Modeling Emissions of High Global Warming Potential Gases

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ABSTRACT

The United States and other countries model the emissions of hyrdofluorocarbons (HFCs) and perfluorocarbons (PFCs) used as substitutes for chemicals that deplete the stratospheric ozone layer. This modeling is performed in part to fulfill commitments made under the United Nations Framework Convention on Climate Change (UNFCCC). HFCs and PFCs are two classes of greenhouse gases (GHGs) identified in a variety of GHG emissions accounting (inventory) schemes as well as within international treaties designed to limit emissions of GHGs. Although only a small percentage of the total emissions of greenhouse gases, HFCs and PFCs are of concern due to their long atmospheric lifetimes, high global warming potentials, and importance to a wide variety of industries. Furthermore, as the production of ozone-depleting substances (ODSs) is phased out, internationally under the *Montreal Protocol* and in the U.S. under Clean Air Act Amendments of 1990, emissions of HFCs and PFCs are expected to grow significantly.

Emissions of HFCs and PFCs as substitutes to ODSs come from numerous sources, including the following industrial sectors: refrigeration and air-conditioning equipment, solvent cleaning, the manufacturing and use of foam products, aerosol propellants, fire extinguishing, and sterilization. For each sector, a separate methodology is applied to model emissions from a variety of end-use sources.

The authors will present the methodology used by the U.S. Environmental Protection Agency in determining historical and projected annual emissions of HFCs and PFCs. The authors will also review the methodologies employed in different industrial sectors and what data is required to accurately estimate emissions. Techniques for correlating results from “bottom-up” modeling with “top-down” information will be discussed. Finally, the authors will offer suggestions on how the methodology can be applied to determine emissions regionally within the U.S. and for other countries.

INTRODUCTION

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are used as alternatives to several classes of ozone-depleting substances (ODSs) that are being phased out under the terms of the *Montreal Protocol* and specifically in the United States under the Clean Air Act Amendments of 1990. These ozone depleting substances—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—are used in a variety of industrial applications, including refrigeration and air conditioning equipment, solvent cleaning, foam production, sterilization, fire extinguishing, and aerosols. Although HFCs and PFCs, unlike ODSs, are not harmful to the stratospheric ozone layer, many of them are potent greenhouse gases with global warming potentials (GWPs) ranging from 140 to 11,700. GWP is a ratio of the warming caused by a substance to the warming caused by a similar mass of carbon dioxide, whose GWP is defined as 1.

The U.S. EPA's Vintaging Model was developed as a tool for estimating the annual chemical emissions from industrial sectors that have historically used ODSs in their products. These industrial sectors have gradually transitioned to more ozone-friendly chemicals; thus domestic production and consumption of ODSs has decreased. As these industries have transitioned, the Vintaging Model has evolved into a tool for estimating the rise in consumption and emissions of these alternatives, as well as the decline of ODSs. This paper provides a brief overview of the model, followed by the equations used to estimate emissions from each sector and some of the specific inputs used. Additionally, this paper presents the results of the Vintaging Model that are used for the U.S. national inventory report and other possible applications, such as State-level emissions, international emissions, and emission projections at all levels. The Vintaging Model can also serve as an example for others wanting to estimate emissions from these fast-growing sectors, by providing the emission estimating equations as well as sample input parameters for use in specific sectors.

The model name refers to the fact that it tracks the use and emissions of annual "vintages" of equipment that enter service or are disposed in each of several end-uses that make up an industrial sector. The Vintaging Model is a "bottom-up" model. Information is collected regarding the annual market size, growth, amount of the chemical required by each unit of equipment, and substitute history. As ODSs are phased out, a percentage of the market share originally filled by the ODSs is allocated to each of its substitutes. Emissions for each end-use are estimated by applying annual emission profiles to each vintage of equipment. For the purpose of projecting the use and emissions of chemicals into the future, the available information about probable evolutions of the end-use markets can be incorporated into the model. By aggregating the output for more than 40 different end-uses, the model produces estimates and projections of annual use and emissions of each chemical.

Alternatively, "top-down" information on total U.S. consumption of a given chemical is sometimes available. These data can be used by estimating the fraction of each chemical that is consumed within each end-use. These allocation schemes are guided by EPA's synthesis of the data available through the variety sources listed below. Additionally, top-down data is used periodically as a quality assurance procedure to determine if market assumptions in the Vintaging Model are correct.

The Vintaging Model synthesizes data from a variety of sources, including data from the ODS Tracking System maintained by the EPA Global Programs Division and information from submissions to EPA under the Significant New Alternatives Policy (SNAP) program. Published sources include documents prepared by the United Nations Environment Programme (UNEP) Technical Options Committees, reports from the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), and proceedings from the International Conferences on Ozone Protection Technologies and Earth Technologies Forum. EPA also coordinates extensively with numerous trade associations and individual companies. For example, the Alliance for Responsible Atmospheric Policy, the Air-Conditioning and Refrigeration Institute, the Association of Home Appliance Manufacturers, the American Automobile Manufacturers Association, and many of their member companies, have provided valuable information over the years. In some instances the unpublished information that the EPA uses in the model is classified as Confidential Business Information (CBI). The annual emissions inventories of chemicals are aggregated in such a way that CBI cannot be inferred. Full public disclosure of the inputs to the Vintaging Model would jeopardize the security of the CBI that has been entrusted to the EPA.

The following section demonstrates the emission estimating equations in use for each sector, and provides sample input directly from the current version of the model. Each sector is modeled separately. Emission and consumption output are generated both disaggregated (by gas or by end use) and aggregated (by year, by sector, and/or total GWP-weighted emissions).

METHODOLOGY

The methodology used by the Vintaging Model to calculate emissions varies by end-use sector. The methodologies, specific equations, and input ranges used by end-use sector are summarized below.

Refrigeration and Air-Conditioning

Refrigeration and air-conditioning are familiar and pervasive technologies in the U.S., from home refrigerators and residential air conditioning systems, to long aisles of dairy products and frozen food in supermarkets. ODSs, being replaced mainly by HFCs, are used as refrigerants in these systems to remove heat from the area being cooled and transfer it to the outside. Although systems are designed to continuously circulate the refrigerant, leaks in pipes, valves, fittings, etc. lead to emissions. Also, although U.S. regulations forbid emitting HFCs during servicing, some emissions do occur. Finally, when a product is thrown away, any refrigerant not recovered before disposal is emitted to the atmosphere.

Refrigeration and air-conditioning is by far the largest sector of the Montreal Protocol industries, accounting for nearly 70 percent of all GWP-weighted emissions from ODS substitutes in 2001 (EPA 2003). The 24 end-uses examined by the Vintaging Model are listed in Table 1. The chemical names refer to the original ODS used for each equipment type, each of which transitioned to alternatives in a different manner, driven largely by the differences in cooling technology used. Emissions in this sector are estimated separately for losses during equipment lifetime, such as annual leakage and service losses, and disposal losses. As new technologies replace older ones, it is generally assumed that there are improvements in their leak, service, and disposal emission rates. In this sector, as in all sectors in the Vintaging Model, emissions are not calculated for the electricity generation required to run the equipment.

Table 1. Refrigeration and air-conditioning end-uses.

End-Use
Mobile Air Conditioners (CFC-12)
Chillers (CFC-11, CFC-12, R-500, HCFC-22, CFC-114)
Retail Food (CFC-12, HCFC-22, R-502)
Cold Storage (CFC-12, HCFC-22, R-502)
Transport Refrigeration (CFC-12, R-502)
Refrigerated Appliances (CFC-12)
Dehumidifiers (HCFC-22)
Industrial Process Refrigeration (CFC-11, CFC-12, HCFC-22)
Ice Makers (CFC-12)
Window Units (HCFC-22)
Residential Unitary Air Conditioners (HCFC-22)
Commercial Unitary Air Conditioners (HCFC-22)
Water and Ground-Source and Unitary Heat Pumps; Packaged Terminal Air Conditioners and Heat Pumps (HCFC-22)

Emissions from refrigeration and air-conditioning are calculated using three steps, first estimating annual emissions, second estimating emissions from disposal of the equipment, and third, summing the two to obtain total emissions.

Step 1: Calculate lifetime emissions

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

Equation (1) $Es_j = (l_a + l_s) \times \Sigma\, Qc_{j-i+1} \quad for\ i=1 \rightarrow k$

where

Es = Emissions from Equipment Serviced. Emissions in a given year from normal leakage and servicing (including recharging) of equipment.
l_a = Annual Leak Rate. Average annual leak rate during equipment operation (expressed as a percentage of total chemical charge).
l_s = Service Leak Rate. Average leakage during equipment servicing (expressed as a percentage of total chemical charge).
Qc = Quantity of Chemical in New Equipment. Total amount of a specific chemical used to charge new equipment in a given year, by weight.
k = Lifetime. The average lifetime of the equipment.

Step 2: Calculate disposal emissions

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:

Equation (2) $Ed_j = Qc_{j-k+1} \times [1 - (rm \times rc)]$

where

Ed = Emissions from Equipment Disposed. Emissions in a given year from the disposal of equipment.
Qc = Quantity of Chemical in New Equipment. Total amount of a specific chemical used to charge new equipment in a given year, 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)*)
k = Lifetime. The average lifetime of the equipment.

Step 3: Calculate total emissions

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

Equation (3) $E_j = Es_j + Ed_j$

where

E = Total Emissions. Emissions from refrigeration and air conditioning equipment in a given year.
Es = Emissions from Equipment Serviced. Emissions in a given year from normal leakage and servicing (recharging) of equipment.
Ed = Emissions from Equipment Disposed. Emissions in a given year from the disposal of equipment.

Leak and service rates for the refrigeration and air-conditioning sector are quite variable with equipment type. Table 2 provides ranges of the annual (leak plus service) emission rates, as well as the average lifetime for each equipment type assumed by the Vintaging Model. The Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance (2000) recommends refrigeration and air-conditioning disposal rates that vary by equipment type from 10 to 30 percent. The Vintaging Model currently estimates disposal rates higher than these recommended values, but is in the process of being updated to reflect the actual disposal rates in the United States.

Table 2. Example leak and disposal loss rates from refrigeration and air-conditioning equipment.

End Use	Annual Loss from Service + Leaks (%)*	Lifetime (Years)
Mobile Air Conditioners	10.8%	12
Chillers		
New Equipment	1 - 14	20 - 27
Existing Equipment	11 - 19.5	
Retail Food		
New Equipment	5 - 30	15 - 20
Existing Equipment	7 - 33	
Cold Storage		
New Equipment	12 - 25	20 - 25
Existing Equipment	22 - 29	
Industrial Process Refrigeration		
New Equipment	4 - 15	25
Existing Equipment	6 - 19	
Transport Refrigeration		
New Equipment	20 - 28	12
Existing Equipment	33	
Ice Makers and Ice Rinks	3 - 7	20
Refrigerated Appliances	<1	20
Residential Unitary A/C		
New Equipment	4 - 12	15
Existing Equipment	5	
Commercial Unitary A/C		
New Equipment	4 - 5	15
Existing Equipment	5	
Water & Ground Source Heat Pumps	2 - 3	20
PTAC/PTHP	2 - 3	12
Window Units	<1	15

Aerosols

ODSs, HFCs and many other chemicals are used as propellant aerosols. Pressurized within a container, a nozzle releases the chemical, which allows the product within the can to also be released. In the U.S., the use of ODSs in consumer aerosols was banned in 1977, and many products transitioned to "not-in-kind" technologies, such as solid deodorants and finger-pump hair sprays. For those items, including vital medical devices and specialty consumer products that use ODSs or HFCs as propellants, emissions occur when the product is used.

All HFCs used in aerosols are assumed to be emitted in the year of manufacture. Since there is currently no aerosol recycling, it is assumed that all of the annual production of aerosol propellants is released to the atmosphere. The aerosol sector is divided into four end-uses, three for metered dose inhalers, based on the original ODS propellant (CFC-11, CFC-12, or CFC-114), and one for all other consumer aerosol products. The following equation describes the emissions from the aerosols sector.

Equation (4) $E_j = Qc_j$

where

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

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

As discussed above, the assumptions for aerosols are much simpler than those for refrigeration and air-conditioning. The lifetime for all aerosols is one year, and 100 percent of the propellant is emitted during that time. The IPCC Good Practice Guidance (2000) recommends that lifetime of all aerosol products is assumed to be two years, with the 50 percent of emissions occurring in each year. The Vintaging Model aerosols sector is currently being updated to reflect this change.

Solvents

ODSs, HFCs, PFCs and other chemicals are used as solvents to clean items. For example, electronics may need to be cleaned after production to remove any manufacturing process oils or residues left. Solvents are applied by moving the item to be cleaned within a bath or stream of the solvent.

Some solvents are assumed to remain in the liquid phase and are therefore not emitted as a vapor. Thus, emissions are considered "incomplete," and are a fixed percentage of the amount of solvent consumed in a year. The remainder of the consumed solvent is assumed to be reused or disposed without being released to the atmosphere. Within the Vintaging Model, the solvent sector is comprised of four end-uses: electronics cleaning; metals cleaning; precision cleaning; and adhesives, coatings and inks. The following equation is used to calculate emissions from solvent applications.

Equation (5) $E_j = l \times Qc_j$

where

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

l = Percent Leakage. The percentage of the total chemical that is leaked to the atmosphere.

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

In the results shown in the following section of this report, the solvent lifetime was one year and emissions were estimated to be only 10 percent of total solvent usage. In reality, actual emissions may be much higher. Additionally, the IPCC (2000) recommends a two-year lifetime with an emission factor of 50 percent for each year, similar to aerosols. The solvent sector is currently undergoing industry review and updates to correct these assumptions.

Fire Extinguishing

ODSs, HFCs, PFCs and other chemicals are used as fire-extinguishing agents, in both hand-held "streaming" applications as well as in built-up "flooding" equipment similar to water sprinkler systems. Although these systems are generally leak-tight, some leaks do occur and of course emissions occur when the agent is released.

Total emissions from fire extinguishing are assumed, in aggregate, to equal a percentage of the total quantity of chemical in operation at a given time. For modeling purposes, it is assumed that fire extinguishing equipment leaks at a constant rate for an average equipment lifetime, as shown in the equation below. This percentage varies between the two end-uses that comprise this sector, streaming and flooding equipment.

Equation (6) $E_j = l \times \Sigma\, Qc_{j-i+1} \quad for\ i=1 \to k$

where

E = Emissions. Total emissions of a specific chemical in year j for fire extinguishing equipment, by weight.

l = Percent Leakage. The percentage of the total chemical in operation that is leaked to the atmosphere.

Qc = Quantity of Chemical. Total amount of a specific chemical used in new streaming fire extinguishing equipment in a given year, j, by weight.

k = Lifetime. The average lifetime of the equipment.

In the Vintaging Model, both streaming and flooding applications have a 15-year lifetime. In streaming systems, emissions are assumed to be 2 percent of all chemical in use in each year, while in flooding systems 1.5 percent of the installed base of chemical is assumed to leak annually.

Foam Blowing

ODSs, HFCs, and other chemicals are used to produce foams, including such items as the foam insulation panels around refrigerators, insulation sprayed on buildings, etc. The chemical is used to create pockets of gas within a substrate, increasing the insulating properties of the item.

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. 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. The emission profiles of the foam types estimating in the Vintaging Model are shown in Table 3. Emissions from the foam-blowing sector are calculated in two steps, one for each type of foam.

Step 1: Calculate emissions from open-cell foam

Emissions from open-cell foams are calculated using the following equation.

Equation (7) $E_j = Qc_j$

where

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

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

Step 2: Calculate emissions from closed-cell foam

Emissions from closed-cell foams are calculated using the following equation.

Equation (8) $E_j = \Sigma\, (ef_i \times Qc_{j-i+1}) \quad for\ i=1 \to k$

where

E = 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 ($1 \to k$). 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.

k = Lifetime. Average lifetime of foam product.

Table 3. Emission profile for the foam end-uses.

Foam End-Use	Loss at Manufacturing (%)	Annual Leakage Rate (%)	Leakage Lifetime (years)	Loss at Disposal (%)	Total
Flexible PU	100	0	0	0	100
Polyisocyanurate Boardstock	10	1.5	50	15	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	25	1.125	32	39	100
Polyolefin	95	2.5	2	0	100
XPS Sheet/Insulation Board	40	2	25	0	90
XPS Boardstock	25	2.5	30	0	100
PU Sandwich Panels	10	0.5	50	65	100

PU – Polyurethane
XPS – Extruded Polystyrene

Sterilization

Sterilization is used to control microorganisms and pathogens during the growing, collecting, storing and distribution of various foods including grains, vegetables and fruits. Currently, the Vintaging Model assumes that the sterilization sector has not transitioned to any HFC or PFC as an ODS substitute, however, the modeling methodology is provided below for completeness.

The sterilization sector is modeled as a single end-use. For sterilization applications, all chemicals that are used in the equipment in any given year are assumed to be emitted in that year, as shown in the following equation.

Equation (9) $E_j = Qc_j$

where

E = Emissions. Total emissions of a specific chemical in year j from use in sterilization equipment, by weight.

Qc = Quantity of Chemical. Total quantity of a specific chemical used in sterilization equipment in year j, by weight.

VINTAGING MODEL RESULTS FOR THE U.S. NATIONAL INVENTORY

By repeating these calculations for each year, the Vintaging Model creates annual profiles of use and emissions for ODSs and ODS substitutes. The results can be shown for each year in two ways: 1) on a chemical-by-chemical basis, summed across the end-uses, or 2) on an end-use basis. Values for use and emissions are calculated both in metric tons and in teragrams of carbon dioxide equivalents (Tg CO_2 Eq.). The conversion of metric tons of chemical to Tg CO_2 Eq. is accomplished through a linear scaling of tonnage by the global warming potential (GWP) of each chemical. Current emission estimates for the years 1990 and 1995-2001 for HFCs and PFCs used as substitutes for ODSs are provided in Table 4 and Table 5 and the time series of emissions from 1990 through 2001 is shown in Figure 1. The estimates presented in Table 4 and Table 5 are those generated for the *Inventory of U.S. Greenhouse Gas*

Emissions and Sinks: 1990-2001 (EPA 2003). Vintaging Model framework and outputs can also be utilized for emissions and projections at the state, national, or international levels. Some of these applications are discussed in the next section.

Table 4. U.S. emissions of HFCs and PFCs from ODS substitution (Tg CO_2 Eq.).

Gas	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
HFC-23	+	0.1	0.1	0.2	0.2	0.3	0.4	0.5
HFC-32	+	+	+	+	+	+	0.1	0.2
HFC-125	+	1.3	1.9	2.5	3.1	3.6	4.4	5.2
HFC-134a	0.7	15.9	21.1	26.2	30.0	33.9	37.6	41.0
HFC-143a	+	0.4	0.8	1.3	1.9	2.6	3.4	4.3
HFC-236fa	+	+	+	0.1	0.8	1.3	1.9	2.3
CF_4	+	+	+	+	+	+	+	+
Others*	0.2	4.0	6.6	7.5	8.5	9.1	9.6	10.1
Total	**0.9**	**21.7**	**30.4**	**37.7**	**44.5**	**50.9**	**57.3**	**63.7**

+ Does not exceed 0.05 Tg CO_2 Eq.

* Others include HFC-152a, HFC-227ea, HFC-4310mee, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications. For estimating purposes, the GWP value used for PFC/PFPEs was based upon C_6F_{14}.

Note: Totals may not sum due to independent rounding.

Table 5. U.S. emissions of HFCs and PFCs from ODS substitution (Mg).

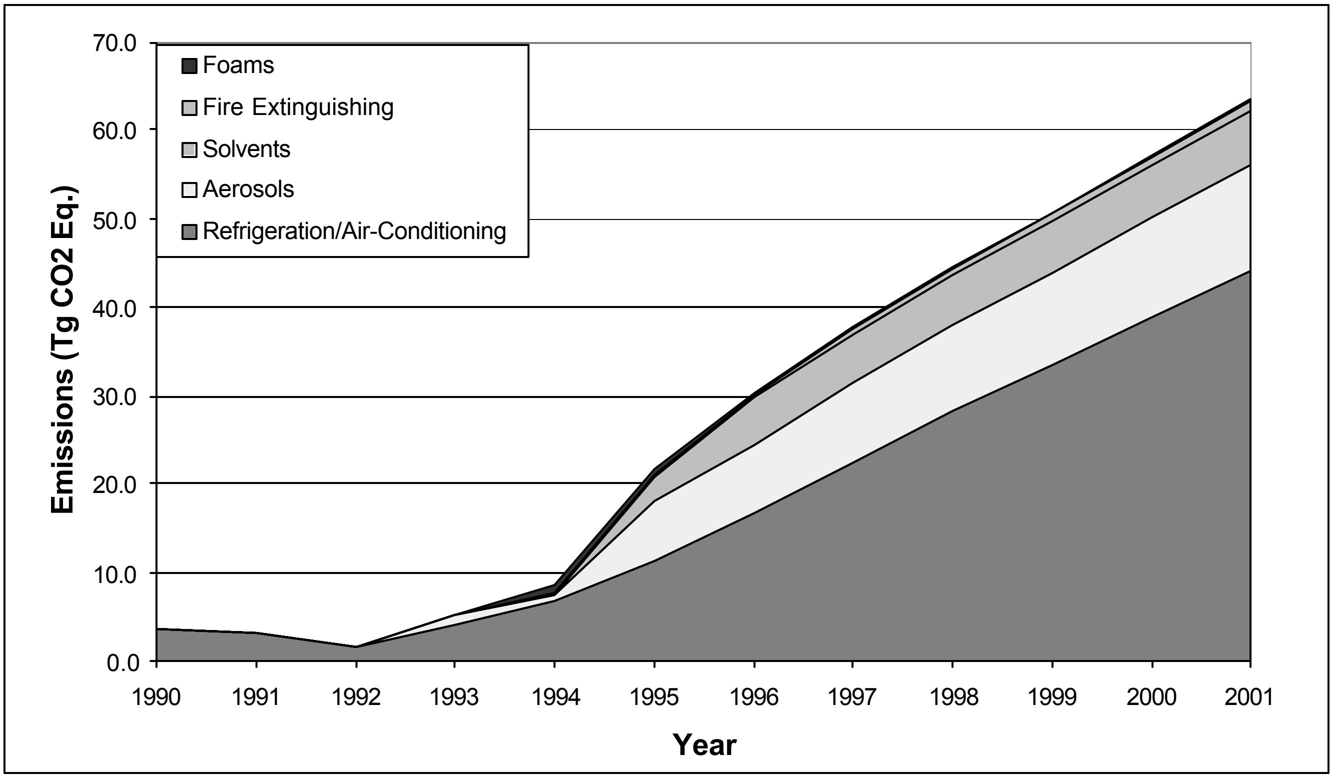
Gas	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
HFC-23	+	5	9	14	19	26	32	39
HFC-32	+	+	3	7	11	17	94	240
HFC-125	+	478	675	889	1,116	1,289	1,559	1,869
HFC-134a	564	12,232	16,211	20,166	23,089	26,095	28,906	31,552
HFC-143a	+	111	209	334	488	676	903	1,142
HFC-236fa	+	+	+	15	120	213	296	370
CF_4	+	+	+	+	+	1	1	1
Others*	M	M	M	M	M	M	M	M

M (Mixture of Gases)

+ Does not exceed 0.5 Mg

* Others include HFC-152a, HFC-227ea, HFC-4310mee and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

Figure 1. U.S. Emissions of ODS substitutes by sector (Tg CO_2 Eq.).



In 1990 and 1991, very few end-uses in the United States had started the transition away from ODSs, and the only significant emissions of HFCs and PFCs as substitutes were small amounts of HFC-152a and HFC-134a from air conditioning and refrigeration. Beginning in 1992, the ODS transition picked up and the use of HFC-134a increased as a refrigerant in motor vehicle air conditioners and in additional refrigerant blends used in a variety of applications, such as R-404A (contains HFC-125, HFC-143a, and HFC-134a) used in supermarket refrigeration. By 1993 and 1994, HFCs had begun to be used in foam production, as an aerosol propellant, and in the solvent sector. As halon production was phased out, the fire-extinguishing sector increased use of ODS substitutes in 1995. Overall, the ODS substitute emissions in the United States have increased from almost zero in 1990 to 63.7 Tg CO_2 Eq. in 2001. This increase was driven by the need to phase out the substances controlled under the Montreal Protocol.

ADDITIONAL APPLICATIONS

In addition to the U.S. national inventory report, the Vintaging Model can be used in a variety of other applications. In the past it has been used to estimate and forecast emissions for state entities, other countries, globally, and to analyze scenarios for emission reduction and monitoring purposes. A few examples of these applications are discussed below.

Once national emissions are known for the United States, it is possible to disaggregate these emissions to the state level. In the absence of the detailed data required to compile the Vintaging Model on a state level, total U.S. and state-level population data can be used to apportion a share of emissions to the state. This can be done on other scales within the United States as well, such as if conducting an inventory for a city or for an entire region of the country. Population can be a good indicator because each sector is comprised of consumer products, the demand for which does not significantly vary regionally within the United States.

However, there are some variations that drive demand, such as the use of air-conditioning in hotter climates. If using the Vintaging Model in this manner, it may be useful to examine the per capita use of residential, commercial, and motor vehicle air-conditioning on a state or regional level. Another refinement might be to examine the production of foam within a State or region compared to national totals. Because a significant source of HFC emissions from foams comes during the manufacture of the foam, it would be reasonable to assume such emissions are higher in areas where production occurs. Likewise, States with a large solvent-using industrial base (e.g., the manufacturing of computer circuit boards) could expect to see higher per-capita emissions from the solvents sector.

An even more complex application of the Vintaging Model is to apply it to other countries. Until recently, few nations have made significant efforts to track and project use and emissions of HFCs and PFCs from ODS substitutes; therefore, this type of modeling approach can be quite useful when data is lacking. One approach would be to collect relevant data and apply a similar framework to the Vintaging Model. Another approach is to use the existing Vintaging Model directly, by applying both the model and its underlying data. To use this methodology, the baseline country-specific consumption of ozone depleting substances prior to substitution can be multiplied by a ratio of U.S. ODS substitute (i.e., HFCs and PFCs) emissions in a future year to U.S. ODS consumption in the baseline year, thus approximating emissions as if the country behaved exactly in the manner as the United States, in terms of emission factors, growth, and substitution scenarios. However, it is unlikely that any country would behave in the exact manner as the United States, and therefore adjustments can be made to the emission estimates to account for changes in substitutes, timing of substitution, recovery and reuse of ODSs and substitutes, and economic growth. Once all of these factors are developed, sector specific emission estimates can be established.

Not only is the Vintaging Model a powerful tool for estimating historical emissions and creating inventories, but also the same substitution scenarios and market data are used to forecast emissions in all sectors. This type of analysis has been used to estimate future emissions for climate modeling purposes, potential benefits of emission reduction technologies, and impacts of substitutions for policy analyses. Additionally, when preparing inventories for years in which data is not yet available, the forecasting abilities of a model such as the Vintaging Model can provide a good assessment of emissions, if the model has been well maintained.

CONCLUSIONS

Given that emissions of ODS substitutes occur from thousands of different kinds of equipment and from millions of point and mobile sources throughout the United States, analytical tools such as the Vintaging Model or the methods outlined in the IPCC (2000) are the most effective way of estimating emissions. The IPCC methods vary in the degree of detail and type of information required, and are separated into a "tiered" approach to estimating emission methods. The Tier 1 approach requires less data, though is less accurate, and is based on potential emissions in a given year, while the Tier 2 approach calculates actual emissions and can be based on either a top-down or a bottom-up method. Though the EPA Vintaging Model is more comprehensive than the IPCC default Tier 2 methodology, uncertainties still exist with regard to the levels of equipment sales, equipment characteristics, and end-use emissions profiles that were used to estimate annual emissions for the various compounds. To minimize uncertainty and keep the model updated as a new data becomes available, throughout its development, the Vintaging Model has undergone modifications. As new or more accurate information becomes available, the model is adjusted in such a way that both past and future emission estimates are often updated.

While setting up a vintaging type model requires considerable initial investment of time for collection of sector and end-use specific data and setting up the modeling parameters, once the initial resources have been invested it will continue to be a useful tool with minimal maintenance. The initial data on ODS market sizes is available under the Montreal Protocol, and once specific market transitions and growth are determined, the model can be used to estimate and project emissions in a variety of business-as-usual or alternative scenarios. As markets or equipment change over time, updates to the model are generally quick, and the variety of outputs allow for checking the data from top-down consumption information. Because the ODS substitute sector is one of the fastest growing sources of greenhouse gas emissions in the United States, as well as other countries, the ability to accurately assess these emissions now and into the future will become increasingly important.

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KEY WORDS
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