficiency of the option. For example, to determine the percent reduction off the 2020 baseline for the conversion of HFC-134a aerosols to HFC-152a, the following calculation is performed:

$$\text{Technical Applicability} \times \text{Market Penetration in 2020} \times \text{Reduction Efficiency}$$

$$83\% \times 50\% \times 89.2\% \approx 37.0\%$$

Thus, using the assumptions in this analysis, converting from HFC-134a to HFC-152a could reduce over one-third of the non-MDI emissions baseline in 2020. This value, along with the other emission reduction potentials, is shown in Table 2-4.

Table 2-4: Emission Reductions off the Total Applicable Aerosols Baseline (Percent)

Option	2005	2010	2015	2020
DPI (MDI) ^a	0	5	20	50
HFC to HC (Non-MDI)	5	10	10	10
HFC to NIK (Non-MDI)	5	10	10	10
HFC-134a to HFC-152a (Non-MDI)	7	19	26	37

^aCalculated percentages are separated by the line to reflect that the MDI option addresses different baseline emissions than the non-MDI options.

2.4 Results

Table 2-5 through Table 2-7 provide a summary of the potential emission reduction opportunities and associated costs for United States, Non-U.S. Annex I countries, and Non-Annex I countries in 2020. The costs, in 2000 U.S. dollars, to reduce one ton of carbon equivalent (TCE) are presented for two different discount rate scenarios: 4 percent and 20 percent. The tax rate associated with each cost scenario is 0 percent and 40 percent, respectively. Within the options that address non-MDI emissions, the results are ordered by increasing costs per TCE. Additionally, the emissions reduced by the option, in MMTCE and percent of the regional aerosols (either MDI or non-MDI) baseline, are presented, as are cumulative totals of these two figures.

Table 2-5: United States Emission Reductions in 2020 and Break-Even Costs for Aerosols

Reduction Option	Break-Even Cost (2000\$/TCE)		Emission Reduction of Option (MMTCE)	Percent Reduction from 2020 Baseline	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
	Discount Rate/ Tax Rate					
	4% / 0%	20% / 40%				
DPI (MDI) ^a	\$1,691.25	\$1,691.25	0.99	50.0%	0.99	50.0%
HFC to HC (Non-MDI)	(\$22.76)	(\$21.95)	0.40	10.0%	0.40	10.0%
HFC to NIK (Non-MDI)	(\$21.37)	(\$20.75)	0.40	10.0%	0.81	20.0%
HFC-134a to 152a (Non-MDI)	\$1.91	\$2.49	1.49	37.0%	2.30	57.0%

^aResults are separated by the line to reflect that the MDI option addresses different baseline emissions than the non-MDI options.

Table 2-6: Non-U.S. Annex I Emission Reductions in 2020 and Break-Even Costs for Aerosols

Reduction Option	Break-Even Cost (2000\$/TCE)		Emission Reduction of Option (MMTCE)	Percent Reduction from 2020 Baseline	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
	Discount Rate/ Tax Rate					
	4% / 0%	20% / 40%				
DPI (MDI) ^a	\$1,691.25	\$1,691.25	1.32	50.0%	1.32	50.0%
HFC to HC (Non-MDI)	(\$22.76)	(\$21.95)	0.67	10.0%	0.67	10.0%
HFC to NIK (Non-MDI)	(\$21.37)	(\$20.75)	0.67	10.0%	1.34	20.0%
HFC-134a to 152a (Non-MDI)	\$1.91	\$2.49	2.48	37.0%	3.83	57.0%

^aResults are separated by the line to reflect that the MDI option addresses different baseline emissions than the non-MDI options

Table 2-7: Non Annex I Emission Reductions in 2020 and Break-Even Costs for Aerosols

Reduction Option	Break-Even Cost (2000\$/TCE)		Emission Reduction of Option (MMTCE)	Percent Reduction from 2020 Baseline	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
	Discount Rate/ Tax Rate					
	4% / 0%	20% / 40%				
DPI (MDI) ^a	\$1,691.25	\$1,691.25	1.10	50.0%	1.10	50.0%
HFC to HC (Non-MDI)	(\$22.76)	(\$21.95)	0.004	10.0%	0.00	10.0%
HFC to NIK (Non-MDI)	(\$21.37)	(\$20.75)	0.004	10.0%	0.01	20.0%
HFC-134a to 152a (Non-MDI)	\$1.91	\$2.49	0.01	37.0%	0.02	57.0%

^aResults are separated by the line to reflect that the MDI option addresses different baseline emissions than the non-MDI options

2.5 Summary

This analysis considers four mitigation options: 1) MDI Replacement with Dry Powdered Inhalers (DPIs); 2) Non-MDI Replacement with Lower GWP HFCs; 3) Non-MDI Replacement with Not-In-Kind (NIK) Alternatives; and 4) Non-MDI Replacement with Hydrocarbon Aerosol Propellants. The first option has the potential to abate emissions from the MDI baseline; while the latter three options have the potential to abate emissions from the non-MDI baseline.

MDI Aerosols

Global baseline HFC emissions from MDI aerosols are estimated to grow from 4.60 to 6.82 MMTCE between the years 2005 and 2020. In 2020, the three regions analyzed (the United States, Non-U.S. Annex I and Non-Annex I) are estimated to be responsible for approximately 29, 39 and 32 percent of the baseline emissions, respectively (see Table 2-1). The highest emissions growth from the MDI baseline, from 0.90 MMTCE in 2005 to 2.21 MMTCE in 2020, is expected to occur in Non-Annex I countries.

As Table 2-5 through Table 2-7 illustrate, converting from HFC MDIs to DPIs is not a cost-effective abatement option—the estimated cost is more than \$1,500 dollars per TCE for all regions—although the option may be popular for other reasons. The option is assumed to abate 50 percent of global MDI emissions, or 3.41 MMTCE, annually, by 2020. The costs per TCE for the three regions are equivalent because available data on costs for abatement technologies were not scaled to reflect potential differences in the costs internationally. Additional research may be performed to determine actual variability in costs across regions.

Non-MDI Aerosols

Baseline HFC emissions from non-MDI aerosols are estimated to grow from 7.66 MMTCE to 10.78 MMTCE globally for years 2005 through 2020. In 2020, Non-U.S. Annex I emissions are assumed to

account for approximately 62 percent of this total, while U.S. and Non-Annex I countries are assumed to account for approximately 37 percent and 0.3 percent, respectively (see Table 2-1). The highest absolute emissions growth, from 4.65 MMTCE in 2005 to 6.71 MMTCE in 2020, is expected to occur in the Non-U.S. Annex I region.

As shown in Table 2-5 through Table 2-7, the greatest emission reduction opportunities in all of the regions analyzed may come from converting HFC-134a to HFC-152a, at a cost of \$1.91 per TCE at a 4 percent discount rate. The other two options, converting to hydrocarbons and NIK, represent a cost savings of \$22.76 and \$21.37 per TCE at a 4 percent discount rate, respectively. Globally, 6.15 MMTCE, or 57 percent of global emissions from non-MDI aerosols, can be reduced in 2020 at a cost below \$2.00/TCE. As with MDI aerosols, costs per TCE for these three regions are equivalent because available data on costs for abatement technologies were not scaled to reflect potential differences in the costs internationally. Additional research may be performed to determine actual variability in costs across regions.

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3 Analysis of Costs to Abate International HFC Emissions from Foams

3.1 Introduction

Various hydrofluorocarbons (HFCs) are currently being used as blowing agents during the manufacture of foams. These high GWP gases are substitutes for ozone depleting substances (ODSs) that were the primary blowing agents historically used in the foams industry. Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol) have agreed to phase out chlorofluorocarbons (CFCs) and many are using hydrochlorofluorocarbons (HCFCs) as interim substitutes. Developed and developing countries are at different phases of replacing CFCs with alternatives. Developed countries such as the United States and the European Union have banned the sale and distribution of most foam products manufactured with HCFCs and have begun transitioning to HFC use in foams where hydrocarbons and other alternatives are not already used. For example, Denmark, Austria, Finland, and Sweden phased out the use of HCFCs for foam blowing on January 1, 2002.

Developing countries have only recently begun transitioning from CFC-11 to HCFCs and other alternatives. Their rate of conversion to HFCs may be limited by the current availability of other ODS substitutes and also by technical barriers and cost. For example, the main blowing agent alternatives for CFC-11 in rigid polyurethane (PU) insulating foams are hydrocarbons (HCs), such as pentanes, and HCFCs. Applying alternative (i.e., HFC) technologies may require the use of higher density foam, which will result in incremental operating costs.

The most commonly used HFCs are HFC-134a, HFC-152a, HFC-245fa, and HFC-365mfc in combination with HFC-227ea. These blowing agents can be released into the atmosphere during the foam manufacturing process, during on-site foam application, while foams are in use, and when foams are discarded. They have 100-year global warming potentials (GWPs) of 1,300, 140, 950, 890, and 2900 respectively, and have replaced historically used ODS blowing agents including CFCs and HCFCs. Foams studied in this analysis include the following:

- Appliance foams found in various commercial and domestic refrigerators, vending machines, freezers, water heaters, picnic boxes, flasks/thermoware and refrigerated containers (reefers);
- Spray polyurethane (PU) foams found in roofing, wall insulation, plus various tank and vessel applications;
- PU continuous and discontinuous sandwich panels foam found in cold storage, entrance and garage doors;
- PU one component foams found in sealing around windows and doors, framing around pipes, cable holes, jointing insulating panels and around certain roof components; and
- Extruded polystyrene (XPS) boardstock foam used in building insulation.

3.2 Baseline Emission Estimates

3.2.1 Emission Estimating Methodology

A full description of the emission model used to calculate ODS substitute emissions from all sectors of the foam market is provided in Appendix A. Specific information on how the model calculates emissions for this sector is described below.

EPA uses a detailed Vintaging Model of ODS-containing equipment and products to estimate the use and emissions of various ODSs and ODS substitutes in the United States, including HFCs and PFCs. Emission equations used by the model are presented below.

Emission Equations

Foams are given emission profiles depending on the foam type (open cell or closed cell). Open cell foams are assumed to be 100 percent emissive in the year of manufacture as described in the first equation below. Closed cell foams are assumed to emit a portion of their total HFC content upon manufacture, a portion at a constant rate over the lifetime of the foam, and a portion at disposal as described in the second equation below.³³

Open-Cell Foam

$$E_j = Qc_j$$

Where:

E_j = *Emissions*. Total emissions of a specific chemical in year j used for open-cell foam blowing, by weight.

Qc_j = *Quantity of Chemical*. Total amount of a specific chemical used for open-cell foam blowing, in year j , by weight.

j = *Year of emission*.

Closed-Cell Foam

$$E_j = \sum (ef_i \times Qc_{j-i+1}) \quad \text{for } i=1 \rightarrow k$$

Where:

E_j = *Emissions*. Total emissions of a specific chemical in year j for closed-cell foam blowing, by weight.

ef = *Emission Factor*. Percent of foam's original charge emitted in each year ($1 \rightarrow k$). This emission factor is generally variable, including a rate for manufacturing emissions (occurs in the first year of foam life), annual emissions (every year throughout the foam lifetime), and disposal emissions (occurs during the final year of foam life).

Qc = *Quantity of Chemical*. Total amount of a specific chemical used in closed-cell foams in year ($j - i + 1$).

³³ Emissions from foams may vary due to handling and disposal of the foam; shredding of foams may increase emissions, while landfilling of foams may abate some emissions (Scheutz, et al. 2002, Scheutz, et al. 2003). Average annual emissions are assumed in the model, which may not fully account for the range of foam handling and disposal practices.

- i = Counter. Runs from 1 to lifetime (k).
- j = Year of emission.
- k = Lifetime. Average lifetime of foam product.

The emissions profile for foams assumed by the Vintaging Model is presented below in Table 3-1.

Table 3-1: U.S. EPA's Vintaging Model Emissions Profile for the Foams Sector

Foams Sector	Loss at Manufacturing (%)	Annual Release Rate (%)	Release Lifetime (years)	Loss at Disposal (%)	Total Released (%)
Flexible PU	100	0	0	0	100
Polyisocyanurate Boardstock	6	1	50	44	100
Rigid PU Integral Skin	95	2.5	2	0	100
Rigid PU Appliance	4	0.25	15	92.25	100
Rigid PU Commercial Refrigeration	6	0.25	15	90.25	100
Rigid PU Spray	25	1.5	50	0	100
One Component	100	0	0	0	100
Rigid PU Slabstock and Other	37.5	0.75	15	51.25	100
Phenolic	23	0.875	32	49	100
Polyolefin	95	2.5	2	0	100
XPS Foam Sheet	40	2	25	0	90
XPS Boardstock	25	2.5	30	0	100
Sandwich Panel	5.5	0.5	50	69.5	100

Regional Adjustments

All global emissions except the U.S. and Canada were estimated in the foam-blowing sector by developing Vintaging Model scenarios that were representative of country- or region-specific substitution and consumption patterns. To estimate baseline emissions, current and projected characterizations of international total foams markets were used to create country or region-specific versions of the Vintaging Model. The market information was obtained from Ashford (2004), based on research conducted on global foam markets. Scenarios were developed for Japan, Europe (both EU and non-EU countries combined), other developed countries (excluding Canada), CEITs, and China. It was assumed that other non-Annex I countries would not transition to HFCs during the scope of this analysis. Once the Vintaging Model scenarios had been run, the emissions were disaggregated to a country-specific level based on estimated 1989 CFC consumption for foams developed for this analysis. Emission estimates were adjusted slightly to account for relative differences in countries' economic growth as compared to the United States (USDA, 2002; and EIA, 2001).

Emission baselines for Canada were derived using country-specific ODS consumption estimates as reported under the Montreal Protocol in conjunction with U.S. Vintaging Model output for each ODS-consuming end-use sector. Preliminary estimates were calculated by assuming that the transition from ODSs to HFCs and other substitutes follow the same general substitution patterns as observed in the United States. A detailed description of the Vintaging Model and the methodology used to estimate and adjust emissions in Canada are presented in Appendix A.

Newly Manufactured Foam Emissions vs. Existing Foam Emissions

Technology options explored in the foams chapter are only applicable to new (not existing) foams. Therefore, the technical applicabilities of the technology options in this sector include only emissions

from relevant end-uses that are from “newly manufactured” foams, where “newly manufactured” is defined as foam manufactured in 2005 or later.

3.2.2 Baseline Emissions

Table 3-2 provides a summary of baseline emissions for the United States, Non-U.S. Annex I and Non-Annex I countries through 2020.

Table 3-2: Baseline Emissions in MMTCE

Regions	2005	2010	2015	2020
United States	0.53	1.90	3.15	7.35
Non-US Annex I	2.40	3.40	4.59	9.01
Non-Annex I	0.00	0.01	0.01	0.01
Total	2.94	5.30	7.76	16.38

3.3 Costs of HFC Emission Reductions from Foams

This section presents a cost analysis of achieving HFC emission reductions from the emissions baseline presented above.

Costs were based on the incremental differences between using the HFC and switching to an HFC alternative. Financial information considered in this analysis includes: capital costs, which account for equipment costs to modify existing plants and to maintain production capacity; blowing agent costs, which address the difference between costs and the quantity of the HFC and non-HFC alternative required; foam costs, which address changes in foam density, the amount of fire retardant used, the quantity and type of polyol, etc.; testing, training or other costs associated with transitioning to non-HFC alternatives; and costs to produce a thicker, denser foam to account for any energy efficiency differences.

In addition, industry has indicated that there will be additional conversion or “learning curve” costs, which are short-term costs incurred due to yield, rate, and density penalties associated with conversion uncertainties as well as technical support costs. Such costs may be highly variable and are not addressed in the analysis.

3.3.1 Description of Abatement Options

Specific opportunities to reduce HFC emissions from foams that were analyzed for this are:

- Replacing HFC-134a, HFC-245fa, and HFC-365mfc/HFC-227ea with hydrocarbons in continuous and discontinuous panel foam;
- Replacing HFC-134a and HFC-152a with hydrocarbons in one component foam;
- Replacing HFC-134a/CO₂(LCD) with CO₂(LCD) in XPS foam;
- Replacing HFC-134a/CO₂ (LCD) with CO₂/Alcohol (LCD/Alcohol) in XPS foam;
- Replacing HFC-245fa/ CO₂ (water) and HFC-365mfc/HFC-227ea with CO₂(water) in spray foam;

- Replacing HFC-245fa/CO₂ (water) and HFC-365mfc/HFC-227ea with hydrocarbons in spray foam;
- Replacing HFC-134a with hydrocarbons in appliance foam;
- Replacing HFC-245fa with hydrocarbons in appliance foam;
- End-of-life appliance foam practice: automated process with foam grinding and landfilling; and
- End-of-life appliance foam practice: manual process with incineration.

The remainder of this section provides a description of the economic assumptions for these abatement options. All abatement option cost analyses assume a 25-year project lifetime.

Replacement Options

The abatement options and costs of options to reduce HFC emissions from the foam sector are presented by foam type: PU spray foams, PU appliance foams, other PU foams, continuous and discontinuous panel foam, one component foam, and XPS foams. Each of the options includes the use of non-HFC blowing agents such as hydrocarbons, water-blown CO₂, and liquid CO₂. These foam technologies are described below, followed by Section 3.3.2, which gives specific analyses of the costs of applying these alternate blowing agents to the particular foam types.

Hydrocarbons (HCs)

Hydrocarbons such as propane, butane, isobutane, n-pentane, isopentane, cyclopentane, and isomers of hexane are alternatives to HFCs in foam blowing appliances. HCs are inexpensive and have lower GWP impacts relative to HFCs. However, key technical issues associated with the use of hydrocarbons exist, as follows:

- **Flammability.** HCs require stringent safety precautions in manufacturing, storage, handling, transport, and customer use. These factors necessitate factory upgrades and employee training. Specialized equipment that might be needed includes a dedicated storage tank for the hydrocarbon, pre-mixers, adapted high-pressure dispensers, suitable molds plus process exhaust, hydrocarbon detectors, and appropriate classification of electrical equipment. In order to reduce fire risks, some applications might also require the use of a larger quantity of flame retardants and/or the use of a more expensive fire retardant.
- **Volatile Organic Compounds (VOCs).** Because HCs contribute to ground level ozone and smog, they tend to be highly regulated. In many places, such as certain areas of the United States, HCs cannot be used without emission controls. Implementation of these controls can lead to significant increases in the costs of conversion.
- **Performance.** Some HCs only yield approximately 85 percent of the insulating value of HCFC-141b and HFC-245fa (and HFC-365mfc/HFC-227ea). Producing a thicker foam can compensate for this energy efficiency difference, but will increase the cost of production. This option might not be viable in fixed thickness applications such as refrigerated trucks or in applications where an R-value is prescribed by code such as in PU spray roofing insulation. Other performance considerations include dimensional stability and solubility. Addressing these factors might require a more expensive and more limited polyol formulation.

Costs of converting to hydrocarbons and addressing technical considerations can be significant, but vary according to factory-specific needs. In spite of these issues, hydrocarbons are being considered in a wide variety of applications (UNEP, 1998; Alliance, 2000; Alliance, 2001).

Liquid Carbon Dioxide (LCD)

The basic principle by which LCD blowing agents operate is the expansion of liquid CO₂ to a gaseous state. Liquid CO₂ is blended with other foam components under pressure prior to the initiation of the chemical reaction. When decompressed, the CO₂ expands, resulting in froth foam, which further expands with the additional release of CO₂ from the water/isocyanate resin reaction that forms the PU foam matrix. LCD might require formulation changes to more readily dissolve the CO₂ and to prevent deactivation of PU catalysts. When LCD is introduced at the head, often referred to as third stream, the metering equipment can be quite complicated and, to date, unreliable. Difficulties encountered in using LCD include the limited solubility of the chemical mixture, controlled decompression, and distribution of the unavoidable froth (UNEP, 1998). Foams blown with CO₂ may suffer from lower thermal conductivity, lower dimensional stability, and higher density versus HCFC-blown foams. To overcome these limitations, CO₂ can be blended with hydrocarbons or HFCs (Williams et al., 1999; Honeywell, 2000; Alliance, 2001).

Water-Blown (in situ) Carbon Dioxide (CO₂ (water))

In this process, CO₂ produced from a chemical reaction between water and polymeric isocyanate is used as a blowing agent. During manufacture, no ODS or high-GWP gases are emitted, and there are limited health and safety risks during processing. However, foams produced using CO₂/water are subject to the same performance limitations discussed for LCD-blown foams: lower thermal conductivity, lower dimensional stability, and higher density versus HCFC- and HFC- blown foams. In some PU foam applications, a major concern associated with using water-generated or LCD systems is the increased percentage of open cell content, which results in poorer water-proofing performance and water-proofing quality of the final product. Another consideration is that the polymeric isocyanate content must be increased, which cannot be accommodated by some spray foam equipment. To overcome these limitations, CO₂ can be blended with hydrocarbons or HFCs (Williams et al., 1999; Honeywell, 2000; Alliance, 2001). In some other applications, e.g. PU Block, there can be problems with uncontrollable exotherms using purely CO₂ (water) systems.

Although LCD and CO₂ generated *in situ* have similar performance issues, the process limitations associated with each differ. Fewer mechanical modifications are required to use *in situ* CO₂, and the foam manufacturer or spray foam applicator can be more certain of the final CO₂ content and overall foam properties, than for LCD (Alliance, 2001).

End-of-Life Appliance Foam Practices

There are several methods for disposal of polyurethane foam, including landfilling and incineration, with or without ODS recovery and recycling/destruction. Two of the methods are described below, followed in Section 3.3.2 by specific analyses of the costs associated with each method.

Landfilling

Traditionally, most of the decommissioned foam products have ended up in landfills. Although the regulations related to the location and management of landfills have improved considerably, there is still concern about the rate of release of blowing agent from foam in the first weeks of entering the landfill. (UNEP, 2002b).

Incineration

Incineration of foams in municipal solid waste incinerators (MSWIs) or waste-to-energy plants is a practical and highly competitive technique for destruction of polyurethane foam. An advantage of this technique is that the foam can be incinerated without separating the foam matrix from the blowing agent prior to incineration, which makes the costs and potential risks of fugitive emissions lower.

3.3.2 Description of Abatement Options

The following section describes all of these options in greater detail and presents a cost analysis for those options for which adequate cost data are available. The technology options explored in this chapter are assumed to penetrate only the markets of new (not existing) foams. “New” foam is defined as foams manufactured in 2005 or later.

Continuous and Discontinuous Panel Foam

The only abatement option that was considered for this category is replacing HFC with hydrocarbons. The blowing agent constitutes approximately 9 percent of the foam, by weight. This cost analysis estimates the break-even carbon price for a hypothetical contractor to replace HFC with hydrocarbons. The foams manufactured with the alternative are assumed to compensate for lower insulating performance relative to HFC-blown foams by increasing the thickness and density of the foam. Although this end-use uses HFC-134a, HFC-245fa, and HFC-365mfc/HFC-227ea, the analysis was performed based on a continuous and discontinuous foam contractor that uses HFC-134a. A contractor that uses HFC-245fa and HFC-365mfc/HFC-227ea would see higher cost savings for this replacement option since these HFCs are more expensive than HFC-134a. But, since they have lower GWPs, the option would yield a lower TCE savings. This analysis is based on a hypothetical continuous and discontinuous foam contractor that uses approximately 1 million pounds per year of HFC-134a (ICF Consulting, 2004).

Table 3-3: Base Case Assumptions for a Contractor Using HFC-134a

Variable	Value	Source
Blowing Agent Component of Foam	8.7%	Cannon, 2001
Blowing Agent Consumption	1,048,600 lbs	UNEP, 2002a
Foam Produced	12,052,874 lbs	Calculation
Foam Cost	\$1.02/lb	Assumption
Price of HFC-134a	\$1.70/lb	Atofina, 2004

Cost factors that are addressed include:

- capital equipment costs;
- increased cost of foam components (e.g., polyols, additives, etc.);
- increased consumption of foam components to compensate for increased foam density;
- increased use of fire retardant; and
- incremental differences in the costs of blowing agents and the quantity required.

Continuous and Discontinuous Panel: Replacing HFC with Hydrocarbons

This option is technically applicable³⁴ to all emissions from the newly-produced continuous and discontinuous panel foams. The technical applicability of this option from 2005 to 2020 is presented in Table 3-20 and Table 3-20. This analysis assumes that the incremental maximum market penetration of this option in 2010 into the newly-produced continuous and discontinuous panel market that uses HFC-134a is 70 percent for the United States and 90 percent for the rest of the world, both rising to 100 percent by 2020 (see Table 3-22), and its reduction efficiency is 100 percent. Assumptions specific to this substitution are presented in Table 3-4.

Cost and Emission Reduction Analysis

- **One-time Costs.** According to industry experts, the one-time cost associated with this abatement option is the cost of installing safety equipment. For this purpose, a one-time cost of \$300,000 was assumed for replacing HFC-134a with hydrocarbons.
- **Annual Costs.** This analysis assumes increased operating costs of \$2,242,777 for this abatement option. These costs result from costs associated with fire retardant use, costs associated with changes in foam density, and worker safety training costs associated with the use of hydrocarbons. Table 3-3 and Table 3-4 summarize the assumptions associated with this abatement option. Costs associated with fire retardant use are \$750,300, calculated as the amount of foam produced (12,052,874 lb) multiplied by the incremental increase in fire retardant used in foam (3%) and the fire retardant costs (\$2.08/lb). Worker training costs are estimated to be \$11,429, calculated by multiplying the costs of training per day by the number of workers and the number of training days (i.e., costs per day = \$4,000/14 days = \$285.71/day; total cost per year = \$286/day × 5 days × 8 workers = \$11,429). Costs associated with foam density increases are \$1,481,057, calculated by multiplying the amount of foam produced by alternative foam costs (\$1.02/lb) and the increase in foam density (12%).
- **Cost Savings.** Because hydrocarbons are less expensive on a per kilogram basis than HFC-134a, there is a \$1,153,460/year cost savings associated with this option. Costs of the current blowing agent are \$1,782,620/yr, while costs of alternative blowing agent are \$629,160/yr. Current costs are calculated by multiplying the per-pound cost of the blowing agent by the total amount of blowing agent (1,048,600lb × \$1.70/lb = \$1,782,620). The calculation of alternative blowing agent cost includes per-pound costs of alternative blowing agent (\$0.60/lb), the amount of blowing agent used (1,048,600 lb), and the blowing agent substitution ratio (100%).
- **Emission Reductions.** This analysis estimates that by replacing HFCs with hydrocarbons, 0.17 MMTCE of the high GWP gas that would have been emitted from foam manufactured by the hypothetical contractor during the lifetime of the foam produced in a given year are eliminated.

Table 3-4: Assumptions and costs used in the cost analysis to substitute HFC-134a Hydrocarbons

Variable	Value	Source
Capital Costs	\$300,000	Assumption

³⁴ In this report, the term *technically applicable* refers to the emissions to which an option can be applied. Because this option examines the replacement of HFC-134a with hydrocarbons, and can not be retroactively applied to HFC-134a foam that has already entered the market, the technical applicability is the percent of baseline foams emissions that comes from HFC-134a from continuous and discontinuous panels placed on the market after 2004. Other factors will affect the market penetration of the option assumed in this analysis. A glossary of terminology may be found in Appendix I.

Variable	Value	Source
Incremental Increase in Fire Retardant Use	3%	Assumption
Cost of Fire Retardant	\$2.08/lb	Exxon, 2004
Blowing Agent Substitution Ratio	100%	Assumption
Increase in Foam Density	12%	ICF Consulting, 2004
Assumed Increase in Cost of Foam	\$0.10/lb	Assumption
Price of Pentane	\$0.60/lb	Exxon, 2004
Training Class Costs	\$4,000	ICF Consulting, 2004
Days per Training Class	14 days	ICF Consulting, 2004
Number of Workers	8 workers	ICF Consulting, 2004
Days of Training	5 days/yr ^a	ICF Consulting, 2004
Employee Training Costs	\$11,429/yr ^b	Calculation

^a Assumes one-week per year of training per worker.

^b Assumes a cost of approximately \$3000 – 5000/training class, 6 – 10 employees, and 4 – 6 days of training. (Costs per day = \$4000/14 days = \$285.71/day; Total cost per year = \$286/day × 5 days × 8 workers = \$11,429)

One Component Foam

Two blowing agent replacement abatement options were considered for this end-use:

- Replacing HFC-134a with propane/butane; and
- Replacing HFC-152a with propane/butane.

An analysis was performed based on a hypothetical one component foam contractor that uses approximately 300,000 pounds per year of HFC-134a or HFC-152a (ICF Consulting, 2004). The blowing agent constitutes approximately 9 percent of the foam, by weight. This cost analysis estimates the break-even carbon price for this hypothetical contractor to replace HFC-134a or HFC-152a with hydrocarbons.

Table 3-5: Base Case Assumptions for a Contractor Using HFC-134a and HFC-152a

Variable	Value	Source
Blowing Agent Component of Foam	8.7%	Cannon, 2001
Blowing Agent Consumption	288,000 lbs	UNEP, 2002a
Foam Produced	3,310,345 lbs	Calculation
Blowing Agent Substitution Ratio	100%	ICF, 2004
Foam Cost	\$1.02/lb	Assumption
Price of HFC-134a	\$1.70/lb	Atofina, 2004
Price of HFC-152a	\$1.93/lb	Atofina, 2004
Price of propane	\$0.50/lb	Atofina, 2004
Price of butane	\$0.50/lb	Atofina, 2004

Cost factors that are addressed include:

- capital equipment costs;
- increased cost of foam components (e.g., polyols, additives, etc.);
- increased consumption of foam components to compensate for increased foam density;
- increased use of fire retardant; and
- incremental differences in the costs of blowing agents and the quantity required.

One Component: Replacing HFC-134a with Hydrocarbons

This option is technically applicable to all HFC-134a emissions from the newly-produced one component foams. The technical applicability of this option from 2005 to 2020 is presented in Table 3-20 and Table 3-21. This analysis assumes that the incremental maximum market penetration in 2010 for this option in the newly-produced one component market that uses HFC-134a would be 70 percent for the United States and 90 percent for the rest of the world, both increasing to 100 percent by 2020 (see Table 3-22), and its reduction efficiency is 100. Assumptions specific to this substitution are presented in Table 3-6.

Cost and Emission Reduction Analysis

- **One-time Costs.** According to industry experts, the one-time costs for replacing HFC-134a with hydrocarbons are \$375,000, which includes the cost of installing safety equipment.
- **Annual Costs.** This analysis assumes operating costs of \$321,103 for this abatement option. These costs result from costs associated with fire retardant use and worker safety training costs associated with the use of hydrocarbons. Table 3-5 and Table 3-6 summarize the assumptions associated with this abatement option. Costs associated with fire retardant use are \$309,103 and are calculated as the amount of foam produced multiplied by the incremental increase in fire retardant used in foam and the fire retardant costs ($3,310,345 \text{ lb} \times 4.5\% \times \$2.08/\text{lb} = \$309,103$). Worker training costs are estimated to be \$12,000, and are calculated by multiplying the costs of training per day by the number of workers and the number of training days ($\$285.71/\text{day} \times 14 \text{ days} \times 3 \text{ workers} = \$12,000$). Costs per training per day are calculated by dividing the total costs of training class by the number of days ($\$285.71/\text{day} = \$4,000/14 \text{ days}$).
- **Cost Savings.** Because propane and butane are less expensive on a per-pound basis than HFC-134a, a \$345,600 annual cost savings is associated with this option. Costs of the current blowing agent are \$489,600/yr, while costs of alternative blowing agent are \$144,000/yr. Current costs are calculated by multiplying the per-pound cost of the blowing agent by the total amount of blowing agent used ($288,000 \text{ lb} \times \$1.70/\text{lb} = \$489,600/\text{yr}$). The calculation of alternative blowing agent cost includes per-pound costs of alternative blowing agent ($\$0.50/\text{lb}$), the amount of blowing agent used (288,000 lb), and the blowing agent substitution ratio (100%).
- **Emission Reductions.** This analysis estimates that by replacing HFC-134a with hydrocarbons, 0.046 MMTCE of the high GWP gas that would have been emitted by this facility during the lifetime of the one component foam produced in a given year are eliminated.

Table 3-6: Assumptions and costs used in the cost analysis to substitute HFC-134a with Hydrocarbons

Variable	Value	Source
Capital Costs	\$375,000	ICF, 2004
Incremental Increase in Fire Retardant Use	4.5%	ICF, 2004
Cost of Fire Retardant	\$2.08	Exxon, 2004
Training Costs	\$4,000/training class	ICF, 2004
Days per Training Class	14 days	ICF, 2004
Number of Workers Trained	14 workers	ICF, 2004
Number of Training Days Needed	3 days/year	ICF, 2004

One Component: Replacing HFC-152a with Hydrocarbons

This option is technically applicable to all HFC-152a emissions from the newly-produced one component foams. The technical applicability of this option from 2005 to 2020 is presented in Table 3-20 and Table 3-21. This analysis assumes that the incremental maximum market penetration in 2010 for this option in

the newly-produced one component foam market that uses HFC-152a would be 70 percent for the United States and 90 percent for the rest of the world, both increasing to 100 percent by 2020 (see Table 3-22), and its reduction efficiency is 100 percent. Assumptions specific to this substitution are presented in Table 3-7.

Cost and Emission Reduction Analysis

- One-time Costs.** According to industry experts, the one-time costs for replacing HFC-152a with hydrocarbons are \$375,000, which includes the cost of installing safety equipment. Although some additional safety precautions already existed to handle the flammability of HFC-152a, they were assumed to be rather minor in comparison to a primary hydrocarbon blowing agent system; therefore, the capital cost is estimated to be the same as the switch from HFC-134a to hydrocarbons.
- Annual Costs.** This analysis assumes operating costs of \$321,103 for this abatement option. These costs result from fire retardant use and worker safety training associated with the use of hydrocarbons. Table 3-5 and Table 3-10 summarize assumptions associated with this abatement option. Costs associated with fire retardant use are \$309,103, and are calculated as the amount of foam produced multiplied by the incremental increase in fire retardant used in the foam and the fire retardant costs. Worker training costs are estimated to be \$12,000 and are calculated by multiplying the costs of training per day by the number of workers and the number of training days.
- Cost Savings.** Because propane and butane are less expensive on a per-pound basis than HFC-152a, a \$410,400 annual cost savings is associated with this option. Costs of the current blowing agent are \$554,400/yr, while costs of alternative blowing agent are \$144,000/yr. Current costs are calculated by multiplying the per-pound cost of the blowing agent by the total amount of blowing agent used ($288,000\text{lb} \times \$1.925/\text{lb} = \$554,400/\text{yr}$). The calculation of alternative blowing agent cost includes per-pound costs of alternative blowing agent (\$0.50/lb), the amount of blowing agent used (288,000 lb), and the blowing agent substitution ratio (100 percent).
- Emission Reductions.** This analysis estimates that by replacing HFC-152a with hydrocarbons, 0.005 MMTCE of the high GWP gas that would have been emitted by this facility during the lifetime of the one component foam produced in a given year are eliminated.

Table 3-7: Assumptions and costs used in the cost analysis to substitute HFC-152a with Hydrocarbons

Variable	Value	Source
Capital Costs	\$375,000	ICF, 2004
Incremental Increase in Fire Retardant Use	4.5%	ICF, 2004
Cost of Fire Retardant	\$2	ICF, 2004
Training Costs	\$4,000/training class	ICF, 2004
Days per Training Class	14 days	ICF, 2004
Number of Workers Trained	14 workers	ICF, 2004
Number of Training Days Needed	3 days	ICF, 2004

Extruded Polystyrene (XPS) Foams

Two blowing agent replacement options were considered for this end-use:

- Replacing HFC-134a/CO₂ (LCD) with CO₂ (LCD); and
- Replacing HFC-134a/CO₂ (LCD) with CO₂ (LCD)/Alcohol.

An analysis was performed based on a hypothetical contractor that produces approximately 8.3 million ft³ of foam per year using an 80/20 blend of HFC-134a and CO₂ as a blowing agent. The conversion to the alternative blowing agent is assumed to take place in only 10 percent of the line. Various “base case” inputs and assumptions are presented in Table 3-8. This cost analysis estimates the break-even carbon price for this hypothetical contractor to replace HFC-134a/CO₂ with one of two non-HFC blowing agents: 1) CO₂ or 2) CO₂/Alcohol. The foams manufactured with the two alternatives are assumed to compensate for lower insulating performance relative to HFC-blown foams by increasing the thickness and density of the foam. Thus, incremental differences in indirect emissions and costs associated with energy penalties are negligible.

Table 3-8: Base Case Assumptions for a Hypothetical Contractor Using HFC-134a/CO₂ (LCD)

Variable	Value	Source
Blowing Agent Consumption	1,500,000 lb/yr	Estimated from Caleb (2001)
Polystyrene Consumption	2.0 lb/ft ³	Assumption
Foam Produced	8,330,000 ft ³ /yr	Assumption
Price of CO ₂	\$0.20/lb	Airproducts, 2003
Price of HFC-134a	\$1.70/lb	Atofina, 2004
Price of Polystyrene	\$0.40/lb	Purchasing.com, 2003

Cost factors that are addressed include:

- blowing agent costs;
- capital equipment costs;
- increased consumption of foam components to compensate for increased foam density; and
- incremental differences in the costs of blowing agents and the quantity required.

XPS: Replacing HFC-134a/CO₂ (LCD) with CO₂ (LCD)

This option is technically applicable to all emissions from the newly-produced extruded polystyrene foam, but the assumed market penetration is tempered by the existence of another feasible option (i.e., CO₂/alcohol). The technical applicability of this option from 2005 to 2020 is presented in Table 3-20 and Table 3-21. The current blowing agent is assumed to be an 80/20 blend of HFC-134a and CO₂. This analysis assumes that the incremental maximum market penetration of this option into the newly-manufactured extruded polystyrene foam market would be 0 percent for the United States through 2020 and 35 percent for the rest of the world in 2010, rising to 45 percent by 2020 (see Table 3-22), and that its reduction efficiency is 100 percent. Assumptions specific to this substitution are presented in Table 3-9.

Cost and Emission Reduction Analysis

- **One-time Costs.** Because the conversion to a CO₂ line requires high pressure equipment, based on industry opinion, this analysis assumes a \$3,500,000 one-time cost for replacing HFC-134a with CO₂.
- **Annual Costs.** This analysis assumes operating costs of \$66,700 for this abatement option due to the increased consumption of polystyrene based on increased foam density. This cost is calculated by multiplying the total amount of foam produced by the amount of polystyrene needed and the per-pound price of polystyrene (8,330,000 ft³ × 2.0 lb/ft³ × \$0.40/lb = \$6,664,000) and then accounting for the 10 percent foam density increase and the conversion of only 10 percent of the line. (\$6,664,000 × 10% × 10% = \$66,640).

- **Cost Savings.** Because the alternative blowing agent is less expensive on a per-pound basis than HFC-134a, there is a cost saving of \$180,000/year associated with this option. This number is derived by subtracting the per pound costs of the alternative blowing agent used from the costs of current blowing agent blend (\$1.40/lb - \$0.20/lb = \$1.20/lb). The cost of the alternative blowing agent (CO₂) is \$0.20/lb, while the cost of the current blowing agent blend (80/20 blend of HFC-134a/CO₂) is \$1.40/lb. The resulting price difference is then multiplied by the total blowing agent used (1,500,000 lb/yr) and by the converted 10 percent of the line.
- **Emission Reductions.** This analysis estimates that by replacing HFC-134a/CO₂ (LCD) with CO₂ (LCD) in 10% of the line, 0.019 MMTCE of high GWP gas that would have been emitted by this contractor during the lifetime of the foam generated in a given year are eliminated.

Table 3-9: Assumptions and costs used in the cost analysis to substitute HFC-134a/CO₂ with CO₂

Variable	Value	Source
Capital Costs	\$3,500,000 ^a	Assumption
Increase in Foam Density	10%	Assumption

^a Assumes that a conversion to a 100 percent CO₂ blowing agent requires high pressure equipment.

XPS: Replacing HFC-134a/CO₂ (LCD) with CO₂ (LCD)/Alcohol

The current blowing agent for XPS is assumed to be an 80/20 blend of HFC-134a and CO₂. This option is technically applicable to all emissions from the newly-produced extruded polystyrene foam, but the assumed market penetration is tempered by the existence of another feasible option (i.e., CO₂). The technical applicability of this option from 2005 to 2020 is presented in Table 3-20 and Table 3-21. The incremental maximum market penetration of this option into the newly-produced extruded polystyrene foam market is assumed to be 0 percent for the United States through 2020, and 35 percent in 2010, rising to 45 percent by 2020 for China (see Table 3-22), with a reduction efficiency of 100 percent. Assumptions specific to this substitution are presented in Table 3-10.

Cost and Emission Reduction Analysis

- **One-time Costs.** According to industry experts, the one-time costs for replacing HFC-134a with a CO₂ and alcohol blend are \$800,000. Blends of CO₂ with alcohol (e.g., ethanol) require lower pressure extrusion. As a result, capital costs associated with this method are lower than the conversion to pure CO₂.
- **Annual Costs.** This analysis assumes annual operating costs of \$33,300/year for this abatement option. Costs are calculated by multiplying the total amount of foam produced in 10 percent of a line by the amount of polystyrene needed and the per-pound price of polystyrene (8,330,000ft³ × 10% × 2.0lb/ft³ × \$0.40/lb = \$666,500) and then accounting for the 5 percent foam density increase (\$666,500 × 5% = \$33,325).
- **Cost Savings.** Because the alternative blowing agent is less expensive on a per-pound basis than HFC-134a, there is \$166,500 annual cost savings associated with this option. This number is derived by subtracting the per-pound cost of the alternative blowing agent used (an 80/20 blend of HFC-134a/ CO₂) from the per-pound cost of the current blowing agent blend (an 80/20 blend of CO₂/ethanol) (\$1.40/lb - \$0.29/lb = \$1.11/lb). The resulting price is then multiplied by the total blowing agent used (1,500,000 lb/yr) and by the 10 percent of the line converted.
- **Emission Reductions.** This analysis estimates that by replacing HFC-134a/CO₂ (LCD) with CO₂ (LCD), 0.019 MMTCE of the high GWP gas that would have been emitted by this contractor during the lifetime of the foam generated in a given year are eliminated.

Table 3-10: Assumptions and costs used in the cost analysis to substitute HFC-134a/CO₂ with CO₂/Alcohol

Variable	Value	Source
Capital Costs	\$800,000 ^a	Assumption
Increase in Foam Density	5%	Assumption
Price of Alcohol	\$0.65	Purchasing.com

^a Blends with alcohol (e.g., ethanol) require lower pressure extrusion; therefore lower capital than pure CO₂.

Polyurethane (PU) Spray Foams

Two blowing agent replacement options were considered for this end-use:

- Replacing HFC-245fa/CO₂ (water) and HFC-365mfc/HFC-227ea with CO₂ (water); and
- Replacing HFC-245fa/CO₂ (water) and HFC-365mfc/HFC-227ea with cyclopentane/isopentane.

An analysis was performed based on a hypothetical spray foam contractor that produces approximately 127,000 pounds of foam per year using a 75/25 blend of HFC-245fa³⁵ and CO₂ (water) as a blowing agent. The blowing agent constitutes approximately 10 percent of the foam, by weight. Various “base case” inputs and assumptions are presented in Table 3-11. The foams manufactured with the two alternatives are assumed to compensate for lower insulating performance relative to HFC-blown foams by increasing the thickness and density of the foam. Thus, there are no incremental differences in indirect emissions and costs associated with energy penalties. Although this end-use uses HFC-245fa and HFC-365mfc/HFC-227ea, the analysis was performed based on a spray foam contractor that uses HFC-245fa.

Table 3-11: Base Case Assumptions for a Hypothetical Spray Foam Contractor Using HFC-245fa/CO₂ (water)

Variable	Value	Source
Blowing Agent Component of Foam	10%	Cannon, 2001; NCFI, 2001
HFC-245fa/CO ₂ Ratio	75/25	Assumption
Blowing Agent Use	12,735 lb	Estimated from Caleb (2001)
Foam Produced	127,347 lb	Calculation
Original Foam Cost	\$0.92/lb	Assumption
Price of Isocyanate	\$1.00/lb	Cannon, 2001
Price of HFC-245fa	\$4.00/lb	Honeywell, 2003

Cost factors that are addressed include:

- fire testing costs incurred by system houses for various formulations;
- capital equipment costs;
- employee training costs (hydrocarbons only);
- increased cost of foam components (e.g., polyols, additives, etc.);
- increased consumption of foam components to compensate for increased foam density;
- increased use of fire retardant; and
- incremental differences in the costs of blowing agents and the quantity required.

³⁵ The EU countries use a blend of HFC-365mfc and HFC-227ea in ratios of 93:7 or 87:13, while Japan uses a blend of HFC-245fa and HFC-365mfc in ratios of 80:20 or 70:30. This report presents a cost analysis based on the 75/25 HFC-245fa/CO₂ blend and applies it globally as a representative estimate.

Annual emission reductions were determined based on the estimated amount of blowing agent consumed by the hypothetical contractor and from the emissions profile used in the Vintaging Model (see Table 3-1).

Spray: Replacing HFC-245fa/CO₂ (water) and HFC-365mfc/HFC-227ea with CO₂ (water)

This option is technically applicable³⁶ to all emissions from the newly manufactured spray polyurethane foam market, but the assumed market penetration is tempered by the existence of another feasible option (i.e., hydrocarbons). The technical applicability of this option as well as other options from 2005 to 2020 is presented in Table 3-20 and Table 3-21. This analysis assumes that the incremental maximum market penetration for this option in 2010 into the newly formulated polyurethane spray foam market is 5 percent for the United States and 7.5 percent for the rest of the world, both rising to 20 percent by 2020 (see Table 3-22), and that its reduction efficiency is 100 percent because the HFC blowing agent is completely replaced (the GWP of CO₂ is not included in the analysis). For cost estimating purposes, this option assumes that the current blowing agent is a 75/25 blend of HFC-245fa and CO₂. Assumptions specific to this substitution are presented in Table 3-12.

Cost and Emission Reduction Analysis

- **One-time Costs.** According to industry experts, contractors that are using HFC-245fa/CO₂ (water) can use the same equipment for CO₂ (water) with only minimal modification (Caleb, 2001). This analysis assumes that a one-time cost of \$4,000 is needed to convert to this alternative blowing agent. This cost is associated with fire testing, which is based on \$250,000 fire testing costs for new formulations, 20 systems houses that will need to pass some tests, and approximately 1,250 spray foam contractors who equally share these costs ($\$250,000 \times 20 / 1,250$) (Caleb, 2001).
- **Annual Costs.** This analysis assumes a unit annual operating cost of \$54,500 for this abatement option. These costs result from fire retardant use, costs due to increased density of foam, and the increased foam costs (refer to Table 3-11 and Table 3-12 for detailed assumptions). Costs associated with fire retardant use are \$2,648 and they are calculated by multiplying the amount of foam produced (127,347 lb) by the incremental percent of fire retardant in the foam (1%) and fire retardant costs (\$2.08/lb). Increased foam costs are \$12,735, and are calculated by multiplying the amount of foam produced by the increase in foam costs (\$0.10/lb). Costs due to increased density are \$39,121 and are calculated by multiplying the amount of foam produced by alternative foam costs (\$1.02/lb) and the increase in foam density (30%).
- **Cost Savings.** Because the alternative blowing agent is less expensive on a per-pound basis than HFC-245fa, there is an \$11,461 annual cost savings associated with this option. Cost of the current blowing agent is \$57,306, while the cost of alternative blowing agent is \$45,845. Current costs are calculated by multiplying the per-pound cost of the blowing agent by the total amount of blowing agent used as follows: total HFC-245fa blowing agent used \times 75% \times per-pound cost of the blowing agent + total CO₂ blowing agent used \times 25% \times isocyanate/CO₂ ratio \times price of isocyanate ($(12,735\text{lb} \times 75\% \times \$4/\text{lb}) + (12,735\text{lb} \times 25\% \times 6 \times \$1/\text{lb}) = \$57,306$). The calculation of alternative blowing agent cost includes the per-pound costs of alternative blowing agent (\$1.00), the amount of blowing agent used (12,735lb), the isocyanate/CO₂ ratio (6), and the blowing agent component of foam ratio (60%). See Table 3-11 for prices of the current and

³⁶ In this report, the term *technically applicable* refers to the emissions to which an option can be applied. A glossary of terminology may be found in Appendix I.

alternative blowing agent and Table 3-12 for other assumptions that are associated with cost savings.

- **Emission Reductions.** This analysis estimates that by replacing HFC-245fa/CO₂ (water) with CO₂ (water), 1,122 TCE (i.e., 12,735 lb, or 5.78 metric tons, blowing agent multiplied by 75 percent content HFC-245fa, the GWP of 950, and the carbon to carbon-dioxide conversion ratio of 12/44) of the high GWP gas that would have been emitted by this hypothetical spray foam manufacturer during the lifetime of the foam produced in a given year are eliminated.

Table 3-12: Assumptions and costs used in the cost analysis to substitute HFC-245fa/CO₂ (water) with CO₂ (water)

Variable	Value	Source
Capital Costs	Negligible ^a	Caleb, 2001
Fire Testing Costs	\$4,000 ^b /Contractor	Caleb (2001)
Incremental Increase in Fire Retardant Use	1%	Assumption
Cost of Fire Retardant	\$2.08/lb	Exxon, 2004
Isocyanate/CO ₂ Ratio	6	Cannon, 2001
CO ₂ /Water Component of Foam	6%	Stepan, 2001
Decrease Blowing Agent Component of Foam	60%	Stepan, 2001
Increase in Foam Density	30 ^c %	Assumption
Assumed Increase in Cost of Foam	\$0.10/lbs	Assumption
Alternative Foam Costs	\$1.02	Calculation

^a Assumes that contractors that are using HFC-245fa/CO₂ (water) have equipment that can use CO₂ (water) with minimal modification.

^b Based on \$250,000 per systems house, 20 systems houses, and approximately 1,250 spray foam contractors (Caleb, 2001).

^c Assumes that foam density increases from 2.5 lb/ft³ to 3.25 lb/ft³.

Spray: Replacing HFC-245fa/CO₂ (water) and HFC-365mfc/HFC-227ea with Hydrocarbons

The difference in costs between this abatement option and replacing HFC-245fa/CO₂ with CO₂ is that this abatement option has factored into the analysis the cost of training workers in handling, storing, and using hydrocarbons. For cost estimating purposes, the current blowing agent is assumed to be a 75/25 blend of HFC-245fa and CO₂, while the alternative blowing agent is assumed to be an 80/20 blend of cyclopentane and isopentane. This option and the previous one are technically applicable to all emissions from the newly-produced spray polyurethane foam market. The technical applicability of this option from 2005 to 2020 is presented in Table 3-20 and Table 3-21. This analysis assumes that the incremental maximum market penetration of this option in 2010 in the newly-produced spray foam market would be 10 percent for the United States and 5 percent for the rest of the world, rising in later years to 30 percent in the United States and 15 percent in the rest of the world (see Table 3-22), and its reduction efficiency is 100 percent. There could be some safety and liability concerns associated with this substitution, which could lead to reduced market penetration or increased cost of this option. Assumptions specific to this abatement opportunity are presented in Table 3-13.

Cost and Emission Reduction Analysis

- **One-time Costs.** According to industry experts, in the US, the one-time costs for replacing HFC-245fa/CO₂ (water) with hydrocarbons are estimated to be \$10,000 (Exxon, 2001). Based on \$250,000 fire testing costs for new formulations, fire testing for 20 systems houses, and approximately 1,250 spray foam contractors, one time costs associated with fire testing in the US are \$4,000/contractor ($\$250,000 \times 20/1,250$) (Caleb, 2001). Fire testing costs in the EU are \$22,642, while in Japan these costs are \$33,924 (BRE, 2004; JUFMA, 2004).

- Annual Costs.** This analysis assumes a unit annual operating cost for this abatement option of \$40,437. These costs result from fire retardant use, costs due to increased density of foam, and worker safety training costs associated with the use of hydrocarbons. Table 3-11 and Table 3-13 summarize assumptions associated with this abatement option. Costs associated with fire retardant use are \$7,927 and are calculated by multiplying the amount of foam produced (127,347 lb) by the incremental percent of fire retardant in foam (3%), and by the additional fire retardant costs (\$2.08/lb). Worker training costs are estimated to be \$6,429 and are calculated by multiplying costs of training per day by the number of workers and the number of training days as shown in the table. Costs due to increased density are estimated to be \$26,081, and are calculated by multiplying the amount of foam produced by the per-pound foam costs (\$1.02/lb) and the increase in foam density (20%).
- Cost Savings.** Because the alternative blowing agent is less expensive on a per kilogram basis than HFC-245fa, there is a \$49,398 annual cost savings associated with this option and is calculated by subtracting current blowing agent costs (\$57,306/yr) from the alternative blowing agent costs (\$7,908/yr). Current costs are calculated as shown in the previous example. The calculation of alternative blowing agent cost includes per-pound costs of alternative blowing agent (i.e., $(80\% \times \$0.80/\text{lb}) + (20\% \times \$0.25/\text{lb}) = \$0.69/\text{lb}$), the amount of blowing agent used (12,735lb), and the blowing agent substitution ratio (90%). See the base case assumptions table (Table 3-11) for prices of the current and alternative blowing agent and Table 3-13 for other assumptions that are associated with cost savings.
- Emission Reductions.** This analysis estimates that by replacing HFC-245fa/CO₂ (water) with hydrocarbons, 1,122 TCE of the high GWP gas that would have been emitted by this hypothetical foam manufacturer during the lifetime of the foam produced in a given year are eliminated.

Table 3-13: Assumptions and costs used in the cost analysis to substitute HFC-245fa/CO₂ (water) with Hydrocarbons

Variable	Value	Source
Capital Costs	\$10,000 ^a	Exxon, 2001
Fire Testing Costs	\$4,000 ^b /Contractor	Caleb, 2001
Incremental Increase in Fire Retardant Use	3%	Assumption
Cost of Fire Retardant	\$2.08/lb	Exxon, 2004
Price of Cyclopentane	\$0.80/lb ^c	Exxon, 2004
Price of Isopentane	\$0.25/lb ^c	Exxon, 2004
Blowing Agent Component of Foam	9%	Exxon, 2001
Increase in Foam Density	20% ^d	Assumption
Blowing Agent Substitution Ratio	90%	Exxon, 2001
Assumed Increase in Cost of Foam	\$0.10/lb	Assumption
Alternative Foam Cost	\$1.02/lb	Calculation
Employee Training Costs	\$6,450/yr ^e	SPF, 2001

^a Assumes that technical issues can be resolved.

^b Based on \$250,000 per systems house, 20 systems houses, and approximately 1,250 spray foam contractors (Caleb, 2001; Industry Communication).

^c HCs used as a BA in foams are approximately an 80/20 blend of cyclopentane and isopentane.

^d Assumes that foam density increases from 2.5 lb/ft³ to 3.0 lb/ft³.

^e Assumes a cost of approximately \$215/employee/day, 2 crews of 3 employees (total of 6 employees), and 5 days of training.

PU Appliance Foams

Two blowing agent replacement abatement options were considered for this end-use:

- Replacing HFC-134a with cyclopentane/isopentane; and
- Replacing HFC-245fa and HFC-365mfc/HCF-227ea and with cyclopentane/isopentane.

This scenario examines a hypothetical facility that manufactures approximately 536,000 refrigerators and consumes about 1.68 million pounds of blowing agent annually. The blowing agent was assumed to constitute approximately 12 percent of the foam. The costs of producing a refrigerator using each blowing agent (e.g., HFC-134a, HFC-245fa, and cyclopentane/isopentane) were provided by the refrigeration industry. Data have been aggregated to protect confidential business information. This scenario was developed for a facility manufacturing large appliances typically used in the United States. While other markets may use different-sized refrigerators and hence per-appliance factors may differ, this analysis assumes that the resulting cost per HFC emissions abated (\$/TCE) is approximately the same. Factors considered in these data include:

- capital costs to convert;
- blowing agent costs;
- foam costs (including density considerations);
- High-Impact Polystyrene (HIPS) and Acrylonitrile-Butadiene-Styrene (ABS) liner costs; and
- additional costs required to meet the U.S. 2001 National Appliance Energy Conservation Act (NAECA) energy efficiency standards.

HFC emission reductions over time were derived from the emissions profile used in the Vintaging Model (see Table 3-1), that account for gases released from the manufacturing process, annual release, and disposal. Because the cost data are based on the assumption that the refrigerators manufactured using various blowing agents meet the same energy efficiency standards, there are no incremental differences in indirect emissions and costs due to energy efficiency.

PU Appliance: Replacing HFC-134a with Hydrocarbons

This option is technically applicable to all HFC-134a emissions from the newly manufactured appliance foam. The technical applicability of this option from 2005 to 2020 is presented in Table 3-20 and Table 3-21. This analysis assumes that the incremental maximum market penetration in 2010 for this option in the newly-manufactured appliance market that uses HFC-134a would be 25 percent for the United States and 85 percent for the rest of Annex I, rising to 70 percent and 90 percent, respectively, by 2020 (see Table 3-22). Because the HFC is completely replaced, the reduction efficiency is 100 percent.

Cost and Emission Reduction Analysis

- **One-time Costs.** According to industry experts, the one-time costs for replacing HFC-134a with hydrocarbons are \$50,000,000, which includes the capital cost to convert.
- **Annual Costs.** This analysis assumes that cyclopentane variable costs will be comparable to HFC-134a variable costs; therefore no increased annual unit operating costs are assumed to be associated with this abatement option. Costs considered include HIPS liner, ABS liner, foam density, and energy costs.
- **Cost Savings.** Because cyclopentane is less expensive on a per-pound basis than HFC-134a, a \$1,506,160 annual cost savings is associated with this option. This result derives from incremental per-unit cost difference (\$2.81/unit) multiplied by the number of units a hypothetical factory manufactures (536,000 units).

- **Emission Reductions.** This analysis estimates that by replacing HFC-134a with hydrocarbons, 0.27 MMTCE of the high GWP gas that would have been emitted by this facility during the lifetime of the appliance foam produced in a given year are eliminated.

PU Appliance: Replacing HFC-245fa and HFC-365mfc/HFC-227ea with Hydrocarbons

Although this end-use uses HFC-245fa and HFC-365mfc/HFC-227ea, the analysis was performed based on the cost to replace HFC-245fa in appliance foams. This option is technically applicable to all emissions from the newly-produced appliance foams that use HFC-245fa. The technical applicability of this option from 2005 to 2020 is presented in Table 3-20 and Table 3-21. This analysis assumes that the incremental maximum market penetration of this option in 2010 into the newly-manufactured appliance market that uses HFC-245fa is 15 percent for the United States and 85 percent for the rest of Annex 1, rising to 50 percent and 90 percent, respectively, by 2020 (see Table 3-22). The increase of market penetration in China is 90 percent in 2020. Because the HFC is completely replaced, the reduction efficiency is 100 percent.

Cost and Emission Reduction Analysis

- **One-time Costs.** According to industry experts, the one-time costs for replacing HFC-245fa with hydrocarbons are \$50,000,000.
- **Annual Costs.** Due to costs associated with overcoming the energy gap between the foam blown with HFC and the foam blown with the alternative blowing agent, total annual costs for replacing HFC-245fa with hydrocarbons are estimated to be \$11,202,400. Costs considered include HIPS liner, ABS liner, foam density, and energy. Individual costs for each of these elements were provided from industry; however, because they are considered confidential, they are presented in aggregate.
- **Cost Savings.** No cost savings are associated with this abatement option.
- **Emission Reductions.** This analysis estimates that by replacing HFC-245fa with hydrocarbons, 0.20 MMTCE of the high GWP gas that would have been emitted by a representative facility during the lifetime of the appliance foam produced in a given year are eliminated.

PU Appliance: End-of-Life Options

In addition to the two blowing agent replacement options considered above, two end-of-life abatement options were considered for this end-use:

- Automated Process with Foam Grinding, HFC Adsorption, and Foam Landfilling in Appliance Foam; and
- Manual Process with Foam Incineration in Appliance Foam.

The baseline emissions assume that the remainder of the blowing agent contained in the appliance foam is released at the foam's end-of-life, as shown in Table 3-1. There are different technologies for abating those end-of-life emissions in PU Appliance Foams. These technologies include landfilling the foam after recovering the blowing agent (which could either be destroyed or reclaimed and sold back to the market) and incinerating the foam in a municipal solid waste incinerator (MSWI) or waste-to-energy plant. This analysis analyzes the landfilling after recovering HFC and the MSWI options. This analysis assumes that when the HFC is recovered, it will still have value and hence contribute revenue to the process. HFC-134a and HFC-245fa are used in appliance foam in some locations. This analysis assumes that half of the appliances processed use HFC-134a and the other half use HFC-245fa in order to account for the chemicals' different GWPs and costs. Further market research could refine this assumption.

The remainder of this section presents cost estimates for each step involved in the removal and/or destruction of HFC contained in the foam, either through MSWI or grinding/adsorption/landfilling. Costs are presented in terms of dollars per refrigerator destroyed and in dollars per pound of HFC destroyed. This analysis uses the best cost information available; however, the costs presented should be considered illustrative rather than definitive. The analysis is done using the U.S. market as an example, recognizing that the size of a U.S. refrigerator/freezer is typically larger than those used in other parts of the world. All assumptions were based on a side-by-side refrigerator type. The final results (i.e., cost per unit of emissions abated) are applied to other regions because it is felt that the relative costs and emissions abated should scale roughly linearly to smaller appliances used elsewhere.

Cost factors that are addressed include:

- collection and consolidation of appliances;
- transportation of appliances to disassembly location;
- disassembly and processing of appliances;
- transportation of foam to landfilling or incineration location; and
- landfilling or incineration of foam.

In general, two basic methods of handling appliances to abate blowing agent emissions exist:

- Automated Process with Foam Grinding, HFC Adsorption, and Foam Landfilling.** This method involves purchasing a sophisticated system where the appliance is brought into the system without much preparation work. The system shreds the appliance and uses various techniques such as magnets and eddy current to separate the metals, plastics and foams. The blowing agent (and the refrigerant) are collected by adsorption³⁷ onto a carbon substrate. Typically, the absorbed gases are then incinerated, or they can be reclaimed and sold back into the market. These systems are capital-intensive, costing roughly \$4 million (JACO, 2004); however, once established, the manual labor is reduced. This type of process is generally only cost-effective if a high flow of appliances (hundreds of thousands per year) is achieved.
- Manual Process with Foam Incineration.** This method uses mostly manual labor to evacuate and recycle the refrigerant, drain and recycle the compressor oil, and disassemble the appliances, recovering and recycling glass shelves, plastic interior parts, steel, aluminum and other valuable metals. The foam is removed in large pieces, which can be quickly sealed in plastic bags to prevent further off-gassing of the blowing agent, and sent for incineration.

Table 3-14 General Assumptions Applicable Both End-of-Life Options

Variable	Value	Source
Refrigerators per Truckload	77 refrigerators	JACO, 2004
Average quantity of foam per unit	22.87 lb	Whirlpool, 2004
Percent of BA remaining at disposal	92.25%	EPA estimates
Labor Rate	\$12.00/hour	Bureau of Labor Statistics, 2004
HFC-245fa content of PU Foam	13%	Whirlpool, 2004
HFC-134a content of PU Foam	7.5%	Whirlpool, 2004
Travel Distance to Disassembly Location	100 miles	Assumption
Truck Operating Rate	\$1.75/mile	JACO, 2004
Volume	6,082 cu ft	Systems Transportation Equipment, 2004
Density of Foam	2 lb/cu ft	ICF, 2004
Cost of steel	0.04/lb	JACO, 2004
Steel content of the unit	132.3 lb	Whirlpool, 2004

Table 3-15 Assumptions Applicable to the Manual Process with Foam Incineration

Variable	Value	Source
Loading Labor Hours	4 hours	JACO, 2004
Unload Labor Hours	2 hours	JACO, 2004
Cost of Disassembly	\$35/unit	JACO, 2004
Cost to Incinerate Foam	\$0.53/lb	JACO, 2004
% Foam Recovered	92.5%	JACO, 2004
% Blowing Agent Incinerated	98%	UNEP, 2002

Table 3-16 Assumptions Applicable to the Automated Process with Foam Landfilling

Variable	Value	Source
Refrigerators Disassembled per Hour	6.00	JACO, 2004
Grinding/Absorption Labor Hours	4 hours/truckload	Assumption
Grinding/Absorption Equipment Operating Hours	4 hours/truckload	Assumption

³⁷ Other methods of blowing agent recovery are possible. For instance, some plants use liquid nitrogen to mitigate explosion potential with hydrocarbon units. The nitrogen also serves to liquefy and collect the blowing agent.

Variable	Value	Source
Grinding/Absorption Equipment Cost	\$20/hour	Assumption
% Blowing Agent Recovered	90%	UNEP, 2002; JACO, 2004
Recovery value of HFC-134a	\$1.70/lb	Atofina, 2004
Recovery value of HFC-245fa	\$2.88/lb	ICF, 2004
Cost Per Container to Landfill	\$250/container	JACO, 2004
Container Volume	540 cu. ft.	JACO, 2004

General Cost Analysis Applicable to Both Processes

- **Collection and Consolidation.** This analysis assumes that appliances are collected and consolidated over a 4-hour period into full truckloads for shipment to a central disassembly location. The cost for collection and consolidation of appliances is \$0.62 per refrigerator (i.e., 4 hours × \$12/hour / 77 refrigerators). The collection and consolidation is roughly the same for both the automated and manual processes.
- **Transportation of Appliances to Disassembly Location.** Transportation costs to the disassembly location are \$2.58 per unit. The analysis assumes the appliances are shipped a distance of 100 miles from the collection and consolidation location to a central disassembly location. The operating cost of the truck is assumed to be \$1.75 per truckload mile. Truck unloading is conducted by two people over a 1 hour period, and 77 refrigerators per truckload is assumed. The labor rate is \$12.00/hour (ICF Estimate; JACO, 2004; Bureau of Labor Statistics, 2004). The calculation is as follows: $((\$1.75 \times 100) + (2 \times \$12.00)) / 77 = \$2.58/\text{refrigerator}$. Transportation of Appliances to Disassembly Location are generally the same for both the automated and manual processes.
 - **Disassembly of Appliances.** The appliances are then disassembled using the manual or automated process. See details below.
 - **Recovery of HFC.** In the Automated Process with Foam Landfilling, the foam is ground and the HFC is recovered. See details below.
 - **Recovery of Metals.** The steel content of the refrigerator is 132.3 lb and steel prices are around \$0.04/lb. Benefits from salvaged steel are therefore \$5.29/unit. The benefits of other recovered materials (other than the HFC) are not included in this analysis.
- **Transportation of Foam to Disposal Location.** The cost to transport and landfill the ground polyurethane foam (automated process) is assumed to be the same as the cost to transport and incinerate the unground polyurethane foam (manual process). This analysis assumes that truckloads of ground or unground polyurethane foam are shipped a distance of 100 miles from the disassembly/grinding location to an incineration/landfill location. The operating cost of the truck is assumed to be \$1.75 per truckload mile (ICF estimate). The total weight of foam in the truck is the volume of that truck (6,082 ft³) multiplied by the packing efficiency (70%) and the density of the foam (2 lb/ft), roughly 8,514.5 lb. The cost to transport the polyurethane foam to the disposal location is equal to \$0.47/refrigerator (i.e., 100 miles × \$1.75/mile / 8,514.5 lb foam × 22.87 lb foam/refrigerator).
- **Disposal of Foam.** In the Automated Process, the ground foam is landfilled. In the Manual Process, the foam pieces are incinerated. See details below.
- **Emission Reductions.** The HFC-134a blowing agent content at manufacture is 1.72 pounds, determined by multiplying 22.87 lb foam by 7.5% HFC-134a content. Likewise, 2.97 pounds of

HFC-245fa are contained in each refrigerator at manufacture. This value is determined by multiplying 22.87 lb foam by 13%. Because only 92.25 percent of the blowing agent remains at disposal, the maximum abatable emissions are 1.58 lb (HFC-134a) or 2.74 lb (HFC-245fa), which translates to 0.254 TCE and 0.322 TCE, respectively. This analysis assumes that half of the refrigerators that are processed will contain HFC-134a foam, and the remainder will contain HFC-245fa foam. Thus, the average emissions potentially reduced per refrigerator are 0.288 TCE.

Cost Analysis Applicable to the Automated Process with Foam Landfilling

- **Disassembly of Appliances.** For the automated process, this analysis assumes that 12.83 labor hours are required to disassemble a full truckload of 77 refrigerators. The refrigerators are assumed to be disassembled at a rate of 6 refrigerators per hour ($77/6 = 12.83$). Total disassembly costs are \$2.00/refrigerator (i.e., $(12.83 \text{ hours} \times \$12/\text{hour})/77 \text{ refrigerators} = \$2.00/\text{refrigerator}$).
- **Automated Grinding of Foam for Landfilling and Adsorption of HFC.** In the automated process, the polyurethane foam is ground, the HFC is adsorbed onto a carbon substrate, and the ground polyurethane waste is transported to the landfill. The non-labor operating cost of the grinding/adsorption equipment (e.g., electricity to operate the plant, periodic maintenance of the plant, etc.) is assumed to be \$20 per hour. By grinding the foam, only an estimated 90 percent of the HFC is recovered, while the remaining 10 percent is lost to the atmosphere (UNEP, 2002b). Therefore, a total of 150 lb of HFC is recovered per truckload (i.e., 166.5 lb of HFC prior to processing/truckload \times 90%). The amount of HFC per truckload prior to processing is calculated by multiplying the amount of HFC in refrigerator foam prior to disposal (assuming 50% of the units have HFC-245fa foam and 50% of the units have HFC-134a foam) by the total number of refrigerators per truckload. The calculation is as follows: $(0.5 \times 2.74 + 0.5 \times 1.58) \times 77 = 166.5$. The content-weighted recovery value of the HFC is \$2.29/lb (i.e., $50\% \times \$2.88 + 50\% \times \1.70). However, there is a cost to recovery the HFC. The cost of HFC recovery is calculated by dividing the grinding and adsorption costs by the total amount of HFC actually recovered ($\$128/\text{truckload} / 150 \text{ lb}/\text{truckload} = \$0.85/\text{lb}$). Grinding and adsorption costs are calculated by summing the grinding and adsorption labor cost (4 hours/truckload \times \$12/hour) and the cost of equipment used in grinding and adsorption ($\$20.00/\text{hour} \times 4 \text{ hours of equipment}/\text{truckload}$). The net recovery value of the HFC is therefore \$1.43/lb (i.e., $\$2.29 - \0.85), or \$215/truckload (i.e., $\$1.43 \times 150$), or \$2.79/unit (i.e., $\$215/77$). Thus, grand total savings that include disassembly, processing, and recovery of the HFC are equal to \$0.79/unit (i.e., costs are $\$2.00 - \2.79).
- **Landfilling of Foam.** This analysis assumes that landfilling of the polyurethane foam occurs in a municipal solid waste landfill at a cost of \$250.00 per pull of foam for a 20 cubic yard cylinder. Since the container volume is 540 ft³ (20 yd³), the packing efficiency is 70 percent, and the density of foam is 2 lb/ft³, the weight of foam loaded is 756 lb/container. Thus, landfilling foam will cost \$0.33/lb. The total cost of landfilling per unit is calculated by multiplying the cost of landfilling per pound of foam with the foam content of the refrigerator (22.87 lb of foam per unit), the cost of landfilling is estimated to be \$7.56 per refrigerator.

Cost Analysis Applicable to the Manual Process with Foam Incineration

- **Manual Dismantling of Foam for Incineration.** For the manual process, this analysis assumes that 90-95 percent of the foam is recovered (for calculation purposes, 92.5% is used). In the manual process, the large foam pieces are separated and sent for incineration. The costs of disassembly are assumed to be \$35.00/refrigerator (JACO, 2004).

- **Incineration of Foam.** The cost of incineration of polyurethane foam is estimated to be \$11.11 per refrigerator. This cost is derived by multiplying the foam content of the refrigerator (22.87 lb) prior to processing by the percent of foam recovered (92.5%) and by the cost of incineration per pound (\$0.53/lb).

PU Appliance: Automated Process with Foam Grinding, HFC Adsorption, and Foam Landfilling

The technical applicability of this option from year 2005 through 2020 is presented in Table 3-20 and Table 3-21. This analysis assumes that the incremental maximum market penetration of this option in 2020 in the newly-manufactured appliance foam market would be 10 percent in the United States, 95 percent in the rest of the developed world (see Table 3-22).

Cost and Emission Reduction Analysis

- **One-time Costs.** This analysis assumes a one-time capital cost of \$4 million for an Adelman or MeWa plant (JACO, 2004).
- **Annual Costs.** The capacity of the facility is 250,000 refrigerators per year (JACO, 2004), therefore, the annual costs for this technology are \$1,290,000, calculated by multiplying the capacity of the facility with the net costs of this technology per unit (see Table 3-17).
- **Cost Savings.** The savings from salvaging the steel (\$5.29/unit) and HFC blowing agent (\$2.79/unit) are accounted for in the Annual Costs, above.
- **Emission Reductions.** This analysis estimates that by treating the appliance foam at the end of life with foam grinding, HFC adsorption, and landfilling, 0.072 MMTCE (i.e., 0.288 TCE/unit × 250,000 units) of the high GWP gas can potentially be eliminated annually. Accounting for the reduction efficiency of 90 percent (UNEP, 2002b), the actual annual emissions abated are 0.065 MMTCE.

Table 3-17: Automated Process with Foam Landfilling

Method	Cost per Unit (\$)
Collection/Consolidation	\$0.62
Transportation to Disassembly Location	\$2.58
Disassembly & Processing of Refrigerators	-\$0.79
Transportation to Disposal Location	\$0.47
Landfilling	\$7.56
Total Costs	\$10.45
Savings (salvaged steel)	\$5.29
Net Costs	\$5.16

PU Appliance: Manual Process with Foam Incineration

The technical applicability of this option from year 2005 through 2020 is presented in Table 3-20 and Table 3-21. This analysis assumes that the incremental maximum market penetration of this option in 2020 in the newly-manufactured appliance foam market would be 30 percent in the United States, and 20 percent in China (see Table 3-22).

Cost and Emission Reduction Analysis

- **One-time Costs.** This analysis assumes a one-time capital cost of \$200,000 (JACO, 2004) for establishing offices, renting some equipment, leasing land for collection, etc.

- **Annual Costs.** The capacity of the facility is 10,000 refrigerators per year (JACO, 2004); therefore, the annual costs for this technology are \$388,292, calculated by multiplying the capacity of the facility with the net costs of this technology per unit. Table 3-18 summarizes costs associated with this specific technique.
- **Cost Savings.** The savings from salvaged steel (\$5.29/unit) are accounted for in the Annual Costs, above.
- **Emission Reductions.** This analysis estimates that by treating the appliance foam at the end of life with incineration, 0.0029 MMTCE (i.e., 0.288 TCE/unit × 10,000 units) of the high GWP gas can potentially be eliminated annually. Accounting for the assumption that 92.5 percent of the foam can be recovered from the appliance, and that incineration destroys 98 percent of the HFC in that foam, the actual annual emissions abated are 0.0026 MMTCE (UNEP, 2000b).

Table 3-18: Manual Process with Foam Incineration

Method	Cost per Unit (\$)
Collection/Consolidation	\$0.62
Transportation to Disassembly Location	\$2.58
Disassembly & Processing of Refrigerators	\$35.00
Transportation to Disposal Location	\$0.47
Incineration	\$11.11
Total Costs	\$49.78
Savings (salvaged steel)	\$5.29
Net Costs	\$44.49

3.3.3 Summary of Technical Applicability and Market Penetration of Abatement Options

Table 3-19 presents a summary of the assumed reduction efficiency, while tables Table 3-20 and Table 3-21 show the technical applicability of the abatement options. Technical applicability values are based on the percent of total foam emissions from each end-use, and are derived from the baseline emissions methodology described in Section 3.2.1. The commercial technology options explored in this chapter are assumed to penetrate only new (not existing) equipment, where “new” equipment is defined as equipment manufactured in 2005 or later.

Table 3-19: Reduction Efficiency of Foam Options (Percent)

Option	Reduction Efficiency
Appliance: HFC-134a to HC	100
Appliance: HFC-245fa and HFC 365mfc/HCF-227ea to HC	100
Appliance: Automated Process with Foam Grinding, Landfilling	90
Appliance: Manual Process with Incineration	91
Spray: HFC-245fa/CO ₂ (water) and HFC-365mfc/HFC-227ea to HC	100
Spray: HFC-245fa/CO ₂ (water) and HFC-365mfc/HFC-227ea to CO ₂ (water)	100
XPS: HFC-134a/CO ₂ to CO ₂	100
XPS: HFC-134a/CO ₂ to CO ₂ / Alcohol	100
PU One Component: HFC-134a to HC	100
PU One Component: HFC-152a to HC	100
PU Panels: HFC to HC	100

Table 3-20: Technical Applicability of Foam Options for the US, Europe, and Japan (Percent)

Reduction Option	2005			2010			2015			2020		
	US	Europe	Japan	US	Europe	Japan	US	Europe	Japan	US	Europe	Japan
Appliance: HFC-134a to HC	3	0	0	2	0	0	6	0	0	4	0	0
Appliance: HFC-245fa and HFC-365mfc/HCF-227ea to HC	26	4	2	10	4	3	8	4	3	40	18	11
Appliance: Automated Process with Foam Grinding, Landfilling	29	4	2	12	4	3	14	4	3	44	18	11
Appliance: Manual Process with Incineration	29	4	2	12	4	3	14	4	3	44	18	11
Spray: HFC-245fa/CO ₂ (water) and HFC-365mfc/HFC-227ea to HC	51	4	13	26	6	16	25	6	17	16	4	17
Spray: HFC-245fa/CO ₂ (water) and HFC-365mfc/HFC-227ea to CO ₂ (water)	51	4	13	26	6	16	25	6	17	16	4	17
XPS: HFC-134a/CO ₂ to CO ₂	0	36	45	53	36	47	54	35	49	34	21	46
XPS: HFC-134a/CO ₂ to CO ₂ / Alcohol	0	36	45	53	36	47	54	35	49	34	21	46
PU One Component: HFC-134a to HC	0	9	1	1	3	1	0	2	1	0	1	1
PU One Component: HFC-152a to HC	0	0	0	0	0	0	0	0	0	0	0	0
PU Panels: HFC to HC	0	0	0	0	0	0	0	0	0	0	0	0

*Assumed technical applicability of options is presented as a percentage of total foam sector baseline emissions.

Table 3-21: Technical Applicability of Foam Options for the CEITs, China, and the Rest of the Developed World (Percent)

Reduction Option	2005			2010			2015			2020		
	CEITs	China	RODW	CEITs	China	RODW	CEITs	China	RODW	CEITs	China	RODW
Appliance: HFC-134a to HC	0	0	0	0	0	0	0	0	0	0	0	0
Appliance: HFC-245fa and HFC 365mfc/HCF-227ea to HC	0	0	7	0	0	9	0	0	9	0	0	18
Appliance: Automated Process with Foam Grinding, Landfilling	0	0	7	0	0	9	0	0	9	0	0	18
Appliance: Manual Process with Incineration	0	0	7	0	0	9	0	0	9	0	0	18
Spray: HFC-245fa/CO ₂ (water) and HFC-365mfc/HFC-227ea to HC	0	0	6	0	0	9	0	0	10	0	0	7
Spray: HFC-245fa/CO ₂ (water) and HFC-365mfc/HFC-227ea to CO ₂ (water)	0	0	6	0	0	9	0	0	10	0	0	7
XPS: HFC-134a/CO ₂ to CO ₂	0	0	0	6	0	0	15	0	0	17	0	0
XPS: HFC-134a/CO ₂ to CO ₂ / Alcohol	0	0	0	6	0	0	15	0	0	17	0	0
PU One Component: HFC-134a to HC	100	100	0	94	100	0	85	100	0	83	100	0
PU One Component: HFC-152a to HC	0	0	0	0	0	0	0	0	0	0	0	0
PU Panels: HFC to HC	0	0	0	0	0	0	0	0	0	0	0	0

A summary of the incremental maximum market penetrations assumed for the abatement options considered are presented Table 3-22 and Table 3-23.

Table 3-22: Incremental Maximum Market Penetration Expressed as Percent of New Emissions for which the Options are Technically Applicable

Reduction Option	2005		2010		2015			2020			
	US	Europe and RODW	US	Europe and Rest of Annex I	US	Europe and Rest of Annex I	China	US	Europe and Rest of Annex I	Japan	China
Appliance: HFC-134a to HC	0	65	25	85	50	90	90	70	90	90	90
Appliance: HFC-245fa and HFC-365mfc/HCF-227ea to HC	0	65	15	85	30	90	90	50	90	90	90
Appliance: Automated Process with Foam Grinding, Landfilling	0	0	0	0	5	90	0	10	95	95	0
Appliance: Manual Process with Incineration	0	0	0	0	20	0	10	30	0	0	20
Spray: HFC-245fa/CO ₂ (water) and HFC-365mfc/HFC-227ea to HC	5	0	10	5	20	10	10	30	15	15	15
Spray: HFC-245fa/CO ₂ (water) and HFC-365mfc/HFC-227ea to CO ₂ (water)	0	5	5	8	10	15	15	20	20	20	20
XPS: HFC-134a/CO ₂ to CO ₂	0	25	0	35	0	35	35	0	45	45	45
XPS: HFC-134a/CO ₂ to CO ₂ / Alcohol	0	0	0	0	0	0	35	0	0	0	45
PU One Component: HFC-134a to HC	50	60	70	90	90	95	95	100	100	100	100
PU One Component: HFC-152a to HC	50	60	70	90	90	95	95	100	100	100	100
PU Panels: HFC to HC	50	60	70	90	90	95	95	100	100	100	100

RODW: Rest of Developed World

Table 3-23: Incremental Maximum Market Penetration Expressed as Percent of All Emissions for which the Options are Technically Applicable

Reduction Option	2005				2010				2015				2020			
	US	Europe and Rest of Annex I	Japan		US	Europe	Japan	Rest of Annex I	US	Europe	Japan	Rest of Annex I	US	Europe	Japan	China
Appliance: HFC-134a to HC	0	47	47		23	64	64	64	12	16	16	16	12	11	11	11
Appliance: HFC-245fa and HFC 365mfc/HCF-227ea to HC	0	54	54		13	65	59	58	24	68	57	53	4	8	6	5
Appliance: Automated Process with Foam Grinding, Landfilling	0	0	0		0	0	0	0	2	28	28	18	9	84	84	0
Appliance: Manual Process with Incineration	0	0	0		0	0	0	0	6	0	0	2	27	0	0	18
Spray: HFC-245fa/CO ₂ (water) and HFC-365mfc/HFC-227ea to HC	4	0	0		9	4	4	3	18	8	8	5	31	15	13	7
Spray: HFC-245fa/CO ₂ (water) and HFC-365mfc/HFC-227ea to CO ₂ (water)	0	4	4		4	7	6	5	9	13	12	8	19	21	18	10
XPS: HFC-134a/CO ₂ to CO ₂	0	0	0		0	52	51	30	0	57	58	22	0	73	76	23
XPS: HFC-134a/CO ₂ to CO ₂ / Alcohol	0	0	0		0	0	0	0	0	0	0	0	0	0	0	23
PU One Component: HFC-134a to HC	0	0	0		70	90	90	90	90	95	95	95	100	100	100	100
PU One Component: HFC-152a to HC	0	0	0		70	90	90	90	90	95	95	95	100	100	100	100
PU Panels: HFC to HC	40	48	48		46	66	59	59	51	67	53	53	51	74	50	50

To calculate the percent of emission reductions off the total foams baseline for each abatement option, the percent of baseline emissions from Table 3-20 and Table 3-21 is multiplied by the market penetration values from table Table 3-23 and reduction efficiencies from Table 3-19. For example, to determine the percent reduction off the 2020 baseline for end-of life option in appliance: manual process with incineration in the United States, the following calculation is used:

$$\text{Technical Applicability} \times \text{Incremental Maximum Market Penetration} \times \text{Reduction Efficiency} =$$

$$44\% \times 27\% \times 91\% \approx 11\%$$

Thus, using the assumptions in this analysis, applying this end-of-life option could reduce U.S. baseline emissions by approximately 11 percent in 2020. This figure, along with the other emission reduction potentials, is shown in Table 3-24.

Table 3-24: Emission Reductions off Total Foams Baseline for the US, Europe, and Japan (Percent)

Reduction Option	2005			2010			2015			2020		
	US	Europe	Japan	US	Europe	Japan	US	Europe	Japan	US	Europe	Japan
Appliance: HFC-134a to HC	0	0	0	0	0	0	1	0	0	1	0	0
Appliance: HFC-245fa and HFC 365mfc/HCF-227ea to HC	0	2	1	1	2	2	2	2	1	2	1	1
Appliance: Automated Process with Foam Grinding, Landfilling	0	0	0	0	0	0	0	1	1	4	13	9
Appliance: Manual Process with Incineration	0	0	0	0	0	0	1	0	0	11	0	0
Spray: HFC-245fa/CO ₂ (water) and HFC-365mfc/HFC-227ea to HC	2	0	0	2	0	1	4	1	1	5	1	2
Spray: HFC-245fa/CO ₂ (water) and HFC-365mfc/HFC-227ea to CO ₂ (water)	0	0	1	1	0	1	2	1	2	3	1	3
XPS: HFC-134a/CO ₂ to CO ₂	0	0	0	0	19	24	0	20	29	0	15	35
XPS: HFC-134a/CO ₂ to CO ₂ / Alcohol	0	0	0	0	0	0	0	0	0	0	0	0
PU One Component: HFC-134a to HC	0	0	0	0	2	1	0	2	1	0	1	1
PU One Component: HFC-152a to HC	0	0	0	0	0	0	0	0	0	0	0	0
PU Panels: HFC to HC	0	0	0	0	0	0	0	0	0	0	0	0
Total	2	2	1	6	24	28	11	27	35	25	32	50

Table 3-25: Emission Reductions off Total Foams Baseline for the CEITs, China, and the Rest of the Developed World (Percent)

Reduction Option	2005			2010			2015			2020		
	CEITs	China	Rest of Annex I	CEITs	China	Rest of Annex I	CEITs	China	Rest of Annex I	CEITs	China	Rest of Annex I
Appliance: HFC-134a to HC	0	0	0	0	0	0	0	0	0	0	0	0
Appliance: HFC-245fa and HFC 365mfc/HCF-227ea to HC	0	0	4	0	0	5	0	0	5	0	0	1
Appliance: Automated Process with Foam Grinding, Landfilling	0	0	0	0	0	0	0	0	1	0	0	10
Appliance: Manual Process with Incineration	0	0	0	0	0	0	0	0	0	0	0	1
Spray: HFC-245fa/CO ₂ (water) and HFC-365mfc/HFC-227ea to HC	0	0	0	0	0	0	0	0	1	0	0	0
Spray: HFC-245fa/CO ₂ (water) and HFC-365mfc/HFC-227ea to CO ₂ (water)	0	0	0	0	0	0	0	0	1	0	0	1
XPS: HFC-134a/CO ₂ to CO ₂	0	0	0	2	0	0	3	0	0	4	0	0
XPS: HFC-134a/CO ₂ to CO ₂ / Alcohol	0	0	0	0	0	0	0	0	0	0	0	0
PU One Component: HFC-134a to HC	0	0	0	85	90	0	81	95	0	83	100	0
PU One Component: HFC-152a to HC	0	0	0	0	0	0	0	0	0	0	0	0
PU Panels: HFC to HC	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	4	87	90	6	84	95	8	87	100	14

3.4 Results

Table 3-26 through Table 3-28 provide a summary of the potential emission reduction opportunities and associated costs for United States, Non-U.S. Annex I and Non-Annex I countries in 2020. The costs to reduce one ton of carbon equivalent (TCE) data are presented for two different discount rate scenarios: 4

percent and 20 percent. The tax rate associated with each cost scenario is 0 percent and 40 percent, respectively.

Table 3-26: Emission Reductions in 2020 and Costs of Abatement for Foams in the US

Reduction Option	Break-Even Price (2000\$/TCE)		Emission Reduction of Option (MMTCE)	Reduction off Baseline (Percent)	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
	Discount /Tax Rate					
	4% /0%	20% /40%				
Spray HFC-245fa/CO2 and HFC-365mfc/HFC-227ea to HC	\$(17.97)	\$(13.98)	0.37	5.1%	0.37	5.1%
PU One Component HFC-152a to HC	\$(9.40)	\$2.77	0.0	0.0%	0.37	5.1%
XPS: HFC-134a/CO2 to CO2/Alcohol	\$(8.50)	\$12.82	0.0	0.0%	0.37	5.1%
PU One Component HFC-134a to HC	\$(0.07)	\$14.08	0.02	0.2%	0.39	5.3%
XPS: HFC-134a/CO2 to CO2	\$11.48	\$122.09	0.0	0.0%	0.39	5.3%
Appliance HFC-134a to HC	\$17.35	\$404.45	0.04	0.5%	0.43	5.8%
Appliance: Automated Process with Foam Grinding, HFC Adsorption, and Foam Landfilling	\$23.82	\$37.16	0.26	3.5%	0.69	9.4%
PU Continuous and Discontinuous HFC to HC	\$43.83	\$56.26	0.0	0.0%	0.69	9.4%
Spray HFC-245fa/CO2 and HFC-365mfc/HFC-227ea to CO2	\$96.45	\$122.55	0.22	3.0%	0.91	12.4%
Appliance: Manual Process with Foam Incineration	\$175.09	\$191.65	0.78	10.7%	1.69	23.0%
Appliance HFC-245fa and HFC 365mfc/HCF-227ea to HC	\$201.80	\$1,115.58	0.12	1.6%	1.81	24.6%

Table 3-27: Emission Reductions in 2020 and Costs of Abatement for Foams in the non-US Annex I Countries

Reduction Option	Break-Even Price (2000\$/TCE)		Break-Even Price (2000\$/TCE)		Emission Reduction of Option (MMTCE)	Reduction off Baseline (Percent)	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
	Discount Rate/Tax Rate		Discount Rate/Tax Rate					
	4% /0%		20% /40%					
	Low	High	Low	High				
Spray HFC-245fa/CO2 and HFC-365mfc/HFC-227ea to HC	\$(17.97)	\$(15.13)	\$(13.98)	\$1.53	0.09	0.9%	0.09	0.9%
PU One Component HFC-152a to HC	\$(9.40)	\$(9.40)	\$2.77	\$2.77	0.0	0.0%	0.09	0.9%
XPS: HFC-134a/CO2 to CO2/Alcohol	\$(8.50)	\$(8.50)	\$12.82	\$12.82	0.0	0.0%	0.09	0.9%
PU One Component HFC-134a to HC	\$(0.07)	\$(0.07)	\$14.08	\$14.08	0.11	1.2%	0.19	2.1%
XPS: HFC-134a/CO2 to CO2	\$11.48	\$11.48	\$122.09	\$122.09	1.70	18.9%	1.89	21.0%
Appliance HFC-134a to HC	\$17.35	\$17.35	\$404.45	\$404.45	0.0	0.0%	1.89	21.0%
Appliance: Automated Process with Foam Grinding, HFC Adsorption, and Foam Landfilling	\$23.82	\$23.82	\$37.16	\$37.16	1.08	11.9%	2.97	32.9%
PU Continuous and Discontinuous HFC to HC	\$43.83	\$43.83	\$56.26	\$56.26	0.0	0.0%	2.97	32.9%
Spray HFC-245fa/CO2 and HFC-365mfc/HFC-227ea to CO2	\$96.45	\$96.45	\$122.55	\$122.55	0.12	1.4%	3.09	34.3%
Appliance: Manual Process with Foam Incineration	\$175.09	\$175.09	\$191.65	\$191.65	0.01	0.1%	3.10	34.4%

Reduction Option	Break-Even Price (2000\$/TCE)		Break-Even Price (2000\$/TCE)		Emission Reduction of Option (MMTCE)	Reduction off Baseline (Percent)	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
	Discount Rate/Tax Rate		Discount Rate/Tax Rate					
	4% /0%	High	20% /40%	High				
Appliance HFC-245fa and HFC-365mfc/HCF-227ea to HC	\$201.80	\$201.80	\$1,115.58	\$1,115.58	0.11	1.2%	3.20	35.6%

^a Costs vary by country/region based on one-time or annual adjustment factors; therefore, the lowest and highest costs for the region are shown.

Table 3-28: Emission Reductions in 2020 and Costs of Abatement for Foams in non-Annex I Countries

Reduction Option	Break-Even Price (2000\$/TCE)		Emission Reduction of Option (MMTCE)	Reduction off Baseline (Percent)	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
	Discount /Tax Rate					
	4% /0%	20% /40%				
Spray HFC-245fa/CO2 and HFC-365mfc/HFC-227ea to HC	\$(17.97)	\$(13.98)	0.0	0.0%	0.0	0.0%
PU One Component HFC to HC	\$(9.40)	\$2.77	0.0	0.0%	0.0	0.0%
XPS: HFC-134a/CO2 to CO2/Alcohol	\$(8.50)	\$12.82	0.0	0.0%	0.0	0.0%
PU One Component HFC-134a to HC	\$(0.07)	\$14.08	0.01	100.0%	0.01	100.0%
XPS: HFC-134a/CO2 to CO2	\$11.48	\$122.09	0.0	0.0%	0.01	100.0%
Appliance HFC-134a to HC	\$17.35	\$404.45	0.0	0.0%	0.01	100.0%
Appliance: Automated Process with Foam Grinding, HFC Adsorption, and Foam Landfilling	\$23.82	\$37.16	0.0	0.0%	0.01	100.0%
PU Continuous and Discontinuous HFC-134a to HC	\$43.83	\$56.26	0.0	0.0%	0.01	100.0%
Spray HFC-245fa/CO2 and HFC-365mfc/HFC-227ea to CO2	\$96.45	\$122.55	0.0	0.0%	0.01	100.0%
Appliance: Manual Process with Foam Incineration	\$175.09	\$191.65	0.0	0.0%	0.01	100.0%
Appliance HFC-245fa and HFC-365mfc/HCF-227ea to HC	\$201.80	\$1,115.58	0.0	0.0%	0.01	100.0%

* Break-even costs do not vary by country within the Non Annex I region.

3.5 Summary

Baseline emissions of HFCs from foams are estimated to grow from 2.94 to 16.38 MMTCE between 2005 and 2020. In 2020, Non-U.S. Annex I countries are assumed to account for about 55 percent of the emissions, while U.S. emissions are assumed to account for 45 percent of this total. Non-Annex I countries contribute less than one percent to 2020 foam emissions. Similar emissions growth is expected in the United States (from 0.53 MMTCE in 2005 to 7.35 MMTCE in 2020) and Non-U.S. Annex I countries (from 2.40 MMTCE in 2005 to 9.01 MMTCE in 2020).

This analysis considers nine replacement emissions mitigation options for spray, appliance, XPS, continuous panel, discontinuous panel and one-component foams, and two end-of-life options for appliance foams:

- Replacing HFC-134a, HFC-245fa, and HFC-365mfc/HFC-227ea with Hydrocarbons in continuous and discontinuous panel foam;

- Replacing HFC-134a with Hydrocarbons in one component foam;
- Replacing HFC-152a with Hydrocarbons in one component foam;
- Replacing HFC-134a/CO₂ (LCD) with CO₂ (LCD) in XPS foam;
- Replacing HFC-134a/CO₂ (LCD) with CO₂ (LCD)/Alcohol in XPS foam;
- Replacing HFC-245fa/CO₂ (water) and HFC-365mfc/HFC-227ea with CO₂ (water) in spray foam;
- Replacing HFC-245fa/CO₂ (water) and HFC-365mfc/HFC-227ea with Hydrocarbons in spray foam;
- Replacing HFC-134a with Hydrocarbons in appliance foam;
- Replacing HFC-245fa and HFC 365mfc/HCF-227ea with Hydrocarbons in appliance foam;
- End of Life Appliance Foam Practice: Automated Process with Foam Grinding, HFC Adsorption, and Foam Landfilling in appliance foam; and
- End of Life Appliance Foam Practice: Manual Process with Foam Incineration in appliance foam.

The emission reduction benefits of each option were compared in each region. For spray end-uses, the costs associated with converting to alternative blowing agent differ between the United States, Europe, and Japan. The costs per TCE of all other abatement options for these three regions are equivalent because available data on costs for abatement technologies were not scaled to reflect potential differences in the costs internationally. Additional research may be required to determine actual variability in costs across regions. This analysis shows that there are variety of options available at or below 25 \$/TCE at 4 percent discount rate and 0 percent tax rate that may be used to eliminate the use of HFCs and reduce HFC associated emissions from foams.

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4 Analysis of Costs to Abate International HFC and PFC Emissions from Fire Extinguishing

4.1 Introduction

The principal greenhouse gases used in and potentially emitted from the fire extinguishing sector are hydrofluorocarbons (HFC-227ea, HFC-236fa, HFC-23), and blends containing perfluoromethane (CF₄). These gases have 100-year global warming potentials (GWPs) that range from 2,900 to 11,700 (IPCC, 1996).

These high GWP gases are substitutes for halons, ozone depleting substances (ODSs) that have been, and in many countries are still, widely used in fire-extinguishing applications. Although halons were produced in much lower volumes than other ODSs, they have extremely high ozone depletion potentials (ODPs) due to the presence of bromine, which reacts more strongly with ozone than chlorine. Halons have been historically used in fire suppression and explosion protection applications because they are electrically non-conductive, dissipate rapidly without residue, are safe for limited human exposure, and are extremely efficient in extinguishing most types of fires (U.S. EPA, 1994).

Halon applications can be divided into two categories: (1) portable fire extinguishers (e.g., streaming applications) that originally used halon 1211, and (2) total flooding applications that originally used halon 1301 or halon 2402 (U.S. EPA, 2004; March Consulting Group, 1998 and 1999). Historically, SF₆, another high-GWP gas, was used in select fire extinguishing systems uses, such as for system discharge testing purposes by the U.S. Navy. For the most part, however, SF₆ is no longer used in any capacity in the fire protection sector.

Portable fire extinguishers are most frequently used in offices, manufacturing and retail facilities, aerospace/marine applications, and homes. Market penetration of HFCs in this sector has been limited, and is unlikely to grow or even keep pace with the growth in portable extinguishers (Wickham, 2003a). PFCs have had a very small penetration in the portable fire extinguisher market. By 2020, only one HFC, HFC-236fa, is expected to be used to a limited extent as a halon replacement in small segments of the portable extinguishing sector. Overall, portable applications represent a much smaller share of total fire extinguishing emissions than do total flooding applications, and the U.S. EPA projects that their relative share of emissions will decrease over time, based on cost reasons outlined in Wickham (2002).

The majority of HFC emissions associated with fire extinguishing come from its use as a replacement for some halon 1301 applications in the total flooding market. Total flooding systems are usually used to protect a variety of spaces, including:

- Electronic and telecommunications equipment, such as tape storage areas, computer facilities, telecommunications gear, medical facilities, control rooms in nuclear power plants, and air traffic control towers;
- Military applications, including aviation engine nacelles³⁸ and dry bays, naval engine compartments, and engine compartments and occupied crew spaces of ground combat vehicles;

³⁸ Nacelles are enclosed engine housings.

- Oil production facilities;
- Flammable liquid storage areas;
- Engine nacelles and cargo bays of commercial aircraft;
- Cultural institutions and museums;
- Records storage areas;
- Bank vaults;
- Warehouses; and
- Special facilities, such as research laboratories and military facilities.

Other than in Russia, which used halon 2402, halon 1301 was widely used in total flooding applications because of its unique features (Wickham, 2002). Halon 1301 is a clean agent, meaning that it does not leave residue on equipment or in the protection enclosure after discharge. In addition, halon 1301 is safe for limited, acute human exposure at the concentration used for fire extinguishing. It is also very effective at extinguishing fires and works well over a broad temperature range. Because halon 1301 was economical and its design and installation was relatively simple compared to other fire extinguishing systems, these systems reached almost all segments of the total flooding fire extinguishing market.

The alternatives to halon 1301 in total flooding applications can be categorized as in-kind, gaseous agent alternatives (i.e., halocarbons, CO₂, inert gases, fluorinated ketones) and not-in-kind alternatives (i.e., dispersed and condensed aerosol extinguishing systems, water sprinklers, water mist, foam,³⁹ inert gas generators). In most Annex I countries, halocarbon HFC-227ea has emerged as the primary replacement for halon 1301 in total flooding applications. Other HFCs, such as HFC-23, HFC-236fa, and HFC-125, as well as PFCs, such as C₃F₈ and C₄F₁₀, have been evaluated and determined to be safe for limited, acute human exposure, but are used in smaller amounts as a result of environmental,⁴⁰ technical, and economic concerns. Based on confidential information collected for this report from members of UNEP's Halon Technical Options Committee (HTOC), this analysis projects that the market share of HFC-23 will increase in Russia as a total flooding agent over the next 20 years, although other information (e.g., Wickham, 2003b) might point to a different conclusion. Use of HFC-125, which has been limited to normally unoccupied specialty applications (e.g., aviation engine nacelles), is also expected to increase in Russia over time. A small number of telecommunications facilities use PFCs, with some of the highest use of these chemicals being in Eastern Europe. In the United States, PFC use in fire suppression will tail off, as the U.S. manufacturer of PFCs for fire suppression withdrew these agents from the market a number of years ago because of concern about their high global warming potential. In addition, hydrochlorofluorocarbons (HCFCs) have historically also been used as halon 1301 replacements, particularly in Eastern and Southern Europe. Over time, the use of HCFCs and PFCs in total flooding applications is expected to be phased out, and replaced primarily with HFCs, in addition to other alternatives.

In particular, other available in-kind, non-halocarbon alternatives in total flooding applications include carbon dioxide systems, used primarily in marine and industrial applications, fluorinated ketones, and inert gas systems, which contain nitrogen or argon or blends of these gases, sometimes incorporating carbon dioxide as a third component. Inert gas systems have become the dominant halon 1301 replacement in many parts of Europe, most notably in northern European countries.

³⁹ Foams can be protein-based or synthetic-based. It should be noted that some synthetic-based foams contain fluorocarbons.

⁴⁰ These gases have high GWPs, ranging from 2,800 to 11,700.

Not-in-kind (NIK) alternatives and technologies available include powdered aerosols, water sprinklers, water mist systems, foams, and combinations of these systems, such as aerosols with a halocarbon agent, or water mist with a gaseous agent or with foam.

4.2 Baseline Emission Estimates

4.2.1 Emission Estimating Methodology

Description of Methodology

A full description of the emission model used to calculate ODS substitute emissions from all sectors is provided in Appendix A. Specific information on how the model calculates fire protection emissions is described below.

U.S. EPA uses a detailed Vintaging Model of ODS-containing equipment and products to estimate the use and emissions of various ODS substitutes in the United States, including HFCs and PFCs. Emission estimates for non-U.S. countries are derived using country-specific ODS consumption estimates as reported under the Montreal Protocol in conjunction with Vintaging Model output for the fire extinguishing sector.

This analysis first incorporates estimates of the consumption of ODSs by country, as provided by the United Nations Environment Programme (UNEP, 1999). Estimates for the European Union (EU) were provided in aggregate and GDP was used as a proxy to distribute consumption among the individual member nations.

Emission Equations

This analysis assumes that total emissions from leakage, accidental discharges, and fire extinguishing, in aggregate, equals a percentage of the total quantity of chemical in operation at a given time. For modeling purposes, fire extinguishing agent is assumed to be released at a constant rate for an average equipment lifetime. This percentage varies for streaming and flooding equipment.

$$E_j = r \times \sum_{i=1}^k Q_{c_{j-i+1}} \quad \text{for } i=1 \rightarrow k$$

Where:

- E = *Emissions*. Total emissions of a specific chemical in year j for fire extinguishing equipment, by weight.
- r = *Percent Released*. The percentage of the total chemical in operation that is emitted to the atmosphere.
- Q_c = *Quantity of Chemical*. Total amount of a specific chemical used in new fire extinguishing equipment in a given year, j-i+1, by weight.
- i = *Counter*. From 1 to lifetime (k).
- j = *Year of emissions*.
- k = *Lifetime*. The average lifetime of the equipment.

Estimates used for the percent released and lifetime of equipment can have a significant effect on resulting emission estimates. For this analysis, the U.S. Vintaging Model assumes emission factors (i.e.,

variable r in the equation above) of 1.5 percent in the total flooding sector (which lies between the range cited in Verdonik and Robin (2004)), and 2 percent in the streaming sector. These estimates are chosen to account, on average, for all emissions from servicing, leaks, accidental/false discharges, system decommissioning, or intentional discharges to extinguish fires. The U.S. Vintaging Model also assumes equipment lifetime for streaming and flooding applications to be 10 and 20 years, respectively.

Regional Variations/Adjustments

To estimate baseline emissions, information collected on current and projected market characterizations of international total flooding sectors was used to create country-specific versions of the Vintaging Model (i.e., country-specific ODS substitution patterns). Information for Australia, Brazil, China, India, Japan, Russia, and the United Kingdom was obtained from HTOC members from those countries.⁴¹ General information was also collected on Northern, Southern, and Eastern Europe. Baseline emission information from some of these countries was used to adjust the substitution patterns for all other non-U.S. countries, as described below:

- Eastern Europe: used as a proxy for the countries in the Former Soviet Union and CEITs.
- Australia: used as proxy for New Zealand.
- Brazil: used as a proxy for countries in Latin America and the Caribbean.
- India: used as a proxy for all other developing countries.

For all other non-U.S. Annex I countries, the U.S. ODS substitution pattern (presented in Appendix A) was used as a proxy.⁴² In addition, an adjustment factor was applied to EU countries to account for European Regulation 2037/2000 on Substances that Deplete the Ozone Layer, which mandated the decommissioning of all halon systems and extinguishers in the EU by the end of 2003 (with the exception of those applications that are defined as critical uses) (Europa, 2003). To reflect this, the methodology assumes that all halon systems in the EU will be decommissioned by 2004.⁴³

4.2.2 Baseline Emissions

The resulting baseline estimates of GWP-weighted HFC and PFC emissions developed for this report are summarized in Table 4-1. The estimates of the global total flooding fire protection market developed for this report are consistent with those in the IPCC/TEAP (1999) report, which estimated that in the late 1990s, between 20 and 22 percent of systems that would formerly have used halons used HFCs, and that less than 1 percent used PFCs.

⁴¹ Fire protection experts in these countries provided confidential information on the status of national halon transition markets and average costs to install the substitute extinguishing systems in use (on a per volume of protected space basis) for 2001 through 2020.

⁴² This analysis assumes that, of the new total flooding protection systems in which halons have been previously used in the United States, the market is currently made up of approximately 33 percent HFC-227ea, 1 percent HFC-23, 14 percent inert gas, and 52 percent other not-in-kind.

⁴³ It should be noted that the use of halon in marine applications is unlikely to meet the 2004 phaseout deadline, because these applications are also governed by regulations issued by the International Maritime Organization (IMO), and that many EU ships still contain halon 1301 fire suppression systems. However, due to a lack of available data on emissions from marine-based fire protection systems as a percentage of the total EU fire extinguishing sector, this analysis simply assumes full compliance with the EU regulation.

Table 4-1: Baseline HFC and PFC Emission Estimates from Fire Extinguishing (MMTCE)

Region	2005	2010	2015	2020
United States	0.43	0.65	0.80	0.89
Non-U.S. Annex I	1.51	1.00	0.87	0.94
Non-Annex I	0.31	0.61	0.98	1.37
Total	2.26	2.26	2.65	3.19

Note: Totals may not sum due to independent rounding.

This analysis assumes that Class A surface fire hazards represent an estimated 95 percent of the total flooding sector in all countries, and that the remaining 5 percent of the applications are for Class B (flammable liquids and gases) hazards.⁴⁴ According to projected global average emission estimates, emissions from Class A fire hazards will account for approximately 71 percent of the global total fire extinguishing sector in 2005, 76 percent in 2010, 81 percent in 2015, and 86 percent in 2020. Table 4-2 presents the estimated global average breakout of total fire sector HFC and PFC emissions by application, as estimated by U.S. EPA’s Vintaging Model.

Table 4-2: Assumed Breakout of Total GWP-Weighted Baseline Fire Extinguishing Emissions^a

	Annex I and Non-Annex I Countries			
	2005	2010	2015	2020
Flooding	75.0%	80.0%	85.0%	90.0%
Class A emissions (95% total flooding)	71.3%	76.0%	80.8%	85.5%
Class B emissions (5% of total flooding)	3.8%	4.0%	4.3%	4.5%
Streaming	25.0%	20.0%	15.0%	10.0%
Total	100%	100%	100%	100%

^a Totals may not sum due to independent rounding.

4.3 Costs of HFC and PFC Emission Reductions from Fire Extinguishing

This section presents a cost analysis for achieving HFC and PFC emission reductions from the baselines presented in Table 4-1. Each abatement option is described below, but costs are analyzed for only those options not assumed to occur in the baseline and for which adequate cost data are available. All cost analyses assume a 20-year project lifetime. To the extent possible, this analysis considered total equivalent warming impacts (TEWI), to account for the cost and greenhouse gas emission impacts of energy consumption (i.e., indirect emissions) associated with the heating/cooling of additional space needed to house alternative agents. However, due to data limitations, a full life cycle analysis was not possible. For example, the cost and emission impacts associated with manufacturing alternative agents and all system components were not assessed in this analysis, though they may potentially be significant.

⁴⁴ Wickham (2002) estimates that over 90 percent of the halon 1301 systems ever installed in the United States were designed to protect hazards where the anticipated fire type was primarily Class A in nature, and that approximately 10 percent of the U.S. applications served by halon 1301 had hazardous materials of the Class B type. However, because much of the former halon 1301 Class B applications have been replaced by non-HFC alternatives (e.g., CO₂), this analysis assumes that only 5 percent of HFC emissions from the total flooding sector are from Class B applications, and that the remaining 95 percent are from Class A applications.

4.3.1 Description and Cost Analysis of Abatement Options

Because it is estimated that only a limited amount of fluorocarbon agents (e.g., HFC-236fa) will be used in streaming applications, this cost analysis focuses only on abatement options in the total flooding sector.⁴⁵ In 2005, the majority of emissions from the fire extinguishing sector will result from leaks and discharges (both accidental and intended use to extinguish fires) from total flooding applications. The options for reducing HFC and PFC emissions from the fire protection sector include the use of alternative fire protection agents and the use of alternative technologies and practices. Eight potential options are identified, but only the first three are explored further in the cost analysis:

- Inert gas;
- Water mist;
- Fluorinated ketone (FK-5-1-12);
- Carbon dioxide;
- Recovery and reuse of HFCs;
- Improved detection systems;
- Aerosols; and
- Inert gas generators.

As described further below, available alternatives to reduce emissions in the fire protection sector may not be technically or economically viable for all end use applications. For example, military applications often have very specialized needs that do not exist in other end use applications. In particular, applications that are space- and/or weight-constrained, such as marine and aviation applications, are more limited in their choice of alternative agents. Electronic and telecommunication applications, which represent the largest use of HFCs in the total flooding sector, offer the greatest opportunities to consider potential alternatives, although some economic penalties and technical challenges may exist.

The remainder of this section provides an overview of each abatement option, and presents the assumptions and results of cost analyses for inert gas, water mist, and fluorinated ketone options. For a variety of reasons discussed further below, these options are assumed to be applicable only to new (not existing) total flooding systems, where “new” is defined as systems installed in 2005 or later.

Inert Gas Systems

The first option considered to displace HFC use is the use of inert gas systems. Inert gas systems use argon or nitrogen or blends of these two gases, sometimes incorporating carbon dioxide as a third component to extinguish fires (UNEP, 2001). Inert gas systems provide an equivalent level of both fire protection and life safety/health protection in most Class A (ordinary combustible) fire hazards, including electronics and telecommunications applications.

⁴⁵ U.S. EPA estimates that more than 90 percent of the halon replacement market in the streaming sector currently consists of not-in-kind alternatives, while HFCs account for less than 5 percent of this market. By 2020, U.S. EPA projects that HFCs will account for an even smaller portion of the halon replacement market in the streaming sector. It is expected that the high cost of HFCs will ensure that they are only used where they are absolutely needed (i.e., in areas where cleanliness is an absolute necessity) (Wickham, 2002).

Despite their effectiveness at extinguishing a fire, because the discharge time for inert gas systems is on the order of 60 seconds or more—significantly slower than the discharge time for HFC systems, for which discharge is typically 10 to 15 seconds (Kucnerowicz-Polak, 2002)—inert gas systems are not recommended for areas where a rapidly developing fire can be expected (UNEP, 2001; Kucnerowicz-Polak, 2002). Advances in fire detection devices may help alleviate these concerns by recognizing and extinguishing fires before they have the opportunity to develop and expand. Another factor impeding the use of inert gas systems in lieu of HFCs is that a substantially larger volume of agent is needed to extinguish fires. The additional space and weight needed to accommodate additional steel cylinders containing inert gas may effectively prohibit the retrofit of many existing HFC systems. For example, the retrofit of an HFC system to an inert gas system on small ships may be virtually impossible. The same may hold true for many other applications for which the system infrastructure is fixed. Another factor to consider with this option is the need to heat and cool this additional space, leading to negative implications for both cost and energy consumption.

This analysis assumes this option is technically applicable⁴⁶ to the emissions from total flooding systems designed for Class A fires. In addition, because of the additional floor space requirements associated with inert gas systems, it is not assumed to be economically feasible to retrofit existing HFC Class A fire extinguishing systems to this option. This analysis therefore assumes that this option is only applicable to new Class A applications (i.e., those installed in 2005 or beyond), as shown in Table 4-4. Because of the additional space and weight requirements and the slower discharge times associated with this option relative to conventional HFC-227ea systems, market penetration rates reflect the assumption that this option cannot fully displace HFC use in new Class A total flooding applications. Furthermore, because this option is associated with additional costs (see discussion below), it is assumed that market penetration estimates in non-Annex I countries are 50 percent less than in Annex I countries for all years—given the greater economic challenges faced by non-Annex I countries. Table 4-4 and Table 4-5 present the assumed market penetration rates of this option in developed and developing countries.

Cost and Emission Reduction Analysis

Various data and assumptions about the costs and emission reductions associated with inert gas were used to analyze this option. U.S. costs were determined relative to conventional HFC-227ea systems, as they dominate the HFC flooding market in the United States. This analysis scales the costs of inert gas systems in other countries to U.S. costs based on confidential country-specific cost information obtained for this report from HTOC members, as described in more detail below. The following bullets describe the inputs used to derive the final \$/TCE for this option, the results of which are presented in Section 4.4:

- **One-Time Costs.** This analysis bases average capital costs for inert gases on average selling prices to distributors/installers, as provided in Wickham (2003b), which provides a comprehensive cost comparison of total flooding systems.⁴⁷ Accordingly, in the United States, inert gas systems cost approximately \$34 per cubic meter of protected space, which is

⁴⁶ In this report, the term *technically applicable* refers to the emissions to which an option can be applied. Because inert gas systems are assumed to be used only in Class A fire total flooding applications, the technical applicability is 100 percent of the emissions associated with those types of systems. Other factors will affect the application of the option, for example to new or existing systems, and the market penetration assumed in this analysis. See Appendix I for a glossary of terminology.

⁴⁷ The cost estimates in Wickham (2003b) do not include agent distribution piping and fittings, pipe supports and hangers, actuation tubing and fittings, electrical cables and junction boxes or labor to install. Although the costs identified in Wickham (2003) for inert gas and HFC-227ea systems will be higher for end users, the cost differential between these two systems is assumed to be relatively comparable.

approximately \$6 more than conventional HFC-227ea systems, which are estimated to cost \$28.05 per cubic meter of protected space. In addition, because inert gas systems require more space to house gas cylinders compared to conventional HFC systems, in some cases there will be additional one-time costs associated with constructing the additional space for storage of the system. Specifically, an additional 0.023 square feet (0.0021 square meters) of floor space is needed per cubic meter of protected space (Wickham, 2003b). Assuming a construction cost of \$150 per square foot, this additional space requirement translates into an incremental one-time cost of nearly \$3.45 per cubic meter of protected space (R.S. Means, 2001). The total incremental capital cost of this option in the United States, therefore, totals \$9.45 per cubic meter of protected space.

In all developing countries, capital costs for this option were scaled based on cost estimates provided by HTOC members from developing countries. Specifically, incremental capital costs (relative to conventional HFC-227ea systems) were assumed to be 10 percent greater in developing countries (Hughes Associates, 2001).

- **Annual Costs.** Depending on the application, the space required to house additional gas cylinders (an additional 0.023 square feet per cubic meter of protected space) will need to be heated and cooled. To be conservative, the additional annual heating and cooling costs are considered in this analysis. Based on average U.S. electricity costs of \$8 per square foot, this option is associated with an annual cost of \$0.18 per cubic meter of protected space in the United States (R.S. Means, 2001). In all other countries, this annual cost was adjusted by average electricity prices (average of 1994-1999) based on EIA (2000).
- **Cost Savings.** Annual savings are associated with the avoided HFC-227ea emissions and associated replacement costs, which would have been incurred had a conventional HFC system been used in place of inert gas (which for this analysis is assumed to have no agent cost). Because on average approximately 0.633 kg of HFC-227ea are needed to protect one cubic meter of space (Wickham, 2003b), and assuming a release rate of 1.5 percent of the installed base, it is assumed that the emission of approximately 0.009 kg of HFC-227ea is avoided each year per cubic meter of protected space. Based on an average HFC-227ea cost of \$34.10/kg (Wickham, 2002), this translates into an annual savings of \$0.32 per cubic meter of protected space ($0.633 \text{ kg} \times 1.5\% \times \$34.10/\text{kg}$).
- **Emission Reductions.** Under the inert gas systems described above, the direct emission of approximately 0.009 kg ($0.633 \text{ kg} \times 1.5\%$) of HFC-227ea can be replaced, resulting in the avoided emissions of nearly 0.008 TCE per cubic meter of protected space. Indirect emission (energy) penalties associated with additional space requirements (of 0.023 ft² per cubic meter of protected space [Wickham, 2003b]) are calculated using the average electricity use to heat/cool the additional space required (assumed to be \$8/ft² [R.S. Means, 2001] at an average electricity cost in the United States of \$0.04/kWh [EIA, 2000]), and the average emission rate from electricity generation (assumed to be 0.606 kg CO₂/kWh [EIA, 2004]). Thus, the indirect emissions lower these emission benefits by nearly 10 percent (approximately 0.0007 TCE per cubic meter of protected space) in the United States. Therefore, in the United States, net annual emission reductions associated with this option are equal to approximately 0.0068 TCE per cubic meter of protected space. In all other countries, the indirect emission penalty was calculated by multiplying the emission penalty assumed for the United States (0.0007 TCE) by a ratio of U.S. to regional national average CO₂ emission rates for electricity production, based on Sand et al. (1997).

Water Mist Systems

Water mist systems use relatively small droplet sprays under low, medium, or high pressure to extinguish fires. These systems use specially-designed nozzles to produce much smaller droplets than are produced by traditional water-spray systems or conventional sprinklers, thereby requiring significantly less water to achieve extinguishment (UNEP, 2001; Wickham, 2002). Another benefit of water mist systems is that, in some applications (e.g., marine applications), they can be brought into action faster than HFC systems, since there is less concern in applying water mist in situations where openings to the space are not all closed—which in turn leads to reduced fire damage. In addition, unlike HFC systems, which are usually limited to a single discharge of agent, most water mist systems have an unlimited water supply in land-based operations, and at least 30 minutes of potable water discharge followed by an unlimited amount of seawater for marine applications (Wickham, 2003b).

To date, water mist systems have been used in shipboard accommodation, storage and machinery spaces, combustion turbine enclosures, flammable and combustible liquid machinery, and light and ordinary hazard sprinkler applications (UNEP, 2001). Water mist systems can provide equivalent fire protection and life safety/health protection for Class B fuel hazards, where low temperature freezing is not a concern. Class B (flammable liquid) fire hazards are estimated to account for approximately 5 percent of the HFC total flooding market in the United States and were assumed to account for the same percent in all non-U.S. countries for lack of data on those countries (Wickham, 2002). Water mist systems have also found acceptance in Class A applications, but as replacements for water sprinklers, not HFCs. Therefore, this report does not consider water mist as an option for abating HFC emissions from Class A applications.

Various difficulties have been identified with the use of water mist systems, impeding deployment of these systems and preventing broader market shares. First, these systems have not proven effective in extinguishing small fires in large spaces (volumes greater than 2,000 m³) (IMO, 2001; Wickham, 2002). Additionally, because the relationship between the mechanism of extinguishment⁴⁸ of water mist systems is non-linear and not well understood, applications of water mist systems have been limited to those where fire test protocols have been developed, based on empirically-tested system performance. Therefore, new applications may require empirical performance testing prior to the installation of such systems, in order to ensure safety and obtain approval of the proper regulatory or standard setting authority. Currently, an International Maritime Organization (IMO) working group is studying this situation and considering proposals that suggest an overhaul to the test methods and approval guidelines. Should IMO change its water mist requirements to something more flexible regarding the extinguishment of small fires in large spaces, it will make a difference in the future cost and, thus, market acceptance of water mist systems (Wickham, 2003b). In addition, the use of additives—such as salts or foam or a combination of these systems with gaseous agents—are other options under investigation to improve system performance for specific applications. Many researchers and industry experts believe that solutions to these market barriers are well within reach (Wickham, 2002).

Other market barriers for this option include additional space requirements for system storage compared to conventional HFC-227ea systems. Indeed, water mist systems require an estimated seven times more space than HFC-227ea (Wickham, 2003b). In addition, water mist systems used in marine applications are cost prohibitive for protecting small spaces (i.e., those less than 3,000 cubic meters in size).⁴⁹

⁴⁸ “Mechanism of extinguishment” refers to the amount of water mist needed to extinguish a given fire in a given volume.

⁴⁹ This cost information is based on water mist systems employed under the current IMO requirements for marine systems, which are much more severe than the requirements for land based systems. The use of water mist systems

This analysis assumes this option is technically applicable to the emissions from total flooding systems designed for Class B fires. Due to the additional space requirements associated with this option, it is assumed that water mist systems could not feasibly replace any existing HFC systems in Class B fire protection applications and, therefore, are only used in new Class B total flooding applications (i.e., those installed in 2005 or beyond).

In terms of market penetration, this analysis assumes that the remaining technical constraints associated with water mist systems will gradually be overcome, and that by 2020 in Annex I countries, water mist systems will reach full market penetration in all new Class B fire suppression systems used to protect large spaces.

Market penetration estimates for non-Annex I countries are assumed to be 50 percent less than those of developed countries, as a result of economic considerations. Table 4-4 and Table 4-5 present the maximum market penetrations assumed for this option.

Cost and Emission Reduction Analysis

The following bullets describe the cost and emission inputs used to derive the final \$/TCE for the water mist option, the results of which are presented in Section 4.4:

- **One-Time Costs.** This analysis bases the average capital costs for water mist systems on the average selling prices to distributors for systems used in marine applications, as provided in Wickham (2003b), which provides a cost comparison of total flooding systems.⁵⁰ According to that report, capital costs of water mist systems used in marine systems to protect large spaces are estimated to be \$29.67 per cubic meter of protected space—or \$4.07 more per cubic meter of protected space than conventional HFC-227ea systems in large spaces (which are estimated to cost \$25.60 per cubic meter of protected space). It should be noted that for non-marine applications, costs are more competitive than those presented here, as the requirements for land based systems are not as stringent as those currently required by the IMO (Wickham, 2003a). This analysis uses the costs for marine rather than land-based systems to obtain conservative results (i.e., higher costs). Other costs presented below are based on non-marine applications.

In addition, because water mist systems require more space than conventional HFC systems, one-time costs associated with constructing additional space are also considered. Specifically, an average of approximately 0.0472 square feet (0.0044 square meters) of additional floor space in the building is needed per cubic meter of protected space (Wickham, 2003b). Assuming a construction cost of \$150 per square foot in the United States (R.S. Means, 2001), this additional space requirement translates into an incremental one-time cost of \$7.08 per cubic meter of protected space. Therefore, the total incremental capital cost of this option in the United States totals \$11.15 per cubic meter of protected space (\$4.07 + \$7.08).

Reliable international cost information on water mist systems was only obtained for India and Russia. According to international experts, capital costs are the same in Russia as in the United States, and about 10 percent higher in India (Hughes Associates, 2001). India is used as a proxy for estimating costs in all other developing countries (i.e., costs are assumed to be 10 percent greater than those in the United States).

in non-marine applications appear to be more cost competitive with other alternatives (Wickham, 2003a).

⁵⁰ The cost estimates provided in Wickham (2003b) do not include feed water pipes, low pressure piping, electrical cables and junction boxes or labor to install. Therefore, water mist and HFC-227ea systems costs will be higher than presented here, but the cost differential between these two systems is assumed to be comparable.

- **Annual Costs.** Because the additional space required to house water mist systems (0.0472 square feet per cubic meter of protected space) will need to be heated and cooled, annual heating and cooling costs for this additional space are considered in this analysis. Based on average U.S. electricity costs of \$8 per square foot (R.S. Means, 2001), this option is associated with an annual cost of \$0.38 per cubic meter of protected space in the United States. In all other countries, this annual cost is adjusted by average electricity prices (average of 1994-1999) based on EIA (2000).
- **Cost Savings.** Annual savings are associated with the avoided HFC-227ea emissions and associated replacement costs, which would have been incurred had a conventional HFC system been used in place of water (which for this analysis is assumed to have no agent cost). Because on average approximately 0.630 kg of HFC-227ea are needed to protect one cubic meter of space (for large spaces) (Wickham, 2003b), and assuming a release rate of 1.5 percent of the installed base, it is assumed that the emission of approximately 0.009 kg of HFC-227ea is avoided each year (0.630 kg \times 1.5%). Based on an average HFC-227ea cost of \$34.10/kg, this translates into an annual savings of \$0.32 per cubic meter of protected space (Wickham, 2002).
- **Emission Reductions.** Under the water mist systems described above, the direct emission of approximately 0.009 kg of HFC-227ea can be avoided, resulting in the reduction of approximately 0.007 TCE per cubic meter of protected space. Indirect emission (energy) penalties associated with additional space requirements (assumed to be 0.0472 ft² per cubic meter of protected space [Wickham, 2003b]) are calculated using the average electricity use to heat/cool the additional space required (assumed to be \$8/ft² [R.S. Means, 2001] at an average electricity cost in the United States of \$0.04/kWh [EIA, 2000]), and the average emission rate from electricity generation (assumed to be 0.606 kg CO₂/kWh [EIA, 2004]). Thus, the indirect emissions lower these emission benefits by roughly 20 percent (approximately 0.0015 TCE per cubic meter of protected space) in the United States. Therefore, in the United States, net annual emission reductions associated with this option are equal to approximately 0.0060 TCE per cubic meter of protected space. In all other countries, the indirect emission penalty was calculated by multiplying the emission penalty assumed for the United States (0.0015 TCE) by a ratio of U.S. to regional national average CO₂ emission rates for electricity production, based on Sand et al. (1997).

Fluorinated Ketone (FK-5-1-12)

FK-5-1-12-mmy2 (also known as 1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)-3-pentanone, and commonly referred to as FK-5-1-12) is a fluorinated ketone with an atmospheric lifetime of up to two weeks and a 100-year GWP of approximately 1 (ICF Consulting, 2003). This alternative received U.S. EPA Significant New Alternatives Policy (SNAP) approval as an acceptable replacement for halon 1301 in flooding applications at the end of 2002 and for halon 1211 in non-residential streaming applications in early 2003.

Compared to HFC-227ea total flooding systems, FK-5-1-12 systems are associated with slight space and weight penalties—on the order of 10 and 15 percent, respectively—which could make its use in confined spaces (e.g., ships, aircraft) less attractive, although some marine installations have already been reported (Werner, 2004a).⁵¹ Moreover, in addition to its cost (see cost analysis below) and its relatively recent entry⁵² into this market as compared to the inert gas and water mist options, the extent of commercial acceptance and future usage of this option is not yet known.

⁵¹ It has been reported that the space penalty is only associated with use in large systems, and that the weight penalty has not proven to be an impediment (Werner, 2004b).

⁵² This agent is in the 2004 edition of the National Fire Protection Association (NFPA) Standard on Clean Agent

While this option is not associated with major floor space penalties and appears not to suffer from any significant technical barriers, it is only assumed to be applicable in new Class A flooding applications (i.e., those installed in 2005 or beyond), because the cost analysis does not assess retrofit costs. Table 4-4 and Table 4-5 present the maximum market penetration assumptions for this option, which project that this option will gain a foothold in the marketplace and out-compete inert gas systems in new Class A total flooding applications. Due to the reasons expressed above, this analysis conservatively assumes that market penetration will be low in early years, although others project higher sales (Werner, 2004b). Market penetration is assumed to be greater in Annex I countries than in non-Annex I countries, as a result of economic considerations.

Cost and Emission Reduction Analysis

The following bullets describe the cost and emission inputs used to derive the final \$/TCE for FK-5-1-12 systems, the results of which are presented in Section 4.4:

- **One-Time Costs.** This analysis bases average capital costs for FK-5-1-12 systems on the average selling prices to distributors/installers, as provided in Wickham (2003b), which provides a cost comparison of total flooding systems.⁵³ According to this report, in the United States, capital costs of FK-5-1-12 systems are estimated to be nearly \$36 per cubic meter of protected space—or nearly \$7.94 more than conventional HFC systems (estimated to cost \$28.05 per cubic meter of protected space). To be conservative, this analysis uses this figure, although others have reported increased costs of only around \$3.60 per cubic meter of protected space (Werner, 2004b). Also, while the floor space requirements for this option are very similar to those of HFC systems, there is a slight increase in the floor space needed to protect each cubic meter of space (less than 0.001 square feet). Assuming an average construction cost of \$150 per square foot (R.S. Means, 2001), this translates into an incremental one-time construction cost of approximately \$0.07 per cubic meter of protected space. Therefore, the total incremental one-time cost of this option is \$8.01 per cubic meter of protected space (\$7.94 + \$0.07). Due to a lack of available data on the costs of this option in other countries, no regional cost adjustments were made to this capital cost.
- **Annual Costs.** Because the additional space requirement associated with this option relative to conventional HFC systems is so small, the additional annual costs associated with heating and cooling are also very small (less than \$0.01 annually per cubic meter of protected space). In all other countries, this annual cost was adjusted by average electricity prices (average of 1994-1999) based on EIA (2000). In addition, it is assumed that an incremental annual cost of \$0.04 per cubic meter of protected space is associated with annual emissions/agent replacement costs. This cost is based on the assumption that approximately 11 percent more FK-5-1-12 agent is required to protect the same amount of space as HFC-227ea for Class A fires, that approximately 0.009 kg of HFC-227ea is used per cubic meter of protected space, and that the agent replacement costs are both equal (roughly \$34/kg, although actual prices vary by region) (Werner, 2004a).
- **Cost Savings.** Because the agent is assumed to cost the same as HFC-227ea, there are no annual cost savings associated with this option.

Fire Extinguishing Systems (NFPA, 2004) and has been accepted for future addition to the ISO International Standard on Gaseous Fire-Extinguishing Systems (Wickham, 2003a).

⁵³ The cost estimates in Wickham (2003b) do not include agent distribution piping and fittings, pipe supports and hangers, actuation tubing and fittings, electrical cables and junction boxes or labor to install. Although the costs identified in Wickham (2003) for FK-5-1-12 and HFC-227ea systems will be higher for end users, the cost differential between these two systems is assumed to be relatively comparable.

- **Emission Reductions.** Under the FK-5-1-12 option described above, the direct emission of approximately 0.009 kg of HFC-227ea can be avoided per cubic meter of protected space, resulting in a reduction of nearly 0.008 TCE per cubic meter of protected space ($0.009 \text{ kg} \times 2,900 \times 12/44 \times 1/1,000$). Indirect emission (energy) penalties associated with additional space requirements (assumed to be 0.0005 ft² per cubic meter of protected space [Wickham, 2003b]) are calculated using the average electricity use to heat/cool the additional space required (assumed to be \$8/ft² [R.S. Means, 2001] at an average electricity cost in the United States of \$0.04/kWh [EIA, 2000]), and the average emission rate from electricity generation (assumed to be 0.606 kg CO₂/kWh [EIA, 2004]). Thus, the indirect emissions reduce this environmental benefit by less than 0.25 percent (0.00002 TCE) in the United States. Therefore, in the United States, net annual emission reductions associated with this option are equal to 0.0075 TCE per cubic meter of protected space. In all other countries, the indirect emission penalty was calculated by multiplying the emission penalty assumed for the United States (0.00002 TCE) by a ratio of U.S. to regional national average CO₂ emission rates for electricity production, based on Sand et al. (1997).

Carbon Dioxide

Carbon dioxide has been used for many decades in total flooding systems. Some of the types of hazards and equipment that carbon dioxide systems protect are flammable liquid materials; electrical hazards, such as transformers, switches, circuit breakers, rotating equipment, and electronic equipment; engines utilizing gasoline and other flammable liquid fuels; ordinary combustibles, such as paper, wood, and textiles; and hazardous solids (NFPA, 2000). Due to the lethal concentrations at which carbon dioxide is required for use as a fire extinguishing agent, there have been concerns with incidences of deaths and injuries attributed to exposure to this agent (U.S. EPA, 2006; Wickham, 2003b). The National Fire Protection Association (NFPA) Technical Committee on NFPA 12 Standard for Carbon Dioxide Fire Extinguishing Systems is currently reviewing a proposal to change the standard to prohibit use of these systems in normally occupied areas (Wickham, 2003b). The IMO's Safety of Life at Sea (SOLAS) standard does not prohibit the use of carbon dioxide in normally occupied areas, but calls for the use of suitable alarms and mandates against the use of automatic release of the fire-extinguishing medium, as noted in U.S. EPA (2000). IMO is also considering whether to prohibit use of carbon dioxide systems in occupied areas as part of that organization's broad review of the current performance testing requirements for all shipboard fire extinguishing systems (IMO, 2003; Wickham, 2003b).

As one of the oldest fire extinguishing agents in use, and as a more economical option than HFCs, carbon dioxide has generally developed its own niche market in narrow-use total flooding applications. While carbon dioxide could and does replace some halon use where permitted by regulations, this analysis assumes that carbon dioxide would be selected as a first-choice replacement of halon, not as a second transition, after more costly HFCs. For example, the majority of U.S. ship owners have shifted from halon 1301 to carbon dioxide for mandatory engine room protection for new ships (Wickham, 2002). For this reason, any use of carbon dioxide is assumed to occur in the baseline, and not as an option to replace HFC systems. It is therefore not considered in the cost analysis.

Recovery and Reuse of HFCs

HFCs can be recovered for reuse at service and decommissioning. For several reasons, however, this analysis does not incorporate this option into the cost analysis. First, responsible halon management practices are assumed to be standard convention in fire protection throughout the world.⁵⁴ Second, given

⁵⁴ Responsible use practices are currently being developed and endorsed worldwide. For example, the halon Recycling Corporation (HRC) published a Code of Practice for Halon Reclaiming Companies. Because the

the high costs of HFCs, there is a strong financial incentive for maximum recovery following the decommissioning of large HFC systems. While most HFC systems—with lifetimes ranging from 10 to 20 years—have not yet reached the end of their useful lifetimes and, therefore, widescale system recovery and recycling at decommissioning has not yet occurred, this analysis assumes that such practices will occur in the baseline.

Improved Detection Systems

One effective way of reducing HFC emissions from the fire extinguishing sector is to install improved detection and control systems to (1) prevent a false discharge (e.g., high sensitivity smoke detection systems that provide early warning to pre-empt the need for actual system discharge), or (2) minimize the amount of agent discharged to extinguish a fire.

Since advanced detection systems have been available for the last decade or so, this analysis assumes that total flooding HFC systems have been and are being equipped with such systems internationally. Because improved detection systems are assumed to be used in the baseline, this option is not considered in the cost analysis.

Fine Aerosols

Aerosols are being developed for use as extinguishing agents in niche markets in the United States, such as aerospace, marine, and some military applications. The NFPA has written a draft standard (NFPA 2010) for this agent (NFPA, 2003). It is possible that if this agent is ever successfully brought to market, that it may be applicable in other end uses (Wickham, 2002).

Because fine aerosols are not currently a viable commercial option to HFCs in fire protection, and much uncertainty exists as to whether or not the associated technical and economic barriers will be overcome to enable them to become a viable alternative, this option is not considered in the cost analysis.

Inert Gas Generators

Inert gas generators use a solid material that oxidizes rapidly, producing large quantities of carbon dioxide and/or nitrogen. While this technology has demonstrated space and weight requirements equivalent to halon 1301, it has thus far only been used in specialized applications in the United States (e.g., dry bays on military aircraft) (Wickham, 2002). Due to insufficient data on these systems and to the uncertainty associated with their applicability in other fire extinguishing applications, this option is not considered in the cost analysis.

equipment and training needed to reclaim halons are also required to reclaim HFCs, the HRC Code of Practice establishes the necessary infrastructure and sets the practice of reclamation as the norm for how business is done in the fire protection industry. While the HRC is a U.S. association, its membership consists of multinational corporations operating throughout the world. Similarly, the Halon Alternatives Research Corporation (HARC), U.S. EPA, and other organizations have recently developed and endorsed the Voluntary Code of Practice for the Reduction of Emissions of HFC and PFC Fire Protection Agents. This Code of Practice will also have international reach, since HARC members include multinational companies in the alternative agent manufacturing, equipment manufacturing, and distribution sectors.

4.3.2 Summary of Technical Applicability and Market Penetration of Abatement Options

Table 4-3 summarizes the technical applicability of each option, which is equal to the estimated global average breakout of total fire sector HFC and PFC emissions for the application (i.e., total flooding, Class A or B) addressed by the option. Technical applicability is used in conjunction with market penetration assumptions to develop the emission reduction potentials for each option, as explained further below. Table 4-4 provides the assumptions on maximum market penetration into annual installations of total flooding systems designed for the particular application (i.e., Class A or B fires) for each option in 2005, 2010, 2015 and 2020. Market penetrations were developed separately for Annex I and non-Annex I countries, to best reflect region-specific qualitative information and possible future action. Table 4-5 presents the final maximum penetration into the installed base of equipment, taking into account the percent of each applicable fire hazard market that is new (i.e., systems installed in 2005 or beyond) in all preceding years. Values from Table 4-5 are multiplied by technical applicabilities from Table 4-3 to generate the percent reduction off baseline emissions, as presented in Table 4-6.

Table 4-3: Summary of Technical Applicability of Abatement Options^a

	Annex I and Non-Annex I Countries			
	2005	2010	2015	2020
Inert Gas (Class A flooding)	71.3%	76.0%	80.8%	85.5%
Water Mist (Class B flooding)	3.8%	4.0%	4.3%	4.5%
FK-5-1-12 (Class A flooding)	71.3%	76.0%	80.8%	85.5%

^a Expressed as a percent of total fire extinguishing emissions.

Table 4-4: Incremental Maximum Market Penetration, Expressed as Percent of Annual Installation of New Class A or Class B Systems

	Annex I Countries				Non-Annex I Countries ^a				Considerations/Rationale
	2005	2010	2015	2020	2005	2010	2015	2020	
Inert Gas (<i>New Class A</i>)	10%	20%	30%	30%	5%	10%	15%	15%	<ul style="list-style-type: none"> ▪ Can displace HFCs in new Class A applications ▪ Additional space and weight requirements ▪ Slower discharge times ▪ Higher costs compared to baseline HFC-227ea systems lead to lower market penetration in developing countries
Water Mist (<i>New Class B</i>)	25%	50%	75%	100%	13%	25%	38%	50%	<ul style="list-style-type: none"> ▪ Can displace HFCs in new Class B applications used to protect large spaces ▪ Technical constraints (assumed to be gradually overcome) ▪ Higher costs compared to baseline HFC-227ea systems lead to lower market penetration in developing countries

	Annex I Countries				Non-Annex I Countries ^a				Considerations/Rationale
	2005	2010	2015	2020	2005	2010	2015	2020	
FK-5-1-12 (New Class A)	4%	20%	40%	50%	2%	10%	20%	25%	<ul style="list-style-type: none"> ▪ Can displace HFCs in new Class A applications ▪ No major additional space requirements ▪ Lowest up-front cost of all alternatives considered in this analysis ▪ Newer player on market compared to inert gas and water mist systems; will take time to gain foothold in market ▪ Higher costs compared to baseline HFC-227ea systems lead to lower market penetration in developing countries

^a To account for economic considerations, assumed market penetration values in developing countries are half of those assumed for developed countries.

Table 4-5: Incremental Maximum Market Penetration Expressed as Percent of Entire Installed Base (Class A or Class B)^a

	Annex I Countries				Non-Annex I Countries			
	2005	2010	2015	2020	2005	2010	2015	2020
Inert Gas (Class A)	0.5%	4.5%	11.0%	18.5%	0.3%	2.3%	5.5%	9.3%
Water Mist (Class B)	1.3%	11.3%	27.5%	50.0%	0.7%	5.7%	13.9%	25.2%
FK-5-1-12 (Class A)	0.2%	3.6%	11.6%	23.1%	0.1%	1.8%	5.8%	11.6%

^a Expressed as a percentage of technical applicability (i.e., both new and existing Class A or Class B emissions).

To calculate the percent of emission reductions off the total fire extinguishing baseline for each abatement option, the technical applicability (from Table 4-3) is multiplied by the market penetration values (from Table 4-5). For example, to determine the percent reduction off the 2020 baseline for FK-5-1-12 in the United States (or other Annex I countries), the following calculation is used:

$$\text{Technical Applicability} \times \text{Incremental Maximum Market Penetration} =$$

$$85.5\% \times 23.1\% \approx 19.8\%$$

Thus, using the assumptions in this analysis, FK-5-1-12 could reduce approximately one-fifth of the Annex I 2020 emissions baseline. This figure, along with the other emission reduction potentials, is shown in Table 4-6.

Table 4-6: Emission Reductions off Total Fire Extinguishing Baseline

	Annex I Countries				Non-Annex I Countries			
	2005	2010	2015	2020	2005	2010	2015	2020
Inert Gas	0.4%	3.4%	8.9%	15.8%	0.2%	1.7%	4.4%	7.9%
Water Mist	0.0%	0.5%	1.2%	2.3%	0.0%	0.2%	0.6%	1.1%
FK-5-1-12	0.1%	2.7%	9.4%	19.8%	0.1%	1.4%	4.7%	9.9%

4.4 Results

Table 4-7 through Table 4-9 provide a summary of the potential emission reduction opportunities and associated annualized costs for United States, Non-U.S. Annex I countries, and Non-Annex I countries in 2020. The costs to reduce one ton of carbon equivalent (TCE) are presented for two different discount rate scenarios: 4 percent and 20 percent. The tax rate associated with each cost scenario is 0 percent and 40 percent, respectively. The results are ordered by increasing costs per TCE, using the highest cost in the region under the 4 percent discount rate. The emissions reduced by the option and a cumulative total of emissions reduced, in MMTCE and percent of the regional fire extinguishing baseline, are presented.

Table 4-7: United States Emission Reductions in 2020 and Break-Even Costs for Fire Extinguishing

Reduction Option	Break-Even Cost (2000\$/TCE)		Emission Reduction of Option (MMTCE)	Percent Reduction from 2020 Baseline	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
	Discount/Tax Rate					
	4%/0%	20%/40%				
Inert Gases	\$81.98	\$410.54	0.14	15.8%	0.14	15.8%
FK-5-1-12	\$83.96	\$335.63	0.17	19.8%	0.31	35.6%
Water Mist	\$146.97	\$587.31	0.02	2.3%	0.33	37.8%

Table 4-8: Non-U.S. Annex I Emission Reductions in 2020 and Break-Even Costs for Fire Extinguishing

Reduction Option	Break-Even Cost (2000\$/TCE) ^a				Emission Reduction of Option (MMTCE)	Percent Reduction from 2020 Baseline	Cumulative Reductions (MMTCE)	% Reduction from 2020 Baseline
	Discount/Tax Rate							
	4%/0%		20%/40%					
	Low	High	Low	High				
FK-5-1-12	\$83.72	\$85.22	\$334.91	\$336.75	0.19	19.8%	0.19	19.8%
Inert Gases	\$71.10	\$136.29	\$369.25	\$483.77	0.15	15.8%	0.33	35.6%
Water Mist	\$111.76	\$287.80	\$467.17	\$761.31	0.02	2.3%	0.36	37.8%

^a Costs vary by country/region based on one-time or annual adjustment factors (e.g., electricity price); therefore, the lowest and highest costs for the region are shown.

Table 4-9: Non Annex I Emission Reductions in 2020 and Break-Even Costs for Fire Extinguishing

Reduction Option	Break-Even Cost (2000\$/TCE) ^a				Emission Reduction of Option (MMTCE)	Percent Reduction from 2020 Baseline	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
	Discount/Tax Rate							
	4%/0%		20%/40%					
	Low	High	Low	High				
FK-5-1-12	\$83.74	\$84.36	\$335.01	\$336.18	0.13	9.9%	0.13	9.9%
Inert Gases	\$81.29	\$114.30	\$414.31	\$486.93	0.11	7.9%	0.24	17.8%
Water Mist	\$126.10	\$219.85	\$529.82	\$740.97	0.02	1.1%	0.26	18.9%

^a Costs vary by country/region based on one-time or annual adjustment factors (e.g., electricity price); therefore, the lowest and highest costs for the region are shown.

4.5 Summary

Baseline HFC and PFC emissions from fire extinguishing are estimated to grow between the years 2005 and 2020, with the highest emissions growth expected to occur in Non-Annex I countries. It is estimated that the vast majority of these emissions will come from total flooding applications; only a minor amount will come from streaming applications.

Several alternatives to ozone-depleting halon 1301 for total flooding applications exist, including gaseous alternatives such as halocarbons (HFCs and PFCs), carbon dioxide, inert gases and fluorinated ketones, as well as non-in-kind alternatives such as dispersed and condensed aerosol systems, water sprinklers, water mist, foam and inert gas generators.

This analysis reviewed these alternatives and analyzed in detail three mitigation options for total flooding fire extinguishing applications: (1) substituting HFC systems used in new Class A fire hazards with inert gas systems; (2) substituting HFCs used in new Class B fire hazards with water mist systems; and (3) substituting HFC systems used in new Class A fire hazards with FK-5-1-12 systems. Inert gas and FK-5-1-12 systems may offer good opportunities to reduce emissions in total flooding applications globally. Water mist systems also have the potential to reduce global emissions from this sector, but to a lesser extent.

This analysis demonstrates that there is a portfolio of alternatives to HFCs and PFCs in the total flooding sector that can be employed to reduce HFC and PFC use and associated emissions. These alternatives include FK-5-1-12, inert gases, water mist, and other agents and systems discussed qualitatively in this report. The global implementation of each option through 2020 is based on a “best guess” scenario. With more data, these forecasts can be improved.

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5 Analysis of Costs to Abate International HFC and PFC Emissions from Solvents

5.1 Introduction

Ozone depleting substances (ODSs) have been used as solvents in a wide range of cleaning applications, including precision, electronics, and metal cleaning (UNEP, 1999a). Chlorofluorocarbons (in particular CFC-113), methyl chloroform (1,1,1-trichloroethane or TCA), and to a lesser extent, carbon tetrachloride (CCl₄), were historically used as solvents in the United States. Similar usage historically occurred elsewhere, with the exception of India and China, where greater volumes of CCl₄ were consumed.

To comply with the requirements of the Montreal Protocol,⁵⁵ many countries started using hydrochlorofluorocarbons (HCFCs), and aqueous and semi-aqueous Not-in-Kind (NIK) solvents as substitutes for ODSs. For example, the majority of metal cleaning end-users and some of the electronics and precision cleaning solvent end-users have already transitioned to no-clean, semi-aqueous cleaning, and aqueous cleaning alternative methods. Many of the in-kind replacement solvents, including hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs), have also taken a share of the substitute market, as they have high reliability, excellent compatibility, good stability, low toxicity, and selective solvency. These HFCs and PFCs have 100-year global warming potentials (GWPs) ranging from 890 to 7,400⁵⁶ times that of carbon dioxide and have relatively low boiling points (50°C to 90°C) that contribute to their inadvertent release to the atmosphere. The replacement solvent technologies used globally are summarized in Table 5-1.

HFC solvents include HFC-4310mee, HFC-365mfc, and HFC-245fa. Of these HFCs, HFC-4310mee is the most common solvent cleaner replacement. HFC-365mfc is used as an additive to form solvent blends with HFC-4310mee, helping to reduce the cost of these products (Micro Care, 2002). HFC-245fa is used in the aerosol solvent industry (Honeywell, 2003). Certain solvent applications, particularly precision cleaning end-uses, will continue to use HCFCs, especially HCFC-225ca/cb (until the HCFC phaseout takes place), and to a much lesser extent, PFCs and perfluoropolyethers (PFPEs).

This report analyzes three solvent end-uses: metal, precision, and electronics cleaning. Metal cleaning involves the removal of contamination such as oils, greases, and particulate matter from metal surfaces during the production of metal parts, and the maintenance and repair of equipment and machinery. Electronics cleaning, or defluxing, consists mainly of the removal of flux residue that remains after a soldering operation for printed circuit boards and other contamination-sensitive electronics applications. Precision cleaning may apply to either electronic components or metal surfaces and is characterized by products that require a high level of cleanliness and generally have complex shapes, small clearances, and other cleaning challenges (UNEP, 1999a). Examples of applications and products requiring precision cleaning include disk drives, gyroscopes, medical devices, and optical components. Based on current

⁵⁵ Parties to the *Montreal Protocol on Substances that Deplete the Ozone Layer* (Montreal Protocol) agreed to phase out all ozone depleting substances, including those used as solvents. In developed countries, the solvent industry has phased out its use of ODS. Developing countries are scheduled to phase out these substances (in particular CFCs and 1,1,1-trichloroethane) between 2008 and 2010.

⁵⁶ 7,400 is the GWP of perfluorohexane (C₆F₁₄), and is used in this report for estimating purposes as the GWP for PFC/PFPEs.

understanding of market trends, HFC emissions from the precision and electronics cleaning end-uses dominate the GWP-weighted emissions from the solvents sector. The metal cleaning end-use has primarily transitioned away from ODSs directly into alternatives or processes that do not use high global warming potential chemicals.

Table 5-1: General Overview of Solvent Technologies Used Globally

Solvent Classes	Metal	Electronics	Precision
Chlorinated Solvents	X	X	X
HCFC Solvents (HCFC-225 ca/cb and HCFC-141b)		X	X
HFC Solvents (primarily HFC-4310mee)		X	X
PFC Solvents		X	X
Hydrofluoroether (HFE) Solvents		X	X
Hydrocarbons	X	X	X
Alcohol Solvents	X	X	X
Brominated Solvents	X	X	X
Methyl Siloxanes	X	X	X
Alternative Cleaning Technologies			
Aqueous Cleaning	X	X	X
Semi-Aqueous Cleaning	X	X	X
No-Clean Processes ^a	X	X	

^aNo-Clean processes include low-solids flux or paste and inert gas soldering.

5.2 Baseline Emission Estimates

5.2.1 Emission Estimating Methodology

Description of Methodology

A full description of the emission model used to calculate ODS substitute emissions from all sectors is provided in Appendix A. Specific information on how the model calculates solvent emissions is described below.

EPA uses a detailed Vintaging Model of ODS-containing equipment and products to estimate the use and emissions of various ODS substitutes in the United States, including HFCs and PFCs. Emission baselines from non-U.S. countries were derived using country-specific ODS consumption estimates as reported under the Montreal Protocol in conjunction with Vintaging Model output for each ODS-consuming end-use sector. For sectors where detailed information was available, these data were incorporated into country-specific versions of the Vintaging Model to customize emission estimates. In the absence of country level data, these preliminary estimates were calculated by assuming that the transition from ODSs to HFCs and other substitutes follows the same general substitution patterns internationally as observed in the United States. From this preliminary assumption, emission estimates were then tailored to individual countries or regions by applying adjustment factors to U.S. substitution scenarios, based on relative differences in (1) economic growth; (2) rates of ODS phaseout; and (3) the distribution of ODS use across end-uses in each region or country.

For solvents, input into the model is based on estimates of the market share attributable to each solvent and projected growth for the precision and electronics applications, provided by industry experts.

Emission Equations

Generally, the emissions model assumes that some portion of solvent use remains in the liquid phase and is not emitted as gas. Thus, emissions are considered “incomplete,” and are set as a fraction of the amount of solvent consumed in a year. For solvent applications, a fixed percentage of the new chemical used in equipment is assumed emitted in that year with the remainder of the used solvent reused or disposed without being released to the atmosphere. The following equation calculates emissions from solvent applications:

$$E_j = L * Qc_j$$

Where:

E_j = *Emissions*. Total emissions of a specific chemical in a given year j from use in solvent applications, by weight.

L = *Percent Leakage*. The percentage of the total chemical that is lost to the atmosphere, assumed to be 90 percent.

Qc_j = *Quantity of Chemical*. Total quantity of a specific chemical sold for use in solvent applications in the given year j , by weight.

j = *Year of emissions*.

Many solvent users have retrofitted their equipment by adding emission control features that have successfully demonstrated proper solvent conservation and resulted in an overall lower solvent consumption. Eventually, nearly all of the solvent consumed in a given year is emitted, as the solvent is continuously reused through a distilling and cleaning process or through recycling, while a small amount of solvent is disposed with the sludge that remains. The model used for this analysis assumes that 90 percent of the solvent consumed annually is emitted to the atmosphere.

Regional Variations/Adjustments

The following adjustment factor assumptions, specific to the solvent sector, were used to customize the global emissions estimating methodology, described above, for solvents:

- PFC/PFPE solvents are assumed to be used only in the United States. Therefore, U.S. emissions estimated for these compounds were removed prior to calculating ratios for other countries.
- Emissions in EU-15 countries are assumed to equal only 80 percent of the preliminary estimate developed using the ratio methodology defined in Appendix A, to reflect that NIK technology has taken a more significant market share in European countries (ECCP, 2001). Consequently, the resulting EU-15 emission estimate was reduced by 20 percent.
- A 50 percent adjustment factor was applied to Countries with Economies in Transition (CEIT), European countries that are not members of EU-15, and developing (Non-Annex I) countries. For these countries, the primary barriers to the transition from ODS solvents to fluorinated solvents has been the high cost of HFC-4310mee and lack of domestic production (UNEP, 1999a; UNEP, 1999b).

5.2.2 Baseline Emissions

Table 5-2 displays total HFC and PFC emission estimates for the solvent sector. In the United States, HFC-4310mee is responsible for the majority of the country’s projected ODS substitute solvent emissions while PFC/PFPE emissions are assumed to decline linearly until they are phased out completely in 2025.

U.S. emissions reflect the continued decline of PFC/PFPE consumption as a result of restrictions, enforced by the U.S. EPA’s Significant New Alternatives Policy program, that limit PFC and PFPE use to those applications where these solvents have been deemed necessary to meet performance or safety requirements. U.S. solvent end-users that have historically used PFC/PFPEs are turning to other solvents, including HFC-4310mee.

Baseline emissions for countries other than the United States do not contain PFCs; rather, the baseline solvent emissions from these countries are entirely composed of HFCs.

Table 5-2: Baseline HFC and PFC Emission Estimates from Solvents (MMTCE)

Region	2005	2010	2015	2020
United States	0.45	0.49	0.52	0.57
Non-U.S. Annex I	0.56	0.57	0.57	0.58
Non-Annex I	0.06	0.09	0.10	0.12
Total	1.07	1.14	1.20	1.26

Note: Totals may not sum due to independent rounding.

5.3 Cost of HFC and PFC Emission Reductions for Solvents

This section presents a cost analysis for achieving HFC and PFC emission reductions from the emission baselines presented in Table 5-2 above. All cost analyses for the solvent emission reduction options assume a 10-year project lifetime. Each abatement option is described below.

5.3.1 Description and Cost Analysis of Abatement Options

Some HFC and PFC emissions from the solvent sector can be eliminated or mitigated through several technologies and practices. The emissions and uses of these compounds can be reduced by retrofitting equipment and improving containment of the solvents, introducing carbon adsorption technologies, and replacing outdated equipment with more modern technologies. Additionally, NIK technologies and processes already used in many solvent markets world-wide employ semi-aqueous, aqueous, or no-clean methods in place of solvents. Ongoing research continues to identify low-GWP alternatives, including low-GWP HFCs and hydrofluoroethers (HFEs) that could replace high-GWP PFCs and HFCs. Some alternative solvent cleaning approaches use other organic solvents including chlorinated solvents, alcohols, petroleum distillates, and aliphatic solvents.

Three potential mitigation options are identified and analyzed in this report. These are:

- Conversion to HFE solvents;
- Improved equipment and cleaning processes using existing solvents (Retrofit); and
- Aqueous and semi-aqueous NIK replacement alternatives.

Because limited technical and cost information is available on fire suppression equipment, explosion proof wiring, and other workplace controls, flammable organic solvent alternatives, such as ketones, ethers, and alcohols—which can potentially replace HFCs and PFCs—are not addressed in this analysis.

The remainder of Section 5.3 describes each of these options in detail, and provides a discussion of associated cost and emission reduction estimates.

Conversion to HFE Solvents

HFC and PFC solvents can be replaced by alternative organic solvents with lower GWPs that are making headway in the market. These alternative solvents include low-GWP HFCs and HFEs, hydrocarbons, alcohols, volatile methyl siloxanes, brominated solvents, and non-ODS chlorinated solvents. For the purpose of this analysis, commercially available HFE-7100 and HFE-7200 are used as proxies for the alternative solvents abatement option because they display materials compatibility properties similar to HFCs and PFCs, a prime factor that has led to their current success in the market. Specifically, HFEs have replaced PFCs, CFC-113, 1,1,1-trichloroethane, HFCs, and HCFCs in certain precision cleaning operations. Many solvent users have successfully transitioned from PFC solvents to HFC-4310mee and HFEs in cleaning applications such as computer disk lubrication, particulate cleaning, and in cleaning electronic assemblies after soldering. HFEs and azeotropes of HFEs are also viable substitute replacements for HFC-4310mee in certain precision and electronics cleaning operations.

Because PFCs are specific to a small portion of the U.S. market only, and they are likely more expensive than HFCs, costs for this analysis are calculated based on a transition from HFC-4310mee to HFEs, rather than from PFCs to HFEs. PFC solvent users in the United States that apply this option may therefore experience a cost savings.

The average GWP of the alternative solvents is 222.5 (HFE-7100 has a GWP of 390 and HFE-7200 has a GWP of 55), compared to the HFC-4310mee GWP of 1300.⁵⁷ Due to the lower average GWP, this option has a reduction efficiency of 82.9 percent (i.e., the difference of the GWPs divided by the GWP of HFC-4310mee). This analysis assumes that the technical applicability⁵⁸ of this option is 100 percent of total solvent emissions for each region (see Table 5-4).

HFE solvents are gaining acceptance in U.S. industry due to their availability, safety, and effectiveness (Salerno, 2001); however, some uncertainty exists regarding the likelihood and ease with which HFC-4310mee users will convert to an HFE alternative solvent because of application-specific requirements (UNEP, 1999b). The incremental maximum market penetration of this option in the United States is assumed to increase from 10 percent in 2005 to 60 percent in 2020, which addresses all PFC solvent emissions and more than half of the HFC solvent emissions in the United States, as shown in Table 5-4.

For all other countries, the incremental maximum market penetration is assumed to increase from 5 percent in 2005 to 25 percent in 2020, representing a slower adoption of this option and less reliance on the use of fluorinated compounds compared to the assumed scenario for the United States (see Table 5-4). This assumption is based on current market data that indicates that HFE solvents are available and being used in the same regions where HFC solvents are being used (3M Performance Materials, 2003).

⁵⁷ Although the GWP value for HFC-4310mee was taken from the *IPCC Second Assessment Report* (1996), that report did not provide GWP values for either HFE; consequently this analysis uses the GWP values listed in the *IPCC Third Assessment Report* (2001) for both HFEs. The GWPs of HFEs are still being studied; for instance, some analyses show the GWP of HFE-7100 to be approximately 300 (3M Performance Materials, 2003).

⁵⁸ In this report, the term *technically applicable* refers to the emissions to which an option can be applied. Because HFEs can be substituted for both HFCs and PFCs, they are technically applicable to all HFC and PFC solvent emissions. Other factors will affect their application and the market penetration assumed in this analysis. See Appendix I for a glossary of terminology.

Cost and Emission Reduction Analysis

The following bullets describe the cost and emission inputs used to derive the final \$/TCE for converting to an HFE solvent, the results of which are presented in Section 5.4:

- **One-time Costs.** HFE solvents are very similar to HFC-4310mee in their key chemical properties such that existing equipment designed with low emission features can still be used. Although the need for minor adjustments, such as resetting the heat balance of the equipment, might arise, these modifications are not likely to amount to a substantial one-time cost (ICF Consulting, 2003; 3M Performance Materials, 2003). This analysis therefore assumes no one-time costs for converting to an HFE solvent.
- **Annual Costs.** According to industry experts, HFE solvents have roughly equal pricing structures compared to HFCs (3M Performance Materials, 2003). Therefore, this analysis assumes no annual costs are incurred when transitioning to an HFE solvent.
- **Cost Savings.** Currently, this analysis does not assume a cost savings. A net cost savings may occasionally be experienced by end-users that choose HFE solvents that are lower in density relative to HFC-4310mee. For example, since the same volume of solvent is used and solvents are sold on a mass basis, formulations blended with HFE-7200 may be lower in cost relative to formulations containing HFC-4310mee (3M Performance Materials, 2003). Long-term savings may be realized when this option is combined with retrofitting the equipment, consequently reducing the costs per item cleaned. These potential cost savings are not analyzed here.
- **Emission Reductions.** For the purpose of this analysis, a one to one mass ratio between HFC-4310mee to an HFE alternative solvent is assumed. Therefore, for every one kilogram of HFC-4310mee avoided, the use of HFE solvents is estimated to reduce emissions by 0.29 metric tons of carbon equivalent (TCE) (i.e., 1 kg or 0.001 metric tons of solvent, multiplied by the difference in GWPs and the conversion factor of carbon to carbon dioxide equivalents of 12/44).

Improved Equipment and Cleaning Processes Using Existing Solvents (Retrofit)

HFC and PFC prices are much higher than those of historically used solvents, such as CFC-113 and HCFC-141b. Attempts to reduce emissions, and hence save costs, have led to significant improvements in the containment technology of degreasing, defluxing, and other cleaning equipment. Engineering controls (such as increasing freeboard height, installing freeboard chillers, and using automatic hoists), improved containment, and other abatement technologies can reduce emissions of HFCs and PFCs used in solvent cleaning (UNEP, 1999a; ICF Consulting, 1992). For example, some cleaning equipment that uses HFC solvents is being retrofitted with higher freeboard height and low-temperature secondary cooling coils. Likewise, it is possible to reduce emissions to a minimal level by implementing good handling practices, such as reducing drag-out losses of solvent from systems by keeping the workload in the vapor zone long enough to drain and dry any entrapped or remaining solvent (UNEP, 1999a; Petroform, 2000). It is also possible to minimize evaporative losses by improving the design of solvent bath enclosures and of vapor recovery condensing systems (March Consulting Group, 1998 and 1999).

As shown in Table 5-3, retrofitting a vapor degreaser with an open-top area of 13 square feet, combined with proper operation and maintenance, can reduce emissions from a solvent process by as much as 46 to 70 percent, depending on the specific retrofit methods chosen (Durkee, 1997). For example, installing a freeboard refrigeration device, sometimes referred to as a chiller (a set of secondary coils mounted in the freeboard), and maintaining a freeboard ratio of 1.0 (to minimize diffusional solvent losses) can reduce emissions by 46 percent, while installing heating coils to produce superheated vapor along with installing a chiller can reduce emissions by 70 percent. For the purpose of this analysis, the reduction efficiency of

the retrofit option is assumed to equal 70 percent, which can be achieved at a one-time cost of \$18,000 dollars (see Table 5-3).

Table 5-3: Retrofit Techniques for Batch Vapor Cleaning Machine (Less than 13 Square Feet)

Retrofit Technique	Reduction Efficiency	One-Time Cost
Freeboard Ratio of 1.0, Freeboard Refrigeration Device	46%	\$12,000
Working Mode Cover, Freeboard Refrigeration Device	64%	\$17,000
Superheated Vapor, Freeboard Refrigeration Device	70%	\$18,000

Source: Durkee, 1997.

For vapor degreasing machines that are larger than 13 square feet, the cost to retrofit increases; however, the emission reduction efficiencies achieved are as high as 85 percent. Furthermore, for larger operations where there is more than one vapor degreaser, retrofit methods, such as installing a carbon adsorber, can be implemented to capture solvent vapor from the air for the entire facility. The reduction efficiency of a carbon adsorber combined with installing heating coils and chillers has been estimated at 88 percent for larger (i.e., greater than 13 square feet) vapor degreasers (Durkee, 1997).

In the United States, many enterprises have bought new equipment or retrofitted aging equipment to be in compliance with the National Emissions Standard for Hazardous Air Pollutants (NESHAP), which limits emissions from degreasers using traditional chlorinated solvents such as trichloroethylene. Fluorinated solvents such as HFCs are not covered by this regulation; but, nonetheless, a number of companies using HFCs and other non-chlorinated solvents have adopted NESHAP-compliant solvent cleaning machines because of the economic, occupational, and environmental benefits associated with NESHAP specifications (Durkee, 1997). Although solvent users are likely to perform regularly scheduled maintenance and good handling practices to ensure the quality and lifetime of their investment, previously retrofitted or new equipment is assumed to already have a combination of emission reduction features that retrofitting offers, such as those techniques listed above. Consequently, end users in the United States are not expected to benefit from this option in the future. Thus, this analysis assumes that the incremental maximum market penetration will drop from 5 percent in 2005 to zero in 2010 through 2020 (i.e., by 2010 and beyond, the solvent equipment in use will either already have been retrofitted or will not require retrofitting, and the resulting lower emissions are already incorporated into the baseline). The resulting maximum market penetrations are shown in Table 5-4.

Likewise, many countries in Europe have imposed stringent environmental and safety regulations that require the lowest level of emissions attainable by solvent degreasing equipment. Retrofit techniques were either already implemented or simply not required if the user had purchased new emission-tight vapor degreasers. Therefore, for Non-U.S. Annex I countries, the maximum market penetration for this option is also assumed to be 5 percent in 2005 dropping to zero by 2010.

This analysis assumes that most solvent users in Non-Annex I (developing) countries may consider the equipment retrofit option, as updating their equipment may be preferred over investing in entirely new units. Consequently, this region is assumed to slowly adopt these techniques such that in 2005, 5 percent of the market adopts this option, increasing at a slow, steady rate to 15 percent in 2020 (see Table 5-4).

Cost and Emission Reduction Analysis

The following bullets describe the cost and emission inputs used to derive the final \$/TCE for the retrofit option, the results of which are presented in Section 5.4:

- **One-time Costs.** The costs of retrofitting modern or high quality batch cleaning equipment ranges from \$12,000 to \$18,000 for small units to approximately \$20,000 or more for larger units.

To be conservative, this report assumes that an \$18,000 investment is required to implement a retrofit on a vapor degreaser with an open-top area 13 square feet in size (Durkee, 1997).

- **Annual Costs.** This analysis assumes no annual labor costs. However, good handling practices, such as employee training and regular maintenance to reduce the risk of leaks, are encouraged on equipment that is retrofitted, and would likely lead to an increase in operating costs (UNEP, 2003).
- **Cost Savings.** According to experts, HFC users that retrofit their equipment will most likely experience a drop in solvent costs per operating hour. The cost savings will depend on the size of the cleaner and the specific solvent conservation features installed. To account for cost savings in the model, the estimated cost of HFC-4310mee (\$48.00 per kilogram) was used to represent the value of the solvent per kilogram saved through retrofitting (ICF Consulting, 2003). The example from Durkee (1997) that reports the emission reduction of 70 percent estimates that 4,898.4 pounds, or 2,221.9 kg, of solvent were still being emitted from the retrofitted cleaner. Thus, it is estimated that 5,184 kilograms (i.e., 2,221.9 kg divided by 30% yields the total cleaner's mass of 7,406.3 kg; a reduction of 70% is thus equal to 5,184 kg) of solvent per year can be avoided for a 13 square foot unit. This savings equates to close to \$250,000 per year. Hence, investments in retrofit options frequently provide a profitable return for the end-user.
- **Emission Reductions.** Assuming a retrofit on a vapor degreaser with an open-top area 13 square feet in size, annual emissions avoided are estimated to be 5,184 kilograms of HFC-4310mee (Durkee, 1997), or 1,838 TCE (i.e., 5.184 metric tons HFC avoided, multiplied by the GWP of 1300 and the conversion factor of carbon to carbon dioxide equivalents of 12/44). The Durkee (1997) data used for this analysis are consistent with industry experience. For example, one anonymous user reduced annual emissions usage by close to 3,500 kilograms after retrofitting two of their solvent cleaners of 27 and 42 gallon capacities (roughly equivalent to vapor degreasers with an open-top area 5 to 7 square feet in size) (Ultrasonics, 2002).

Aqueous and Semi-Aqueous Not-In-Kind (NIK) Replacement Alternatives

In addition to the emission reduction approaches that use a combination of improved equipment and cleaning practices, NIK technology processes and solvent replacements can be used to substitute for PFC- and HFC-containing systems. In the aqueous process, a water-based cleaning solution is used as the primary solvent and is usually combined with a detergent to remove contaminants. In the semi-aqueous process, the cleaning solution is an organic solvent that is blended with a surfactant, making it water-soluble. An example of a solvent/surfactant blend would be a terpene/water combination blended with glycol ethers (UNEP, 1999a). The reduction efficiency of NIK abatement options is assumed to be 100 percent, since the HFC is completely replaced by water and an organic solvent, combinations of which have low to no global warming potential.

Many enterprises in the electronics, metal, and precision cleaning end-uses have already switched to aqueous and semi-aqueous NIK cleaning methods. Both NIK processes have proven very successful for large-scale metal cleaning where equipment and wastewater treatment costs are less of a concern due to the large volumes processed (UNEP, 1999a). Aqueous cleaning technologies have been available and widely used for over 25 years and have replaced many electronics cleaning solvent systems in developed countries (Chaneski, 1997; UNEP, 1999a). Semi-aqueous cleaning has also been available for years as a popular option; however, it has since lost much of its initial promise in many developed nations for the cleaning of electronic assemblies due to the expenses associated with the technology (UNEP, 1999a).

Because the NIK options are applicable to both the electronic and precision cleaning end-uses, the NIK options are assumed to be applicable to 100 percent of HFC solvent emissions, resulting in a technical

applicability of 100 percent, for all regions except for the United States, where the technical applicability is equivalent to the percent of HFC emissions out of total solvent emissions (see Table 5-4).

Technical limitations in the use of NIK technologies arising from issues such as substrate corrosion, or inadequate performance for applications with complex parts, can lead to reduced market acceptability. The U.S. incremental maximum market penetrations for these options are assumed to be smaller than in other regions to reflect that the U.S. market will likely prefer fluorinated solvents such as HFCs and HFEs (see Table 5-4), and because a large percentage of the operations that can use aqueous and semi-aqueous technologies already are doing so. For Non-U.S. Annex I and Non-Annex I regions, the maximum market penetrations of these two NIK options are assumed to be similar to one-another from 2005 to 2020. NIK alternatives are currently gaining market share in European countries, a trend that is assumed to continue for this region (ECCP, 2001).

NIK technologies also are assumed to be preferred by some developing countries because of their perceived low costs. For instance, aqueous cleaning is popular in China because of the very small cost per kilogram of the non-fluorinated cleaning chemicals used, despite the high costs per unit cleaned that result from newly introduced costs such as wastewater treatment. Conversely, the availability of water, the costs associated with energy to dry the product, and local wastewater treatment regulations can discourage companies in developing regions of the world from considering this option (UNEP, 2003). For all regions, the semi-aqueous option is assumed to have slightly smaller market penetrations relative to the aqueous cleaning option.

Cost and Emission Reduction Analysis

The following bullets describe the cost and emission inputs used to derive the final \$/TCE for the aqueous and semi-aqueous cleaning options, the results of which are presented in Section 5.4:

- **One-time Costs.** This cost analysis assumes that the incremental investment required to convert to a typical NIK process is approximately \$67,000 for aqueous cleaning and \$8,000 for semi-aqueous cleaning (ICF Consulting, 1992).⁵⁹
- **Annual Costs.** Annual increased operating costs are dependent on a variety of factors, including the cost of aqueous cleaning chemicals, electricity and/or other utilities, and the specific parts being cleaned. In general, the drying process is more energy-intensive for aqueous processes. Similarly, wastewater treatment and effluent monitoring can add to the cost of aqueous processes. In addition, as the geometry of the parts increases in complexity (i.e., blind holes or other cleaning agent entrapment sites), so too does the drying operation, which in turn leads to increased costs. Because cost savings have yet to be quantified for this analysis, which may offset increased operating costs, this analysis does not assume annual costs for this option; however, future work could be performed to investigate annual costs and cost savings realized.
- **Cost Savings.** Due to the potential complexity of the process, this report assumes no cost savings for NIK technologies; however, many companies that have installed NIK systems have realized long-term cost savings because annual solvent expenditures are significantly reduced (Chaneski, 1997).
- **Emission Reductions.** This analysis assumes that when converting to either NIK process, annual emissions avoided for a standard unit are 3,494 kilograms (ICF Consulting, 1992). Assuming the HFC avoided is HFC-4310mee, this reduction equates to 1,239 TCE for both semi-aqueous and aqueous cleaning.

⁵⁹ Costs taken from the 1992 study were updated to 2000 dollars.

5.3.2 Summary of Technical Applicability and Market Penetration of Abatement Options

Table 5-4 summarizes the technical applicability and the maximum market penetration of the solvent options presented in the discussions above. By 2020, it is assumed that these options can be applied to 75 percent of the baseline solvent emissions in the United States, 55 percent of the baseline solvent emissions in the Annex I countries, and 70 percent of the baseline solvent emissions in Non-Annex I countries.

Table 5-4: Technical Applicability and Incremental Maximum Market Penetration of Solvent Options (Percent)^a

Option	Technical Applicability (All Years)			2005			2010			2015			2020		
	US	Non-US Annex I	Non-Annex I	US	Non-US Annex I	Non-Annex I	US	Non-US Annex I	Non-Annex I	US	Non-US Annex I	Non-Annex I	US	Non-US Annex I	Non-Annex I
Conversion to HFE Solvents	100	100	100	10	5	5	30	10	10	45	15	15	60	25	25
Retrofit	90-98 ^b	100	100	5	5	5	0	0	8	0	0	12	0	0	15
NIK Replacements	-	-	-	4	8	8	8	15	15	12	23	23	15	30	30
<i>Semi-Aqueous</i>	<i>90-98</i>	<i>100</i>	<i>100</i>	<i>1</i>	<i>3</i>	<i>3</i>	<i>3</i>	<i>5</i>	<i>5</i>	<i>4</i>	<i>8</i>	<i>8</i>	<i>5</i>	<i>10</i>	<i>10</i>
<i>Aqueous</i>	<i>90-98</i>	<i>100</i>	<i>100</i>	<i>3</i>	<i>5</i>	<i>5</i>	<i>5</i>	<i>10</i>	<i>10</i>	<i>8</i>	<i>15</i>	<i>15</i>	<i>10</i>	<i>20</i>	<i>20</i>

^aAssumed maximum market penetration of options is presented as a percentage of total sector emissions for which the options are technically applicable. The baseline market penetration is assumed to be zero to assess the emission reductions possible due to increased use of each option.

^bThe percent of total emissions represented by HFCs varies by year. The technical applicability is 90 percent in 2005, 93 percent in 2010, 96 percent in 2015, and 98 percent in 2020.

To calculate the percent of emission reductions off the total solvent baseline for each abatement option, the technical applicability (Table 5-4) is multiplied by the market penetration value (Table 5-4), and by the reduction efficiency of the option. For example, to determine the percent reduction off the 2020 baseline for the conversion to HFE solvents in the United States, the following calculation is performed:

$$\text{Technical Applicability} \times \text{Market Penetration in 2020} \times \text{Reduction Efficiency} =$$

$$100\% \times 60\% \times 82.9\% \approx 49.7\%$$

Thus, using the assumptions in this analysis, converting to an HFE solvent could reduce approximately 50 percent of the U.S. emissions baseline in 2020. This figure, along with the other emission reduction potentials, is shown in Table 5-5.

Table 5-5: Emission Reductions off the Total Solvent Baseline (Percent)

Option	2005			2010			2015			2020		
	US	Non-US Annex I	Non-Annex I	US	Non-US Annex I	Non-Annex I	US	Non-US Annex I	Non-Annex I	US	Non-US Annex I	Non-Annex I
Conversion to HFE Solvents	8.3	4.1	4.1	24.9	8.3	8.3	37.3	12.4	12.4	49.7	20.7	20.7
Retrofit	3.5	3.5	3.5	0.0	0.0	5.6	0.0	0.0	8.4	0.0	0.0	10.5
NIK Replacements	3.8	7.5	7.5	7.5	15.0	15.0	11.3	22.5	22.5	15.0	30.0	30.0
<i>Semi-Aqueous</i>	1.3	2.5	2.5	2.5	5.0	5.0	3.8	7.5	7.5	5.0	10.0	10.0
<i>Aqueous</i>	2.5	5.0	5.0	5.0	10.0	10.0	7.5	15.0	15.0	10.0	20.0	20.0

5.4 Results

Table 5-6 through Table 5-8 provide a summary of the potential emission reduction opportunities and associated costs for the United States, Non-U.S. Annex I countries, and Non-Annex I countries for 2020. The costs to reduce one ton of carbon equivalent (TCE) data are presented for two different discount rate scenarios: 4 percent and 20 percent. The tax rate associated with each cost scenario is 0 percent and 40 percent, respectively. The results are ordered by increasing costs per TCE; also presented are the emissions reduced by the option, in MMTCE and percent of the regional solvents baseline, and cumulative totals of these two figures.

Table 5-6: United States Emission Reductions in 2020 and Break-Even Costs for Solvents

Reduction Option	Break-Even Cost (2000\$/TCE)		Emission Reduction of Option (MMTCE)	Percent Reduction from 2020 Baseline	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
	Discount Rate/Tax Rate					
	4% / 0%	20% / 40%				
Retrofit	(\$134.18)	(\$132.14)	0.00	0.0%	0.00	0.0%
HFC to HFE	\$0.00	\$0.00	0.28	49.7%	0.28	49.7%
NIK Semi-Aqueous	\$0.80	\$2.14	0.03	5.0%	0.31	54.7%
NIK Aqueous	\$6.67	\$17.89	0.06	10.0%	0.37	64.7%

Table 5-7: Non-U.S. Annex I Emission Reductions in 2020 and Break-Even Costs for Solvents

Reduction Option	Break-Even Cost (2000\$/TCE)		Emission Reduction of Option (MMTCE)	Percent Reduction from 2020 Baseline	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
	Discount Rate/Tax Rate					
	4% / 0%	20% / 40%				
Retrofit	(\$134.18)	(\$132.14)	0.00	0.0%	0.00	0.0%
HFC to HFE	\$0.00	\$0.00	0.12	20.7%	0.12	20.7%
NIK Semi-Aqueous	\$0.80	\$2.14	0.06	10.0%	0.18	30.7%
NIK Aqueous	\$6.67	\$17.89	0.12	20.0%	0.29	50.7%

Table 5-8: Non Annex I Emission Reductions in 2020 and Break-Even Costs for Solvents

Reduction Option	Break-Even Cost (2000\$/TCE)		Emission Reduction of Option (MMTCE)	Percent Reduction from 2020 Baseline	Cumulative Reductions (MMTCE)	Cumulative % Reduction from 2020 Baseline
	Discount Rate/Tax Rate					
	4% / 0%	20% / 40%				
Retrofit	(\$134.18)	(\$132.14)	0.01	10.5%	0.01	10.5%
HFC to HFE	\$0.00	\$0.00	0.02	20.7%	0.04	31.2%
NIK Semi-Aqueous	\$0.80	\$2.14	0.01	10.0%	0.05	41.2%
NIK Aqueous	\$6.67	\$17.89	0.02	20.0%	0.07	61.2%

5.5 Summary

Baseline global HFC and PFC emissions from solvents are estimated to grow from 1.07 to 1.26 MMTCE between the years 2005 and 2020. In 2020, U.S. emissions are assumed to account for approximately 45 percent of this total, while Non-U.S. Annex I and Non-Annex I countries are assumed to account for approximately 46 percent and 9 percent, respectively. The highest absolute emissions growth, from 0.45 MMTCE in 2005 to 0.57 MMTCE in 2020, is expected to occur in the United States. In relative terms, however, the largest percent growth occurs in Non-Annex I countries from 0.06 to 0.12 MMTCE, an increase of 100 percent.

This analysis considers three emissions mitigation options for solvent use: 1) adoption of alternative (HFE-7100 or HFE-7200) partially fluorinated solvents; 2) improved system design through retrofitting solvent processes; and 3) conversion to NIK (aqueous and semi-aqueous replacements). The costs and emission reduction benefits of each option were compared in each region. For all regions, retrofitting represents the most cost-effective option for reducing HFC emissions from the solvent sector with a cost savings of \$134.18 dollars per TCE at a 4 percent discount rate and zero percent tax rate, though by 2020 this option is assumed to be fully implemented in the baseline in all Annex I countries. Converting to an HFE solvent is a cost-neutral option for all regions. Costs per TCE for the three regions are equivalent because available data on costs for abatement technologies were not scaled to reflect potential differences in the costs internationally. Actual costs for abatement options for specific countries may vary and subsequently affect these estimates. Additional research is required to determine actual variability in costs across regions.

In terms of greatest emission reductions, converting to alternative solvents represents the greatest opportunity in the United States. NIK aqueous technology and alternative solvents equally represent the greatest emission reduction opportunities for both Non-U.S. Annex I and Non-Annex I countries. By 2020, 0.73 MMTCE, or 58 percent of global baseline emissions from solvents, can be reduced at a cost under \$20/TCE.

5.6 References

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