United States
Environmental Protection
Agency

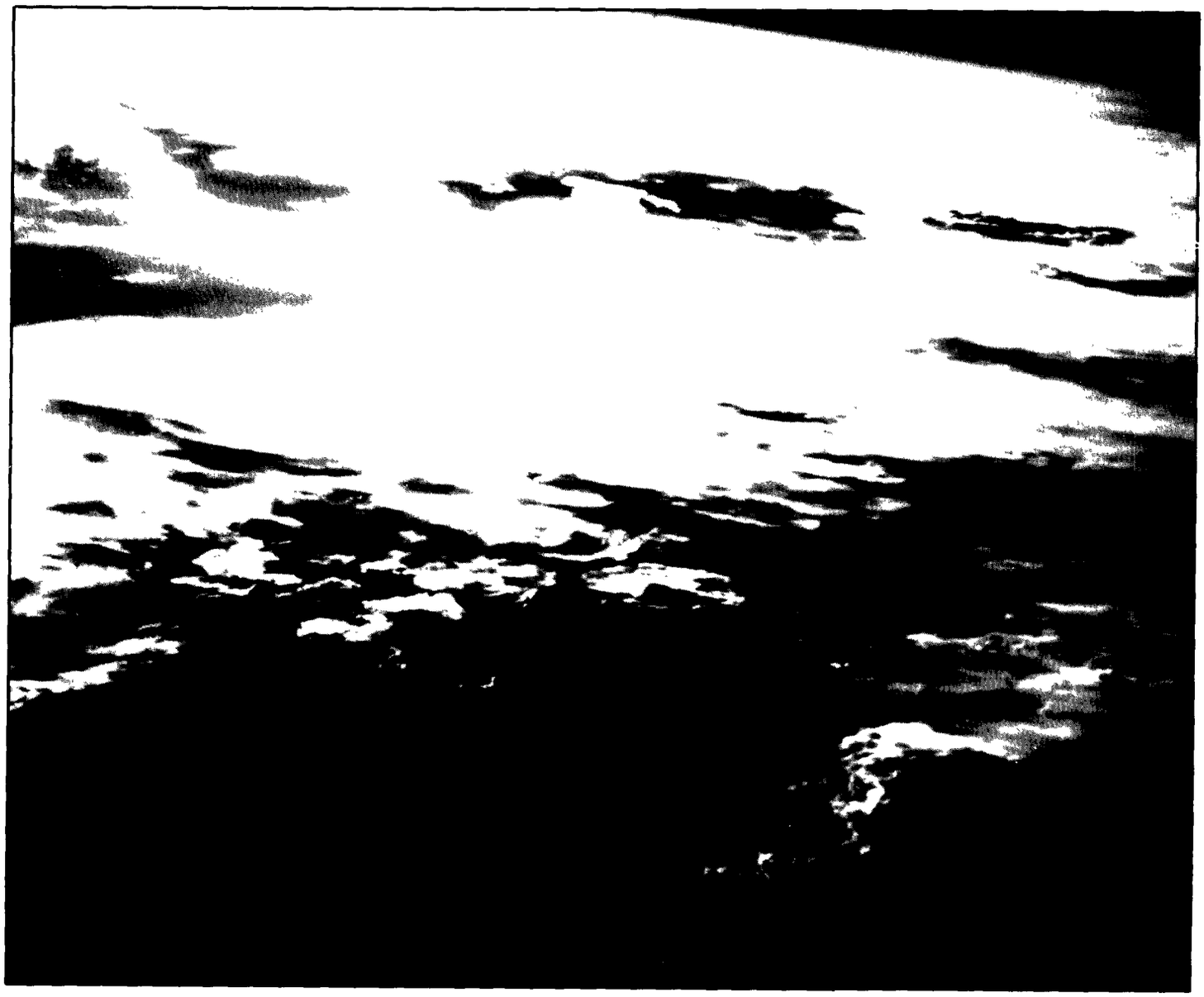
Office of Air and Radiation
Washington D.C. 20460

EPA 400/1-87/001F
December 1987

EPA

Assessing the Risks of Trace Gases That Can Modify the Stratosphere

Volume VI:
Technical Support Documentation
Production Projections



Assessing The Risks of Trace Gases That Can Modify The Stratosphere

Volume VI: Technical Support Documentation Production Projections

Senior Editor and Author: John S. Hoffman

Office of Air and Radiation
U.S. Environmental Protection Agency
Washington, D.C. 20460

December 1987

U.S. Environmental Protection Agency
Region 5, Library (5PL-16)
230 S. Dearborn Street, Room 1670
Chicago, IL 60604

APPENDIX C

TABLE OF CONTENTS

	TAB
Probabilistic Projections of Chlorofluorocarbon Consumption, by William D. Nordhaus (Yale University) and Gary W. Yohe (Wesleyan University) (1986)	1
Scenarios of CFC Use: 1985-2075, by Michael J. Gibbs (ICF Incorporated) (1986)	2
Product Uses and Market Trends for Potential Ozone Depleting Substances 1985-2000, by James K. Hammitt, et al. (RAND Corporation) (1986)	3
Joint Emission Scenarios for Potential Ozone Depleting Substances, by Frank Camm, et al. (RAND Corporation) (1986)	4

PROBABILISTIC PROJECTIONS OF CHLOROFLOUROCARBON CONSUMPTION

Dr. William D. Nordhaus
Department of Economics
Yale University
New Haven, CT 06520

Dr. Gary W. Yohe
Department of Economics
Wesleyan University
Middletown, CT. 06457

June 1986

Recent scientific evidence indicates that significant ozone depletion is likely to occur if atmospheric concentrations of chloroflourocarbons (CFCs) continue to grow at current rates. The precise health and welfare ramifications of this depletion are not yet completely understood, but the potential for widespread increases in the incidence of skin cancer, along with damage to animals and crops, and dramatic climatic change is now apparent. Increased concentrations are a manmade phenomenon, the result of increased production and emission of a bevy of fluorocarbons over the past 40 years. Reductions in the emissions of these compounds are possible, but can be realistically expected only if the cost of the required regulatory activity can be justified in terms of avoiding expensive environmental damage.

Assessing the value of a policy response to the potential environmental consequences of CFC emissions is thus a vital undertaking, but it is inextricably linked with forecasting CFC emissions into the next century. It is in the next century that most of the potential problems linked with CFC emissions are likely to occur, but it is in the next few decades that policy designed to avoid those problems would be most effective and least costly. The need for long term forecasting is thus clear, but so too is the observation that such forecasting is dominated by uncertainty. In the case of CFC's, rates of emissions beyond the year 2000 will certainly depend upon circumstances that cannot be accurately predicted.

If the appropriate decisions are to be made in dealing with the potentially harmful effects of emissions, then, a balance of future risks and costs must be struck. Given the impossibility of conducting policy debate with any degree of confidence on the basis of one, two, or ten

alternative scenarios, this balance must be weighed in the context of not only the estimates of most likely future emissions, but also probabilistically weighted ranges of other possible trajectories that deviate from any specified "best guess". Only then can policymakers survey the full menu of policy options -- a menu that may include direct and immediate intervention, to be sure, but might also include contingency intervention schemes to be triggered if future scientific findings indicate that the emissions or health risks are more serious than is now thought. Despite some significant effort in the past, the literature has not yet provided policymakers with the evidence required either to evaluate the relative value of options or to legitimize any but the simplest of options listed there.

The earliest studies undertaken under the auspices of the National Academy of Sciences produced estimates of future emissions of CFC's by simply projecting constant emissions forward from a specified date [see, e.g., NAS 1976 and 1979]. While these studies helped bring CFC emissions to the attention of the world scientific community, they were unable to provide an accurate understanding of the sources of the various forecasts, the uncertainties surrounding those forecasts, or the relative social values and costs of the potential policy alternatives. A second generation of analyses overcame some of the shortcomings of the initial exercises by constructing precisely articulated scenarios of how the future might unfold [e.g., Gibbs, ICF, 1986 and Quinn et. al., RAND, 1986]. Each traced future emissions trajectories from well defined models based upon sets of explicitly recorded assumptions and statistical analyses. While these studies have been successful in identifying interesting "what if" scenarios,

they have still been nonprobabilistic in nature. They continue, therefore, to fail to provide policymakers with any quantified notion of the likelihood of the specified scenarios.

The present study will try to provide the next step by explicitly incorporating uncertainty into the modeling exercise so that more definite estimates of likelihoods can be associated with possible future trajectories of CFC emissions. The technique to be employed, called probabilistic scenario analysis, was designed by Nordhaus and Yohe [1983] to investigate the problem of forecasting carbon dioxide emissions and concentrations from an economically consistent model of future energy markets. It identifies the most important sources of uncertainty in our present understanding of future CFC emissions, examines the current knowledge and disagreement about these variables and parameters, specifies a range of values that they might assume with specified relative frequency, and incorporates both the ranges and their relative frequencies into a simulation or Monte Carlo exercise. The focus is not, therefore, on resolving uncertainty. It is, instead, on representing existing uncertainty as accurately as possible and integrating that uncertainty explicitly and consistently into the analysis. The results not only provide a "best guess" trajectory for CFC emissions through the middle of the next century, but also suggest a set of alternative trajectories and associated probabilities that quantify the range of outcomes that is consistent with the current state of knowledge and ignorance.

Section I describes the analytical framework within which the probabilistic scenario analysis is conducted; coverage of the details of the modeling has been relegated to supporting appendices. Section II reviews

the judgmental values assigned to the major random variables identified in Section I. Section III presents the results of the scenario analysis assuming only the regulatory impetus on reducing aerosol consumption that produced the ban in the United States nearly a decade ago. Section IV follows with an extension of the regulatory environment to include the indefinite continuation of the voluntary restrictions now imposed on aerosol consumption by various countries across the rest of the world. Comparisons of the aerosol consumption distributions produced in Sections III and IV can therefore provide some insight into the possible effect of continuing voluntary regulatory initiatives outside the United States.

I. The Analytical Framework.

This study analyses the future worldwide emissions of four separate "CFC commodities": CFC-11 aerosols, CFC-12 aerosols, CFC-11 nonaerosols, and CFC-12 nonaerosols. Each is derived from the sum of CFC consumption in the United States and the rest of the world, but the models used to develop the individual forecasts have different empirical foundations. Because the models for both components of the four CFC commodities are nonetheless identical in structure, it is convenient to describe that structure. It is also convenient to focus initial attention on the modeling that produced the consumption trajectories, because their derivation is the most elaborate part of the analysis. CFC emissions flow in part from consumption through a straightforward linear allocation between emissions from current consumption and deposits into a CFC bank. The rest of current emissions are the result

of leakage from the existing CFC bank and therefore also depend upon (past) consumption. To describe the modeling that produced the consumption scenarios is thus to describe the heart of the analytical framework.

The central uncertainty in projecting future CFC emissions can be traced to the imprecision with which we understand the demand for CFC consumption. The general process employed here to model that demand is illustrated in Figure I-1. Four separate factors, taken in this study to be exogenous and uncertain, directly effect the demand for consumption: technological developments including the development of new products and processes; the level of population and its distribution across different regions of the globe; the level of per capita income and its distribution across different regions of the globe; and the regulatory environment. Depending upon the demand schedule for CFC consumption, each of these four plays a role in tracing out the path of future consumption.

The approach taken here to model CFC demand is based upon four major premises. First of all, most of the observed history of CFC use in the United States mirrors the experience of a rapidly developing technology in the early phase of its growth cycle. It should not, however, be expected that the rapid growth rates of the last two or three decades will continue into the future as the CFC-using technologies run their courses to maturity and market saturation in the United States. In our demand modeling, therefore, we recognize that the growth phase for CFCs has come to an end (or will do so in the near future), and that the demand patterns for CFCs are likely to resemble more conventional products in subsequent years.

Secondly, it is assumed that CFC use is likely to be determined by the presence or absence of major new CFC-using products along with the income

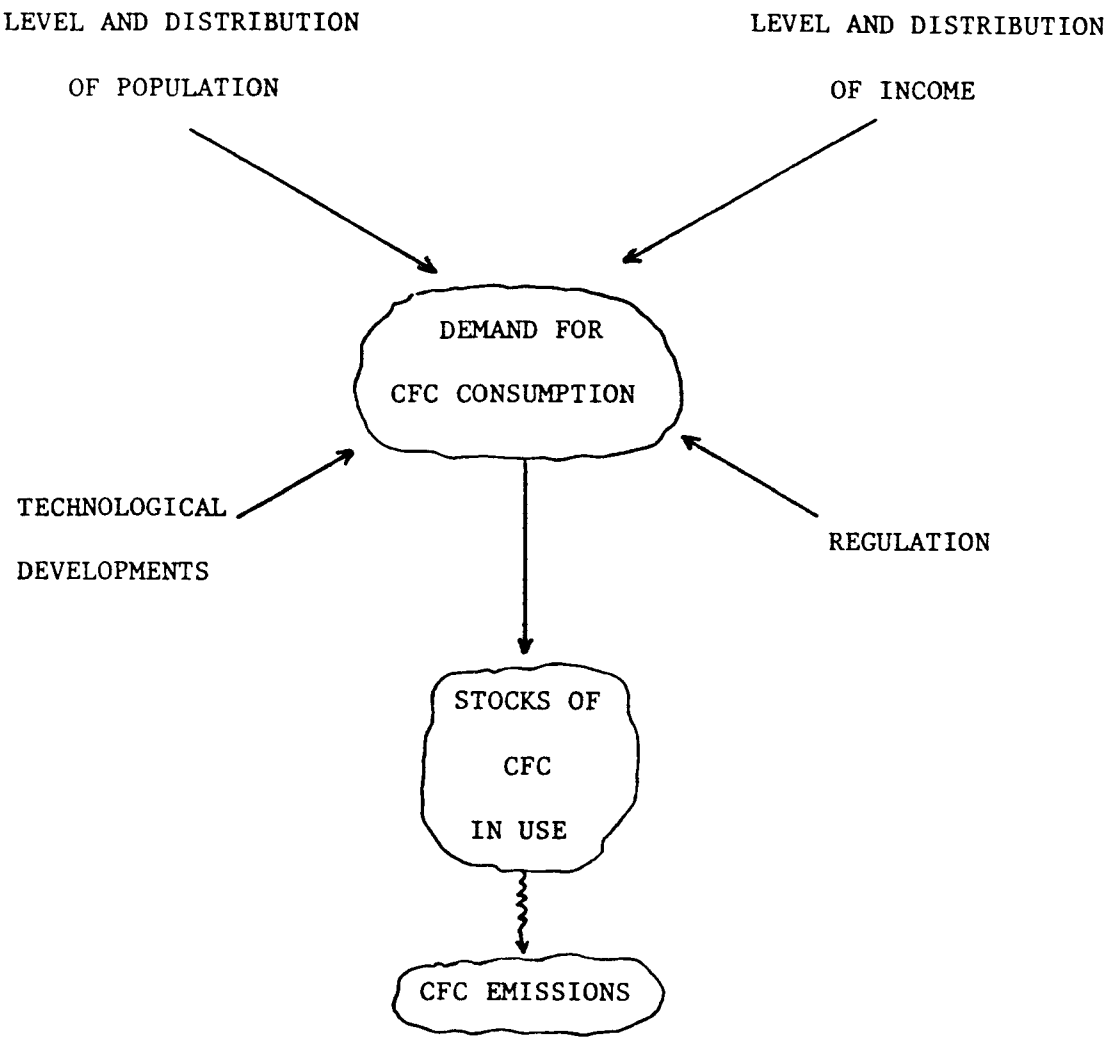


Figure I-1 Steps in the Generation of CFC Consumption and Emission

elasticity of current CFC-using products. If the inherent possibilities for major new CFC-using products were to be low because the potential for regulation inhibited research and development into new CFC uses, then we should expect that the volume of CFC use per unit of output in the United States would remain stable or perhaps even decline. If, on the other hand, major new CFC-using technologies were developed, then, at least for nonaerosols, the growth in CFC use could continue into the future.

In addition, future trends in CFC use will be significantly affected by the extent to which current CFC-using products are ones that tend to be more or less extensively used as peoples' incomes rise (or, technically, depending upon whether the income elasticities of CFC-using products are greater or less than unity). If CFC-using products are extensively contained in CFC-using products that appeal to high-income consumers (like automobiles or air conditioning), then CFC use will tend to rise more rapidly than income. Conversely, if CFCs are associated with products like food that tend to take a lower share of income as income rises, then CFC use will tend to rise relatively slowly.

In estimating CFC use outside the United States, finally, we view development as a process through which, abstracting from regulatory constraints, technologies that have emerged in the most advanced countries (particularly the United States) are likely to be increasingly adopted by less advanced countries. Put differently, if and when a particular country is able to attain the living standards prevailing in the United States, then we expect that country will exhibit consumption patterns similar to those supported by today's American consumer -- to buy refrigerators and air conditioners, to purchase deodorants and insecticides, to employ plastic

foams and sprays, and so on. When we project the consumption patterns of the rest of the world, then, we begin with the assumption that CFC use will be driven, as have many other commodities, by incomes, prices, and available technologies.

Figure I-2 illustrates more specifically the determinants of U.S. consumption over time. A logistics equation defines a trajectory for consumption per constant dollar of GNP (locus AB) that asymptotically converges to an asymptotic CFC frontier (locus CF). The notion behind this frontier is that the growing technological maturity in CFC markets dictates gradual movement toward a path of slow growth or decline in the income intensity of CFC demand (the ratio of CFC use per dollar of real GNP) rather than a trajectory of immediate convergence. CFCs first came into use in the 1930's, and the widespread introduction of products over the next 30 years produced an extremely rapid rate of growth. As the potential market became saturated, however, the growth rate slowed. This abbreviated history is depicted by the left half of locus AB in Figure I-2 with the early 1980's appearing near an inflexion point in the logistics curve. Eventually, if all markets are saturated and if no new uses are discovered, the actual CFC frontier will approach some potential CFC frontier like locus CF.

The frontier locus CF depicts the usage pattern when CFC products ultimately and completely penetrate every available submarket; that is, once the introduction of the new technologies has been played out. The potential frontier is thus determined by the level of per capita income in the United States, the prices of CFC-using products, and climatic, cultural, and other miscellaneous factors. As drawn in Figure I-2, the frontier has a positive slope, but that need not be the case. The slope would be positive if (1)

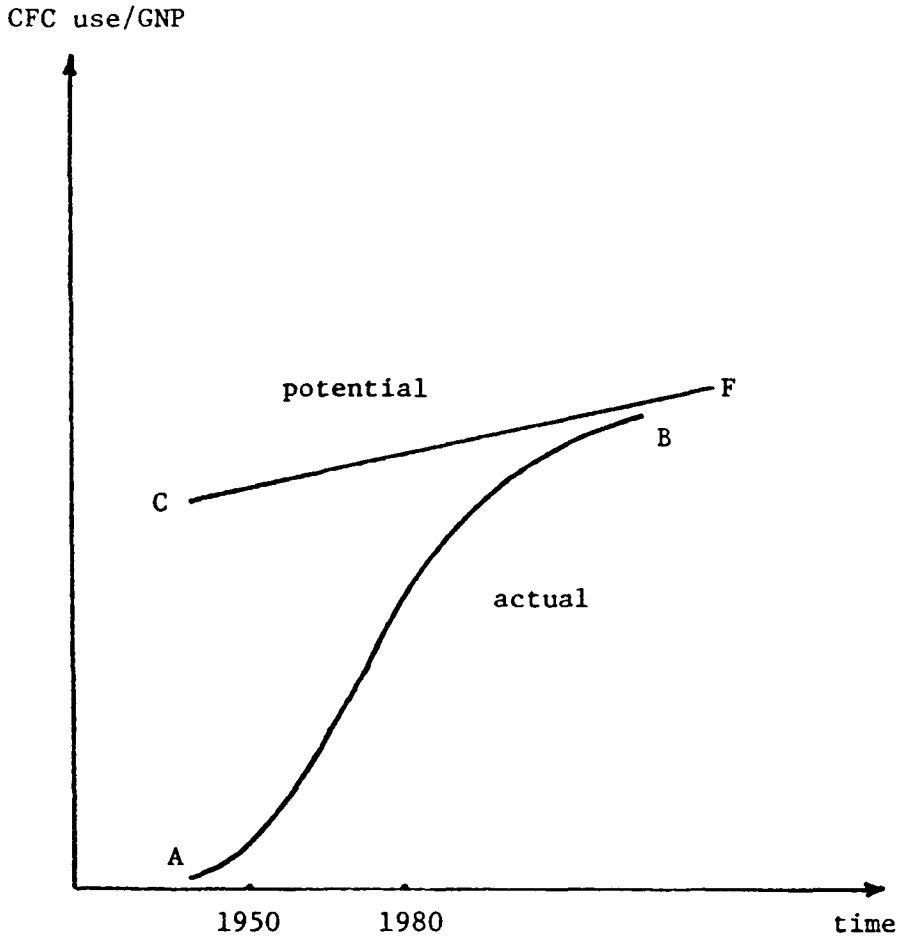


Figure I-2 Illustration of the Dynamic Logistics Curve for the U.S. Consumption of CFCs Approaching a Positively Sloped CFC Frontier

new products and processes developed over the coming decades were CFC-intensive, (2) CFC-using products displayed income elasticities greater than unity, or (3) the prices of CFC-using products and services were declining relative to other commodities. The CFC-intensity of the economy would tend to decline, giving the frontier a negative slope, if the reverse of these conditions were true.

It must be emphasized that we have no a priori conviction whether the CFC frontier has a positive or negative slope. We simply do not know, at this point, how CFC-intensities, income elasticities, and relative prices will fit together to determine the trend in the potential for future demand. It should be clear, nonetheless, that the inclusion of such a frontier in the modeling focuses attention on a convenient method of capturing all of that uncertainty with a device that is commonly employed in the economics literature (e.g., potential GNP). The frontier is, moreover, a convenient vehicle with which to incorporate even complicated regulatory options in a straightforward and uncomplicated way. Finally, the dynamic nature of the frontier, with its potential for a nonzero slope, represents an important extension of the usual logistics approach that envisions trajectories climbing asymptotically to a fixed limit.

A system of equations depicting these loci must be estimated on the basis of U.S. time series data that shows dramatic reductions in the rate of growth of CFC consumption since the middle of the 1970's -- a slowdown that poses significant difficulty in interpretation. Recall that it was in the middle of that decade that increased awareness of the potential for CFC's contribution to ozone depletion produced an aerosol ban in the United States. General concern that regulatory efforts would extend to other

fluorocarbons was also voiced at that time and probably led to a reduction in the vitality of CFC market activity at all levels.

The uncertainty about the effect of regulation leads to another important issue in forecasting trajectories. Figure I-2 illustrates a single potential CFC frontier. In fact, we do not know either the level or the growth rate (positive or negative) of the CFC frontier. This uncertainty reflects the general problem of "specification uncertainty" in estimating statistical models.

Figure I-3 illustrates this difficulty more clearly; there, a second set of actual and potential trajectories (labeled A'B' and C'D', respectively) is drawn. Based on the data at hand, it is impossible to sure whether the frontier is CF or C'F'; i.e., the specification of the underlying relationship is, itself, uncertain. This type of specification uncertainty creates fundamental estimation problems in models like the present one. The procedure for incorporating specification uncertainty into this study employs historical CFC end-use data for the United States to estimate the likelihood of different rates of growth supporting different potential CFC frontiers. Logistics paths converging to these frontiers are then estimated, again on the basis of the observed U.S. experience. The procedure is explained in some detail in Appendix A.

One critical source of uncertainty has thus been identified (the frontier growth parameter), along with a statistical procedure for estimating its probability distribution. This procedure provides not only a distribution of growth rates for the frontier, but also an associated distribution of initial starting points (like C and C' in Figure I-3). Locus C'F' begins, in other words, in 1950 (e.g.) at some level of intensity

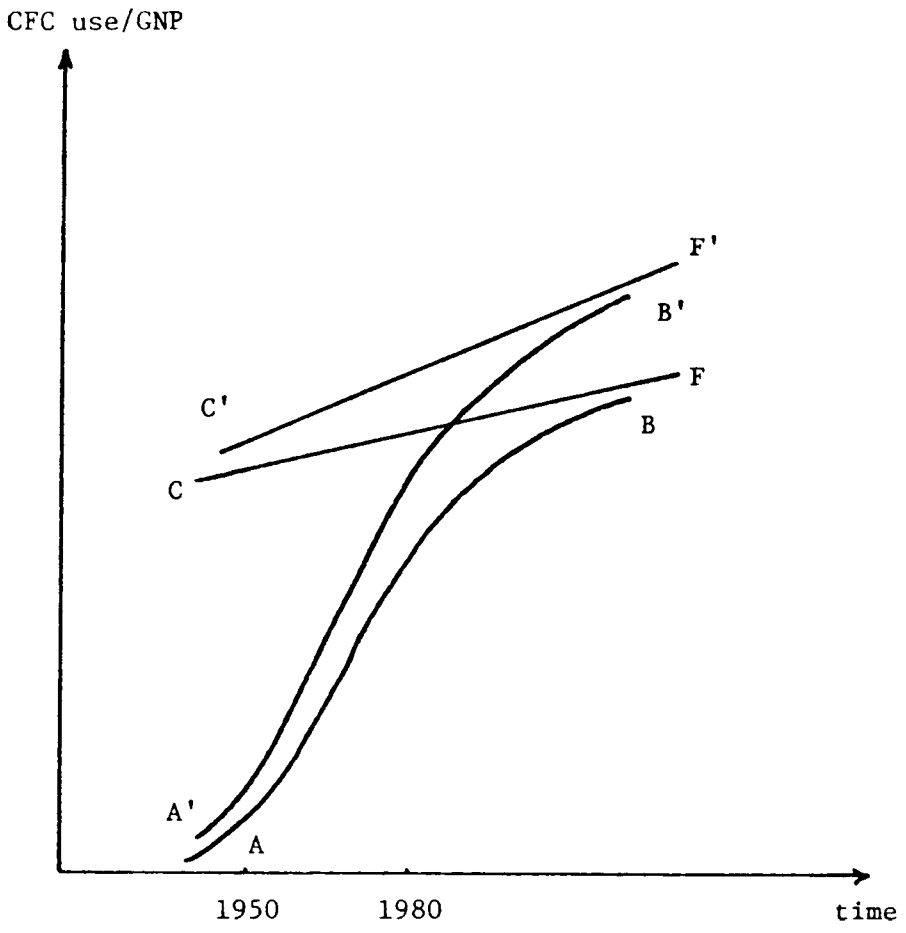


Figure I-3 Illustration of the Possibility of Alternative Paths for Actual and Potential CFC use

that is consistent with the estimated rate of growth along C'F', and that initial boundary point need not be the same as the point C that anchors the first alternative locus CF.

Consumption per constant dollar of GNP for the U.S. can now easily be translated into total consumption for the U.S. for any given year simply by multiplying the number read from the AB loci by real per capita GNP and population for the year in question. Both the rate of growth of per capita GNP through the middle of the next century, denoted in most economic work as labor productivity, and the rate of growth of population over the same period of time are, however, uncertain. Both multiplicative factors are thus uncertain or random variables. Population and productivity projections through 2050 are based only partially upon statistical exercises for which standard errors can be computed. They are, in addition, based upon judgmental views of the structure of long term economic and demographic trends that vary from expert to expert. A procedure has been developed to extract a representation of the underlying (or "true") distribution of that uncertainty for such a random variable from disagreement across published projections. The details of the procedure, developed initially for the Nordhaus and Yohe contribution to the National Academy of Science's Changing Climate was refined on the basis of some subsequent work by Nordhaus on macroeconomic forecasts, and its application to productivity and population growth rates in the United States is outlined in Appendix B.

With consumption for the U.S. sufficiently specified, turn next to the rest of the world. The United States has, historically, led the rest of the world to new uses of CFC's. The experience of the rest of the world can therefore be described reasonably well by a function that reflects the speed

with which the rest of the world adopts U.S. patterns of production and consumption. A time series for the rest of the world can, in fact, be constructed from an estimated equation that relates differences in the relative size of CFC consumption per constant dollar of GNP between the rest of the world and the U.S. to corresponding differences in the relative size of per capita GNP. Figure I-4 shows how such a time series might evolve. Curves AB and CF are defined as in Figure I-2; that is, they represent actual and potential CFC usage in the United States. We know that lower-income countries in Europe, Africa and Asia currently have significantly lower CFC use per unit of GNP. This is reflected in the rest of the world curve shown in Figure I-4 as DE; it lies everywhere below the U.S. curve AB. The rest of the world curve gradually moves toward the frontier, but it lags behind the U.S. curve because incomes outside the U.S. are lower and because there is a diffusion lag of technology developed and introduced in the United States.

The rate of convergence is determined jointly by an estimated intensity factor and by projected rates of growth of per capita GNP in the rest of the world. It is therefore uncertain along two dimensions. Two more sources of uncertainty must, in other words, now be noted. First, the intensity parameter must be estimated from cross sectional data, and the confidence of its estimation captured by a likelihood distribution; this estimation is also discussed in Appendix A. Secondly, the rate of growth of productivity in the rest of the world, another exogenous variable whose distribution is gleaned from disagreement across published projections in Appendix B, enters at this point. CFC consumption per dollar of GNP has thus been specified, but a fourth and fifth source of uncertainty have also been revealed.

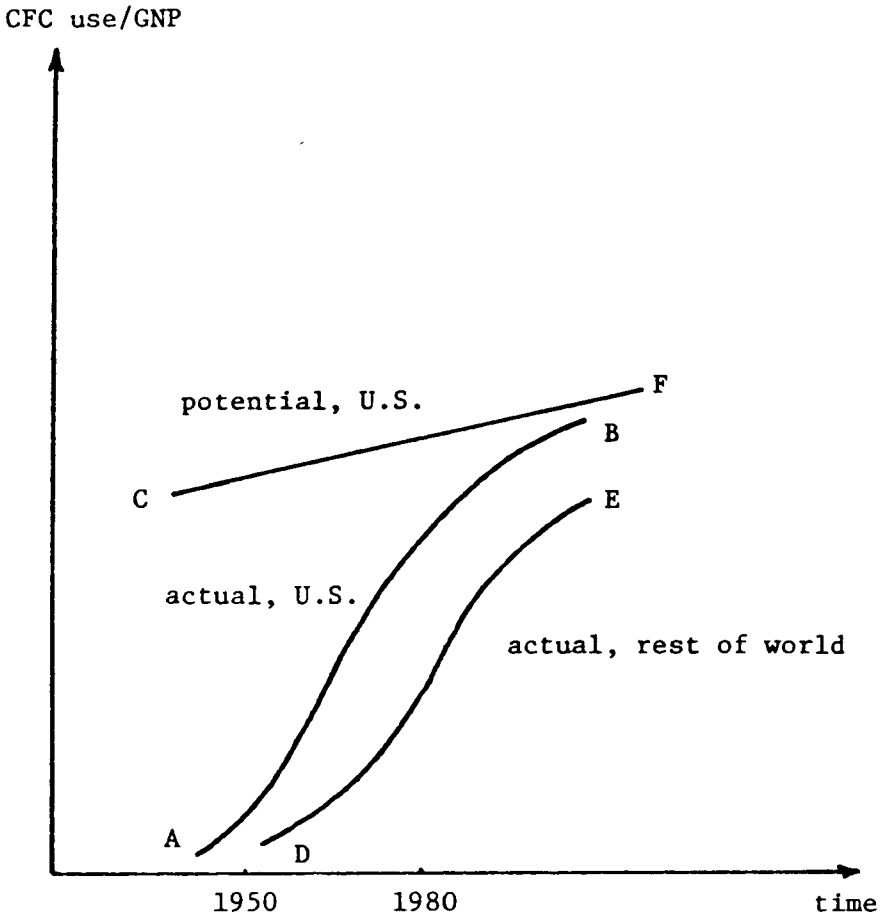


Figure I-4 Illustration of the Rest of the World Given a U.S. Frontier

A sixth factor appears quickly when CFC consumption per constant dollar of GNP is translated into total CFC consumption for the rest of the world. As before, the consumption per dollar series needs to be multiplied by both per capita GNP and population. Per capita GNP is already available from productivity growth projections employed in the transition from U.S. consumption to the rest of the world, but the level of population has yet to be specified for the rest of the world. This sixth uncertainty is quantified by the procedure of comparing forecast disagreement cited above. Appendix B records the specifics of this process.

A more detailed summary of the entire process can now be presented schematically; a representation of the computations required each year for each sampled combination of uncertain parameter and variable values is depicted in Figure I-5. The interaction of population, per capita GNP, and CFC consumption per constant dollar of GNP produces an estimate for total U.S. consumption of CFC's in period t, as shown at point A in the upper left hand corner. Two uncertain exogenous variables and one uncertain parameter imply that three sources of uncertainty need to be quantified just to cover the U.S. The middle part of the upper half of the figure shows the interaction of U.S. consumption per constant dollar of U.S. GNP, real per capita GNP in the U.S., and real per capita GNP in the rest of the world to produce an estimate of CFC consumption per constant dollar of GNP for the rest of the world at point B. A third uncertain exogenous variable and a second uncertain parameter come into play there. The upper right hand part of the figure reflects at point C the determination of total CFC consumption for the rest of the world on the basis of CFC consumption per constant dollar of GNP in the rest of the world, real per capital in the rest of the

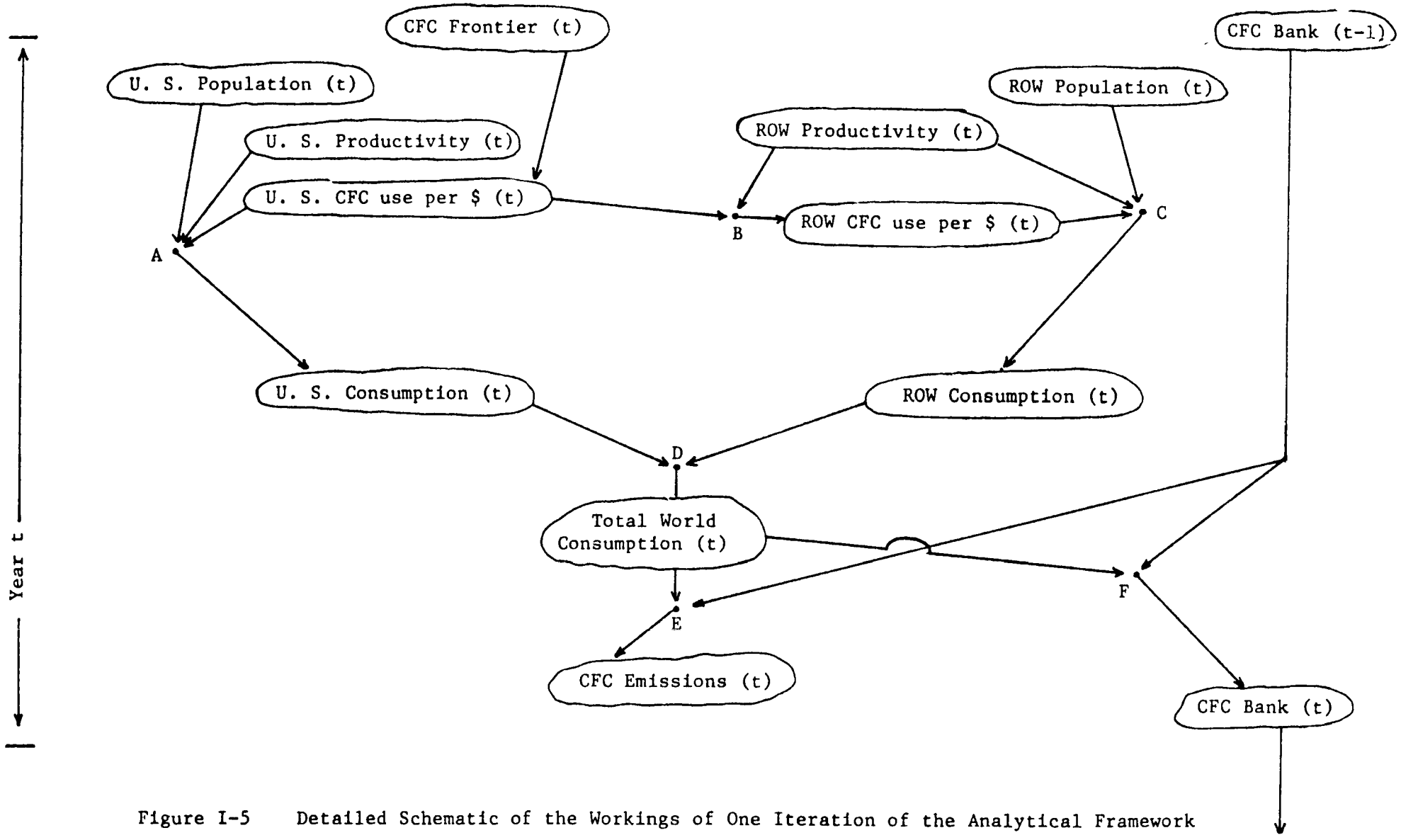


Figure I-5 Detailed Schematic of the Workings of One Iteration of the Analytical Framework

world, and the population level in the rest of the world. The uncertain exogenous variable required there is the sixth explicit source of uncertainty that must be quantified to construct a probabilistic scenario exercise.

The final stage of the model construction, the part that takes CFC consumption to CFC emissions, is displayed at point E found toward the bottom of Figure I-5. Part of the world's total consumption -- the sum of the U.S. consumption and the rest of the world accomplished at point D -- leaks into the atmosphere during the period of consumption. This fraction depends upon the mix of products using the CFC's that are produced in any one year and the difference between the quantity produced and the quantity consumed. It is claimed that CFC inventories are currently very low worldwide because they are difficult and expensive to store. It is also claimed that the decade-long glut of capacity has dampened trade. The leakage parameter may not, therefore, be significantly affected by the production/consumption distortion. It may, however, vary significantly with product mix in a manner that would make the leakage factor from current consumption the third uncertain parameter of an emissions model and the seventh source of uncertainty requiring some quantification.

A second source of emission is leakage from the CFC bank that exists like a vast reservoir of unreleased fluorocarbons. Each year, the proportion of CFC's consumed which does not leak into the environment is deposited through point F in Figure I-5 into a bank from which it will eventually leak. The schema for period t must, therefore, display some of current consumption being deposited through point F into the reservoir bank at the same time it displays some proportion of the bank inherited from

period (t-1) leaking through point E into the environment as emissions. The first flow proceeds at a rate equal to one minus the current leakage parameter just defined; its uncertainty has already been noted. The second flow combines with direct emissions to produce, for any given year, total emissions and, given well accepted CFC molecular atmospheric lifetimes, corresponding atmospheric concentrations.

The grand total for identified sources of quantifiable uncertainty is 8. In the Monte Carlo estimates, we discretized the probability distributions into high, middle, and low cells with 25 percent, 50 percent, and 25 percent likelihoods to facilitate the sampling process. As a result, there are 6561 possible combinations of values for the 4 exogenous variables and 4 estimated parameters or 6561 potential trajectories for CFC emissions for each of the four types of CFC's to be studied. Even before emissions are computed, there are 729 possible combinations of 4 random exogenous variables and 2 estimated parameters upon which total consumption distributions will depend. Appendix C records the detailed equations of the complete model just described.

Finally, we need to discuss the regulatory environment presumed throughout the analysis. Because we begin every run at the actual 1980 consumption levels in the United States and the rest of the world, the impact of the U.S. aerosol ban is automatically captured in all of the results. The ban was, of course, applied only to "nonessential" uses, so 1980 consumption levels were not zero, even in the United States. Aerosol consumption was, instead, some small fraction of the peak levels of the mid 1970's, and the frontier growth methodology is applied to that quantity in all cases.

Section III reports results for the rest of the world based on scenarios that envision regulation going no further than the U.S. aerosol ban. These runs assume, in other words, that the voluntary restraint presently imposed by the EEC and other countries on themselves will lapse when economic growth makes those restrictions binding. Section IV goes to the other extreme and reports results based on scenarios that envision existing worldwide restraint on aerosol consumption and/or capacity continuing as presently written for the next seventy years. The reader is thus provided some well defined regulatory benchmarks against which to measure expectations of the future demand for aerosol regulation. It should be noted, too, that nonaerosols are never assumed to be subjected to any direct regulatory restraint. Association with aerosols may have depressed their consumption levels over the past ten years, but that possibility would be captured, if it were true, in the lower statistical estimates of the frontier growth rates.

II. The Subjective Distributions.

Probabilistic scenario analysis applied to the eight sources of uncertainty just noted requires that we sample randomly over the judgmental distributions of each source. It is most convenient, for the purposes of this sampling, to discretize each distribution into high, middle, and low cells with 25 percent, 50 percent and 25 percent likelihood weights attached, respectively. Table II-1 records the values assigned to these cells for the four exogenous random variables identified in the previous section: population growth in the United States and the Rest of the World and productivity growth in the United States and the Rest of the World. The technique with which the subjective distributions for these variables were

TABLE II-1

Judgmental Cell Values for
Exogenous Random Variables

VARIABLES	LIKELIHOOD WEIGHT	1980-2000	2000-2020	THEREAFTER
A. U.S. Population Growth (% per year)				
High	.25	0.8	0.8	0.15
Middle	.50	0.7	0.4	0.1
Low	.25	0.6	0.3	0.0
B. Rest of the World Population Growth (% per year)				
High	.25	2.0	1.5	0.9
Middle	.50	1.7	1.1	0.5
Low	.25	1.3	0.7	0.2
C. U.S. Productivity Growth (% per year)				
High	.25	3.2	3.2	1.7
Middle	.50	2.1	1.6	1.1
Low	.25	1.0	0.0	0.0
D. Rest of the World Productivity Growth (% per year)				
High	.25	2.9	2.8	1.7
Middle	.50	2.0	1.8	1.1
Low	.25	1.1	0.9	0.0

produced is described in some detail in Appendix B. The underlying data are recorded there, as well.

Table II-2 records the cell values assigned to the two uncertain parameters that specify CFC demand: the rate of growth of the CFC frontiers for the United States and the relative intensity elasticities for the rest of the world. They are based upon the estimates that emerge from the statistical procedures outlined in Appendix A. Table II-3 finally records the values assumed by the parameters that take consumption of the four CFC compounds in any one year into current and future emissions: the distribution of current consumption between release into the atmosphere as current emission and deposit into the bank for future emission; the annual rate of release from the bank, and the annual rate of molecular decay in the atmosphere.

TABLE II-2

Judgmental Cell Values for
Exogenous Random Parameters

VARIABLES	LIKELIHOOD WEIGHT	1980-2000	2000-2020	THEREAFTER
A. Frontier Growth Rate for CFC-11 Nonaerosols				
High	.25	2.283	1.706	1.749
Middle	.50	-0.304	-0.246	-0.250
Low	.25	-2.885	-2.214	-2.250
B. Frontier Growth Rate for CFC-12 Nonaerosols				
High	.25	2.518	2.0	2.0
Middle	.50	-0.729	0.0	0.0
Low	.25	-2.647	-2.0	-2.0
C. Frontier Growth rate for CFC-11 Aerosols				
High	.25	2.451	2.0	2.0
Middle	.50	-0.043	0.0	0.0
Low	.25	-2.590	-2.0	-2.0
D. Frontier Growth Rate for CFC-12 Aerosols				
High	.25	2.451	2.0	2.0
Middle	.50	-0.095	0.0	0.0
Low	.25	-2.596	-2.0	-2.0
E. Relative Intensity Elasticity: Rest of the World for CFC-11 Nonaerosols				
High	.25	1.62	1.62	1.62
Middle	.50	1.27	1.27	1.27
Low	.25	0.92	0.92	0.92
F. Relative Intensity Elasticity: Rest of the World for CFC-12 Nonaerosols				
High	.25	1.43	1.43	1.43
Middle	.50	1.15	1.15	1.15
Low	.25	0.87	0.87	0.87
G. Relative Intensity Elasticity: Rest of the World for CFC-11 Aerosols				
High	.25	1.82	1.82	1.82
Middle	.50	1.30	1.30	1.30
Low	.25	0.78	0.78	0.78
H. Relative Intensity Elasticity: Rest of the World for CFC-12 Aerosols				
High	.25	1.31	1.31	1.31
Middle	.50	0.93	0.93	0.93
Low	.25	0.55	0.55	0.55

TABLE II-3

Judgmental Cell Values
for Emissions Parameters

VARIABLE	LIKELIHOOD WEIGHT	VALUE
A. Fraction of Consumption emitted Directly:		
CFC-11 Nonaerosols	1.0	0.1
CFC-12 Nonaerosols	1.0	0.1
CFC-11 Aerosols	1.0	1.0
CFC-12 Aerosols	1.0	1.0
G. Fraction of Bank Emitted:		
CFC High	.25	.85
CFC Middle	.50	.80
CFC Low	.25	.75
C. Annual Rate of Atmospheric Decay		
CFC-11 Nonaerosols	1.0	0.01
CFC-11 Nonaerosols	1.0	0.0143
CFC-12 Aerosols	1.0	0.01
CFC-12 Aerosols	1.0	0.043

III. Results

In reporting the results of this analysis, we show not only the global consumption (production), emissions, mass in the banks, and concentrations for the identified CFC compound, but also a number of important ingredients: the division of total world production of CFCs between the U. S. and the rest of the world, GNP levels for the U. S. and the Rest of the World, population for the U.S. and the rest of the world, and other key driving variables. Recall, particularly in reading the aerosol results recorded in this section, that they include only the effects of the U.S. aerosol ban. Voluntary restrictions presently in place in various countries around the world are reflected explicitly in the results reported in Section IV. Nonaerosols are assumed to face no formal restraint. Finally, the concentration and bank volume trajectories are nominally based on estimates of the 1980 levels, but the long term results are almost completely insensitive to their initial specification; virtually all of the CFC's in the banks and in the atmosphere in the year 2020 and beyond will have been produced since 1980.

Table III-1 shows the base or "most likely" cases obtained by setting each of the uncertain random variables equal to its middle or most likely value. The remaining tables present the probabilistic results based on 200 randomly selected runs. The runs were chosen by drawing one of the three values for each of the uncertain variables and parameters from a random number generator; the probability of selecting each was proportional to the corresponding judgmental probability under the assumption that all of the variables were independently distributed. For example, because there were 7 uncertain variables (the distribution of CFC consumption between immediate

Table III-1

Base Case Secenarios

	1980	1990	2000	2010	2020	2030	2040	2050
Major Driving Variables:								
U.S. POPULATION (10**9)	0.225	0.241	0.258	0.269	0.279	0.282	0.285	0.288
ROW POPULATION (10**9)	4.226	5.009	5.884	6.608	7.310	7.731	8.127	8.544
US LABOR PRODUCTIVITY (1985$ 10**3/CAP*YR)	15.150	18.690	22.885	26.991	31.437	35.268	39.369	43.947
RW LABOR PRODUCTIVITY (1985$ 10**3/CAP*YR)	2.520	3.078	3.748	4.496	5.327	5.988	6.684	7.461
U.S GROSS OUTPUT (1985$ 10**12/YR)	3.409	4.510	5.896	7.260	8.761	9.958	11.227	12.658
ROW GROSS OUTPUT (1984$ 10**12/YR)	10.550	15.418	22.054	29.711	38.939	46.294	54.326	63.752
WORLD GROSS OUTPUT (1985$ 10**12/YR)	14.058	19.928	27.951	36.970	47.701	55.251	65.553	76.410
CFC-11 Nonaerosols:								
RATIO OF CFC/GNP (US) (10**3 MT/YR)	19.836	19.504	19.032	18.593	18.153	17.710	17.274	16.848
US CFC CONSUMPTION (10**3 MT/YR)	67.616	87.969	112.222	134.983	159.041	175.346	193.937	213.270
ROW CFC CONSUMPTION (10**3 MT/YR)	125.700	176.680	244.901	329.347	430.616	500.719	573.142	656.005
WORLD CFC CONSUMPTION (10**3 MT/YR)	193.316	264.650	357.122	464.330	589.657	677.065	767.078	869.275
WORLD CFC BANK (10**3 MT)	689.193	1,051.439	1,438.844	1,893.235	2,435.381	2,888.110	3,287.048	3,726.254
WORLD CFC EMISSIONS (10**3 MT/YR)	148.134	229.779	315.072	415.269	535.140	637.397	725.880	822.907
WORLD CFC CONCENTRATIONS (10**3 MT)	1,935.351	3,618.248	5911.371	8,882.086	12,631.320	17,115.297	22,042.629	27,384.535
CFC-12 Nonaerosols:								
RATIO OF CFC/GNP (US) (10**3 MT/YR)	37.647	35.427	33.448	33.261	33.281	33.288	33.291	33.292
US CFC CONSUMPTION (10**3 MT/YR)	128.324	159.781	197.224	241.461	291.582	331.471	373.471	421.425
ROW CFC CONSUMPTION (10**3 MT/YR)	120.800	162.697	218.350	298.276	398.888	475.424	557.960	654.794
WORLD CFC CONSUMPTION (10**3 MT/YR)	249.124	322.478	415.574	539.738	690.470	806.894	931.722	1,076.220
WORLD CFC BANK (10**3 MT)	883.011	1,303.290	1,697.653	2,201.117	2,843.410	3,419.687	3,964.472	4,580.465
WORLD CFC EMISSION (10**3 MT/YR)	189.612	285.514	372.468	482.814	624.546	754.063	874.646	1,010.593
WORLD CFC CONCENTRAIONS (10**3 MT)	2,749.781	4,699.805	7,195.145	10,281.656	14,160.613	18,827.820	24,003.590	29,690.176
CFC-11 Aerosols:								
RATIO OF CFC/GNP (US) (10**3 MT/YR)	24.062	24.282	24.314	24.348	24.365	24.371	24.373	24.374
US CFC CONSUMPTION (10**3 MT/YR)	4.101	5.476	7.168	8.838	10.673	12.134	13.682	15.427
ROW CFC CONSUMPTION (10**3 MT/YR)	111.900	161.371	229.493	316.515	424.388	505.979	593.827	696.887
WORLD CFC CONSUMPTION (10**3 MT/YR)	116.001	166.847	236.661	325.353	435.061	581.113	607.409	712.313
WORLD CFC BANK (10**3 MT)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WORLD CFC EMISSIONS (10**3 MT/YR)	116.001	166.847	236.661	325.353	435.061	518.113	607.509	712.313
WORLD CFC CONCENTRATIONS (10**3 MT)	2,506.029	3,633.926	5,239.586	7,456.504	10,442.164	14,059.691	18,135.649	22,756.617
CFC-12 Aerosols:								
RATIO OF CFC/GNP (US) (10**3 MT/YR)	31.695	31.797	31.690	31.716	31.736	31.743	31.746	31.747
US CFC CONSUMPTION (10**3 MT/YR)	5.402	7.171	9.343	11.512	13.902	15.804	17.821	20.093
ROW CFC CONSUMPTION (10**3 MT/YR)	178.800	257.287	364.936	499.856	665.987	793.429	931.178	1,092.786
WORLD CFC CONSUMPTION (10**3 MT/YR)	184.202	264.457	374.278	511.368	679.889	809.234	948.999	1,112.879
WORLD CFC BANK (10**3 MT)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WORLD CFC EMISSIONS (10**3 MT/YR)	184.202	264.457	374.278	511.368	679.889	809.234	948.999	1,112.879
WORLD CFC CONCENTRATIONS (10**3 MT)	3,380.393	5,057.617	7,416.750	10,628.937	14,891.117	19,970.742	25,602.395	31,913.781

release into the atmosphere and deposit into the bank was not included as a random variable in the probabilistic runs), the most likely run had .0078 = $.5^7$ chance of being chosen.

Table III-2 presents the mean values of the different variables for the period 1980 through 2050. As can be seen, these differ from the most likely values shown in Table III-1. More precisely, the mean levels of CFC consumption, emission, bank volume, and atmospheric concentration are all higher when uncertainty is allowed than when uncertainty is ignored. The reason for this difference can be traced to the nonlinear nature of the demand model. Location of the mean above the most likely scenario can occur only if the extreme trajectories on the high side deviate further from the best guess than do the extreme runs on the low side. Further evidence of this skewness will be drawn from tabulations of 25th and 75th percentile boundaries provided below.

Table III-3 records the rates of growth of the different variables over the next seven decades. These show that CFC production grows faster than GNP for both aerosols and non aerosols over the near term. By the middle of the next century, though, consumption increases slow, but to rates that still exceed the rate of growth of GNP. Remember that these growth rates emerge from simulations that ignore the possibility of increased regulatory activity.

Table III-4 shows the quartile projections of the estimates of CFC production along with the other critical variables. The 25th and 75th percentile paths show, respectively, the trajectory below which the outcome is thought to lie with probability one-quarter and above which the outcome is thought to lie with probability one-quarter. Put differently, the

Table III-2

Mean Estimates Based on Probabilistic Scenario

	1980	1990	2000	2010	2020	2030	2040	2050
Major Driving Variables:								
US POPULATION (10**9)	0.225	0.241	0.258	0.270	0.270	0.281	0.287	0.290
ROW POPULATION (10**9)	4.226	5.015	5.904	6.665	7.421	7.913	8.395	8.901
US LABOR PRODUCTIVITY (1985$ 10**3/CAP*YR)	15.150	18.915	23.596	28.779	34.879	39.874	45.298	51.570
RW LABOR PRODUCTIVITY (1985$ 10**3/CAP*YR)	2.520	3.087	3.786	4.603	5.539	5.267	7.050	7.954
US GROSS OUTPUT (1985$ 10**12/YR)	3.409	4.568	6.092	7.783	9.807	11.360	13.031	14.981
ROW GROSS OUTPUT (1984$ 10**12/YR)	10.649	15.481	22.358	30.694	41.137	49.648	59.264	70.986
WORLD GROSS OUTPUT (1985$ 10**12/YR)	14.058	20.049	28.449	38.477	50.944	61.007	72.295	85.968
CFC-11 Nonaerosols:								
RATIO OF CFC/GNP (US) (10**3 MT/YR)	19.836	20.090	20.793	21.748	23.069	24.872	27.201	30.123
US CFC CONSUMPTION (10**3 MT/YR)	67.614	91.881	127.288	171.174	230.565	290.039	366.555	470.212
ROW CFC CONSUMPTION (10**3 MT/YR)	125.699	182.803	277.910	431.751	682.259	962.655	1,369.580	2,000.110
WORLD CFC CONSUMPTION (10**3 MT/YR)	193.313	274.686	405.195	602.921	912.824	1,252.689	1,736.134	2,470.333
WORLD CFC BANK (10**3 MT)	687.732	1,084.663	1,603.191	2,378.147	3,601.833	5,090.520	7,023.227	9,902.477
WORLD CFC EMISSIONS (10**3 MT/YR)	149.581	233.000	343.462	509.032	771.112	1,093.563	1,508.082	2,125.121
WORLD CFC CONCENTRATIONS (10**3 MT)	1,936.767	3,624.866	6,059.812	9,594.180	14,855.895	22,507.977	32,905.691	47,272.129
CFC-12 Nonaerosols:								
RATIO OF CFC/GNP (US) (10**3 MT/YR)	37.645	37.772	39.127	42.056	46.033	51.176	57.700	65.869
US CFC CONSUMPTION (10**3 MT/YR)	128.321	172.787	239.732	331.542	461.098	598.228	779.570	1,030.872
ROW CFC CONSUMPTION (10**3 MT/YR)	120.797	174.039	263.400	414.791	664.279	952.858	1,377.317	2,040.773
WORLD CFC CONSUMPTION (10**3 MT/YR)	249.121	346.826	503.124	746.321	1,125.379	1,551.099	2,156.903	3,071.668
WORLD CFC BANK (10**3 MT)	881.141	1,377.701	2,000.347	2,947.394	4,445.590	6,295.930	8,722.164	12,323.117
WORLD CFC EMISSION (10**3 MT/YR)	191.463	296.206	428.816	630.988	951.686	1,351.506	1,870.871	2,640.922
WORLD CFC CONCENTRAIONS (10**3 MT)	2,751.606	4,734.773	7,535.559	11,544.707	17,502.113	26,154.359	37,915.098	54,195.031
CFC-11 Aerosols:								
RATIO OF CFC/GNP (US) (10**3 MT/YR)	24.061	24.982	26.489	28.426	30.957	34.230	38.385	43.589
US CFC CONSUMPTION (10**3 MT/YR)	4.101	5.713	8.108	11.186	15.470	19.958	25.864	34.021
ROW CFC CONSUMPTION (10**3 MT/YR)	111.899	166.782	260.069	416.439	680.136	989.654	1,452.441	2,189.739
WORLD CFC CONSUMPTION (10**3 MT/YR)	116.000	172.495	268.177	427.624	695.605	1,009.613	1,478.304	2,223.763
WORLD CFC BANK (10**3 MT)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WORLD CFC EMISSIONS (10**3 MT/YR)	116.000	172.495	268.177	427.624	695.605	1,009.613	1,478.304	2,223.763
WORLD CFC CONCENTRATIONS (10**3 MT)	2,506.003	3,654.350	5,426.937	8,254.383	12,912.727	19,949.750	30,030.828	44,998.930
CFC-12 Aerosols:								
RATIO OF CFC/GNP (US) (10**3 MT/YR)	31.693	32.632	34.352	36.724	39.871	44.002	49.268	55.878
US CFC CONSUMPTION (10**3 MT/YR)	5.402	7.290	10.019	13.368	17.982	22.829	29.224	38.076
ROW CFC CONSUMPTION (10**3 MT/YR)	178.797	270.379	426.177	682.794	1,104.890	1,595.984	2,319.579	3,452.257
WORLD CFC CONSUMPTION (10**3 MT/YR)	184.200	277.669	436.193	696.163	1,122.887	1,618.817	2,348.805	3,490.336
WORLD CFC BANK (10**3 MT)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WORLD CFC EMISSIONS (10**3 MT/YR)	184.200	277.669	436.193	696.163	1,122.870	1,618.817	2,348.805	3,490.336
WORLD CFC CONCENTRATIONS (10**3 MT)	3,380.376	5,110.043	7,803.324	12,113.250	19,162.270	29,654.949	44,464.031	66,151.687

TABLE III-3

Rates of Growth-Base Case and Mean Estimates

	1980-1990	1990-2000	2000-2010	2010-2020	2020-2030	2030-2040	2040-2050
Base Case							
US POPULATION	0.700	0.655	0.430	0.355	0.130	0.100	0.100
ROW POPULATION	1.700	1.610	1.160	1.010	0.560	0.500	0.500
US LABOR PRODUCTIVITY	2.100	2.025	1.650	1.525	1.150	1.100	1.100
RW LABOR PRODUCTIVITY	2.000	1.970	1.820	1.695	1.170	1.100	1.100
US GROSS OUTPUT	2.800	2.680	2.080	1.880	1.280	1.200	1.200
ROW GROSS OUTPUT	3.700	3.580	2.980	2.705	1.730	1.600	1.600
WORLD GROSS OUTPUT	3.489	3.383	2.797	2.548	1.649	1.530	1.533
CFC-11 Nonaerosols:							
RATIO OF CFC/GNP (US)	-0.169	-0.245	-0.233	-0.240	-0.247	-0.249	-0.250
US CFC CONSUMPTION	2.631	2.435	1.847	1.640	1.033	0.951	0.950
ROW CFC CONSUMPTION	3.404	3.265	2.963	2.681	1.508	1.351	1.350
WORLD CFC CONSUMPTION	3.141	2.997	2.625	2.389	1.382	1.248	1.251
WORLD CFC BANK	4.224	3.137	2.744	2.518	1.705	1.294	1.254
WORLD CFC EMISSIONS	4.390	3.157	2.761	2.536	1.749	1.300	1.255
WORLD CFC CONCENTRATIONS	6.257	4.909	4.072	3.521	3.038	2.530	2.170
CFC-12 Nonaerosols:							
RATIO OF CFC/GNP (US)	-0.608	-0.575	-0.056	0.006	0.002	0.001	0.000
US CFC CONSUMPTION	2.192	2.105	2.024	1.886	1.282	1.201	1.200
ROW CFC CONSUMPTION	2.978	2.942	3.199	2.907	1.755	1.601	1.600
WORLD CFC CONSUMPTION	2.581	2.536	2.614	2.463	1.558	1.438	1.442
WORLD CFC BANK	3.893	2.644	2.597	2.560	1.845	1.478	1.444
WORLD CFC EMISSIONS	4.093	2.659	2.595	2.574	1.885	1.484	1.445
WORLD CFC CONCENTRATIONS	5.360	4.259	3.570	3.201	2.849	2.429	2.126
CFC-11 Aerosols:							
RATIO OF CFC/GNP (US)	0.091	0.013	0.014	0.007	0.002	0.001	0.000
US CFC CONSUMPTION	2.891	2.693	2.094	1.887	1.282	1.201	1.200
ROW CFC CONSUMPTION	3.661	3.522	3.215	2.933	1.758	1.601	1.600
WORLD CFC CONSUMPTION	3.635	3.496	3.183	2.906	1.747	1.592	1.592
WORLD CFC BANK	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WORLD CFC EMISSIONS	3.635	3.496	3.183	2.906	1.747	1.592	1.592
WORLD CFC CONCENTRATIONS	3.716	3.659	3.528	3.368	2.975	2.546	2.270
CFC-12 Aerosols:							
RATIO OF CFC/GNP (US)	0.032	-0.034	0.008	0.006	0.002	0.001	0.000
US CFC CONSUMPTION	2.832	2.646	2.088	1.886	1.282	1.201	1.200
ROW CFC CONSUMPTION	3.639	3.495	3.147	2.869	1.751	1.601	1.600
WORLD CFC CONSUMPTION	3.616	3.473	3.121	2.848	1.742	1.593	1.593
WORLD CFC BANK	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WORLD CFC EMISSIONS	3.616	3.473	3.121	2.848	1.742	1.593	1.593
WORLD CFC CONCENTRATIONS	4.029	3.828	3.598	3.372	2.935	2.484	2.204

TABLE III-3
(Continued)

Rates of Growth-Base Case and Mean Estimates

	1980-1990	1990-2000	2000-2010	2010-2020	2020-2030	2030-2040	2040-2050
Means							
US POPULATION	0.707	0.667	0.463	0.386	0.130	0.096	0.096
ROW POPULATION	1.712	1.632	1.211	1.074	0.643	0.590	0.596
US LABOR PRODUCTIVITY	2.220	2.211	1.986	1.922	1.339	1.275	1.297
RW LABOR PRODUCTIVITY	2.029	2.041	1.954	1.850	1.235	1.178	1.206
US GROSS OUTPUT	2.927	2.879	2.451	2.311	1.470	1.373	1.395
ROW GROSS OUTPUT	3.741	3.676	3.169	2.929	1.880	1.770	1.805
WORLD GROSS OUTPUT	3.550	3.499	3.019	2.807	1.803	1.698	1.732
CFC-11 Nonaerosols:							
RATIO OF CFC/GNP (US)	0.127	0.344	0.449	0.590	0.753	0.895	1.021
US CFC CONSUMPTION	3.067	3.260	2.962	2.979	2.295	2.341	2.490
ROW CFC CONSUMPTION	3.745	4.189	4.405	4.576	3.443	3.526	3.787
WORLD CFC CONSUMPTION	3.513	3.887	3.974	4.148	3.165	3.264	3.527
WORLD CFC BANK	4.556	3.907	3.943	4.151	3.459	3.218	3.436
WORLD CFC EMISSIONS	4.432	3.880	3.934	4.153	3.494	3.214	3.430
WORLD CFC CONCENTRATIONS	6.268	5.139	4.595	4.372	4.155	3.798	3.623
CFC-12 Nonaerosols:							
RATIO OF CFC/GNP (US)	0.034	0.352	0.722	0.904	1.059	1.200	1.324
US CFC CONSUMPTION	2.975	3.275	3.242	3.299	2.604	2.648	2.794
ROW CFC CONSUMPTION	3.652	4.144	4.541	4.709	3.608	3.684	3.932
WORLD CFC CONSUMPTION	3.309	3.720	3.943	4.107	3.208	3.297	3.535
WORLD CFC BANK	4.470	3.729	3.876	4.110	3.480	3.260	3.456
WORLD CFC EMISSIONS	4.364	3.700	3.863	4.109	3.507	3.252	3.447
WORLD CFC CONCENTRATIONS	5.427	4.647	4.266	4.161	4.017	3.713	3.572
CFC-11 Aerosols:							
RATIO OF CFC/GNP (US)	0.376	0.586	0.706	0.853	1.005	1.146	1.271
US CFC CONSUMPTION	3.315	3.501	3.219	3.242	2.547	2.592	2.741
ROW CFC CONSUMPTION	3.991	4.443	4.708	4.906	3.751	3.836	4.105
WORLD CFC CONSUMPTION	3.968	4.413	4.666	4.865	3.725	3.813	4.083
WORLD CFC BANK	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WORLD CFC EMISSIONS	3.968	4.413	4.666	4.865	3.725	3.813	4.083
WORLD CFC CONCENTRATIONS	3.772	3.955	4.194	4.475	4.350	4.090	4.044
CFC-12 Aerosols:							
RATIO OF CFC/GNP (US)	0.292	0.514	0.668	0.822	0.9086	1.130	1.259
US CFC CONSUMPTION	2.997	3.179	2.884	2.965	2.387	2.470	2.646
ROW CFC CONSUMPTION	4.136	4.550	4.713	4.813	3.677	3.739	3.976
WORLD CFC CONSUMPTION	4.104	4.517	4.675	4.781	3.658	3.722	3.961
WORLD CFC BANK	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WORLD CFC EMISSIONS	4.104	4.517	4.675	4.781	3.658	3.722	3.961
WORLD CFC CONCENTRATIONS	4.132	4.233	4.397	4.586	4.367	4.051	3.973

TABLE III-4

25th and 75th Percentile Scenarios
Based on Probabilitistic Scenarios

	1990	2000	2010	2020	2030	2040	2050
Major Driving Variables:							
25% Points from Highest							
U.S. POPULATION (10**9)	0.263	0.280	0.295	0.301	0.306	0.310	
ROW POPULATION (10**9)	5.162	6.257	7.306	8.413	9.260	10.133	11.087
US LABOR PRODUCTIVITY (1985$ 10**3/CAP*YR)	20.863	28.731	39.567	53.276	64.103	75.981	90.060
RW LABOR PRODUCTIVITY (1985$ 10**3/CAP*YR)	3.078	3.748	4.496	5.327	5.988	6.684	7.461
U.S GROSS OUTPUT (1985$ 10**12/YR)	4.985	7.256	10.328	14.265	17.216	20.406	24.187
ROW GROSS OUTPUT (1984$ 10**12/YR)	15.887	23.454	32.852	44.814	55.452	67.729	82.724
WORLD GROSS OUTPUT (1985$ 10**12/YR)	20.922	30.856	43.494	59.661	73.550	89.397	108.665
25% Points from Lowest							
US POPULATION (10**9)	0.241	0.258	0.269	0.279	0.282	0.285	0.288
ROW POPULATION (10**9)	5.009	5.884	6.608	7.310	7.731	8.127	8.544
US LABOR PRODUCTIVITY (1985$ 10**3/CAP*YR)	18.690	22.885	26.991	31.437	35.268	39.369	43.947
RW LABOR PRODUCTIVITY (1985$ 10**3/CAP*YR)	3.078	3.748	4.496	5.327	5.988	6.684	7.461
US GROSS OUPUT (1985$ 10**12/YR)	4.465	5.780	7.045	8.418	9.472	10.573	11.802
ROW GROSS OUPUT (1985$ 10**12/YR).650	14.813	20.359	26.351	33.232	38.302	43.619	49.675
WORLD GROSS OUTPUT (1985$ 10**12/YR)	19.323	26.255	33.611	41.993	48.259	54.846	62.333
CFC-11 Nonaerosols:							
25% Points from Highest							
RATIO OF CFC/GNP (US) (10**3 MT/YR)	25.263	31.627	37.797	44.887	53.457	63.680	75.854
US CFC CONSUMPTION (10**3 MT/YR)	103.098	151.766	206.053	285.687	341.956	401.323	470.970
ROW CFC CONSUMPTION (10**3 MT/YR)	216.726	369.757	612.346	1,007.599	1,354.829	1,777.063	2,330.753
WORLD CFC CONSUMPTION (10**3 MT/YR)	311.733	506.536	784.184	1,176.177	1,617.706	2,215.491	3,045.602
WORLD CFC BANK (10**3 MT)	1,236.624	1,915.576	3,081.874	4,694.414	6,737.695	9,239.391	12,442.797
WORLD CFC EMISSION (10**3 MT/YR)	254.521	413.702	650.924	994.623	1,395.858	1,902.741	2,598.740
WORLD CFC CONCENTRAIONS (10**3 MT)	3,768.578	6,581.363	11,180.367	18,018.219	27,858.199	41,106.008	58,880.211
25% Points from Lowest							
RATIO OF CFC/GNP (US) (10**3 MT/YR)	19.504	19.032	18.593	18.153	17.710	17.274	16.848
US CFC CONSUMPTION (10**3 MT/YR)	78.806	89.387	94.415	98.731	98.218	95.406	90.303
ROW CFC CONSUMPTION (10**3 MT/YR)	147.620	169.343	179.709	198.749	196.861	193.402	188.634
WORLD CFC CONSUMPTION (10**3 MT/YR)	230.760	274.975	330.995	390.663	406.863	427.685	446.512
WORLD CFC BANK (10**3 MT)	903.568	1,140.644	1,372.464	1,666.671	1,849.729	1,941.073	2,082.438
WORLD CFC EMISSIONS (10**3 MT/YR)	208.710	251.501	303.486	361.648	394.130	412.398	441.535
WORLD CFC CONCENTRATIONS (10**3 MT)	3,473.714	5,450.258	7,568.594	10,062.211	12,712.559	15,189.402	17,991.176

TABLE III-4
(Continued)

25th and 75th Percentile Scenarios
Based on Probabilistic Scenarios

	1990	2000	2010	2020	2030	2040	2050
CFC-12 Nonaerosols:							
25% Points from Highest							
RATIO OF CFC/GNP (US) (10**3 MT/YR)	49.017	62.846	77.288	94.457	115.397	140.958	172.172
US CFC CONSUMPTION (10**3 MT/YR)	200.035	301.57	398.559	523.771	642.762	793.560	983.937
ROW CFC CONSUMPTION (10**3 MT/YR)	197.649	322.568	545.165	892.341	1,220.446	1,663.748	2,285.084
WORLD CFC CONSUMPTION (10**3 MT/YR)	406.578	651.229	1,000.736	1,629.301	2,387.655	3,372.282	4,802.164
WORLD CFC BANK (10**3 MT)	1,608.779	2,448.530	3,859.858	6,011.305	8,782.383	11,837.477	15,966.754
WORLD CFC EMISSIONS (10**3 MT/YR)	321.359	538.702	841.222	1,321.166	1,971.746	2,905.516	4,033.716
WORLD CFC CONCENTRATIONS (10**3 MT)	4,903.859	8,251.828	13,770.059	21,886.211	34,148.199	52,692.902	78,302.437
25% Points from Lowest							
RATIO OF CFC/GNP (US) (10**3 MT/YR)	35.427	33.448	33.261	33.281	33.288	33.291	33.292
US CFC CONSUMPTION (10**3 MT/YR)	144.575	160.505	171.519	181.010	184.616	187.421	190.260
ROW CFC CONSUMPTION (10**3 MT/YR)	138.628	158.029	183.845	208.512	211.656	211.673	223.563
WORLD CFC CONSUMPTION (10**3 MT/YR)	291.868	345.501	409.812	490.486	522.164	559.566	600.251
WORLD CFC BANK (10**3 MT)	1,153.086	1,404.957	1,738.043	2,103.559	2,325.642	2,656.364	2,813.909
WORLD CFC EMISSIONS (10**3 MT/YR)	265.582	318.594	376.784	449.639	501.927	537.825	576.768
WORLD CFC CONCENTRATIONS (10**3 MT)	4,566.410	6,784.160	9,187.453	11,772.969	14,651.266	17,508.289	20,500.742
CFC-11 Aerosols:							
25% Points from Highest							
RATIO OF CFC/GNP (US) (10**3 MT/YR)	31.297	40.068	49.272	60.222	73.574	89.872	109.774
US CFC CONSUMPTION (10**3 MT/YR)	6.386	9.614	13.491	19.172	23.528	28.312	34.067
ROW CFC CONSUMPTION (10**3 MT/YR)	198.482	346.312	603.360	1,004.243	1,387.192	1,868.938	2,517.841
WORLD CFC CONSUMPTION (10**3 MT/YR)	203.958	355.553	612.198	1,014.916	1,400.137	1,883.608	2,541.287
WORLD CFC BANK (10**3 MT)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WORLD CFC EMISSIONS (10**3 MT/YR)	203.958	355.553	612.198	1,014.916	1,400.137	1,883.608	2,541.287
WORLD CFC CONCENTRATIONS (10**3 MT)	3,807.616	6,139.672	10,215.488	17,174.477	27,287.613	40,535.016	58,003.902
25% Points from Lowest							
RATIO OF CFC/GNP (US) (10**3 MT/YR)	24.282	24.314	24.348	24.365	24.371	24.373	24.374
US CFC CONSUMPTION (10**3 MT/YR)	4.905	5.710	6.202	6.626	6.758	6.732	6.533
ROW CFC CONSUMPTION (10**3 MT/YR)	134.384	157.610	172.506	195.365	198.280	198.298	198.305
WORLD CFC CONSUMPTION (10**3 MT/YR)	140.497	166.609	183.693	201.608	214.583	207.788	220.319
WORLD CFC BANK (10**3 MT)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WORLD CFC EMISSIONS (10**3 MT/YR)	140.497	166.609	183.693	201.608	214.583	207.788	220.319
WORLD CFC CONCENTRATIONS (10**3 MT)	3,503.788	4,655.246	5,898.242	7,181.227	8,488.150	9,805.414	10,991.805

TABLE III-4
(Continued)

25th and 75th Percentile Scenarios
Based on Probabilitistic Scenarios

CFC-12 Aerosols:	1990	2000	2010	2020	2030	2040	2050
25% Points from Highest							
RATIO OF CFC/GNP (US) (10**3 MT/YR)	41.016	52.284	64.133	78.236	95.559	116.727	142.576
US CFC CONSUMPTION (10**3 MT/YR)	8.286	12.278	16.536	22.636	27.324	32.857	40.740
ROW CFC CONSUMPTION (10**3 MT/YR)	315.540	551.745	896.992	1,505.762	2,061.926	2,770.571	3,853.907
WORLD CFC CONSUMPTION (10**3 MT/YR)	322.711	561.088	920.720	1,509.080	2,064.678	2,836.096	3,944.146
WORLD CFC BANK (10**3 MT)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WORLD CFC EMISSIONS (10**3 MT/YR)	322.711	561.088	920.720	1,509.080	2,064.678	2,836.096	3,944.146
WORLD CFC CONCENTRATIONS (10**3 MT)	5,327.379	8,798.227	14,816.363	24,085.199	37,460.031	55,562.504	80,272.687
25% Points from Lowest							
RATIO OF CFC/GNP (US) (10**3 MT/YR)	31.797	31.690	31.716	31.736	31.743	31.746	31.747
US CFC CONSUMPTION (10**3 MT/YR)	6.360	7.294	7.853	8.142	8.251	8.334	8.418
ROW CFC CONSUMPTION (10**3 MT/YR)	222.848	274.189	328.231	380.385	382.926	405.643	436.901
WORLD CFC CONSUMPTION (10**3 MT/YR)	230.090	283.735	339.614	395.121	403.926	438.033	475.294
WORLD CFC BANK (10**3 MT)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WORLD CFC EMISSIONS (10**3 MT/YR)	230.090	283.735	339.614	395.121	403.926	438.033	475.294
WORLD CFC CONCENTRATIONS (10**3 MT)	4,890.773	6,671.895	8,723.535	11,047.801	13,335.801	15,284.191	17,503.582

results suggest that it is equally likely that the value of future CFC production will lie between the two paths as it is that it will lie outside their boundary.

A few words may be necessary to explain exactly what this and the other dispersion measures are intended to convey. At the present time, we have some information, but only very imperfect information, about the factors that determine future CFC production. We are unsure about future population levels, about the course of technological change, about new products that will embody CFCs or substitutes, and so forth. Using a combination of statistical techniques and informed judgment, we have attempted to measure the extent of the uncertainty about future trends. To take a particular case, we have surveyed experts on population and have from them derived estimates of possible likely paths of population growth over the coming decades. From these estimates, we have formed a judgment about how likely different CFC production outcomes seem to be. When all of the uncertain factors are incorporated, Table III-4 indicates, for example, that it is equally likely that world CFC-12 (nonaerosol) production in 2020 will lie between 490 thousand and 1600 thousand MT/yr as it is that it will lie outside that range. That represents enormous uncertainty for a 35 year glimpse into the future, but it is our view that such uncertainty accurately reflects the current state of knowledge and ignorance about future CFC use trend.

It should also be clear that relying upon maximum likelihood or best guess scenarios to evaluate the severity of potential CFC damage could be a serious mistake. If conditions in the future turn out to correspond with the combinations of population growth, productivity growth, and CFC

intensity that have here produced simulated trajectories above the best guess, then the skewness or the results means that our present view of the best guess will seriously underestimate the magnitude of the future problem.

Table III-5 records an alternate measure of dispersion, the standard deviations of the various important variables. Tracking these statistics into the future reveals the ever increasing uncertainty that surrounds our understanding. Computing the associated t-statistics, a dimensionless composite measure of dispersion based on these standard deviations, supports the validity of an interesting conjecture: emissions of nonaerosols, at any point in time, should be less uncertain than the consumption that produces them. As revealed in Table III-6, this conjecture is true, but only to a limited degree. The estimated t-statistics for world consumption are, indeed, always smaller than those for world emissions; i.e., the standard deviation measured as a fraction of the corresponding mean is always higher for consumption than for emissions. This result obtains, of course, because depositing of nonaerosols into the bank delays their release into the atmosphere, and thus spreads the full effect of their uncertainty into the future. Still, the net effect of the delay is spent in less than ten years.

TABLE III-5

Estimated Standard Deviations
Based on Probabilistic Scenarios

	1990	2000	2010	2020	2030	2040	2050
Major Driving Variables:							
U.S. POPULATION (10**9)	0.000	0.004	0.007	0.010	0.011	0.013	0.015
ROW POPULATION (10**9)	0.119	0.280	0.493	0.746	0.988	1.253	1.549
US LABOR PRODUCTIVITY (1985$ 10**3/CAP*YR)	1.377	3.537	7.227	12.077	15.860	0.029	25.019
RW LABOR PRODUCTIVITY (1985$ 10**3/CAP*YR)	0.193	0.476	0.882	1.421	1.947	2.551	3.271
U.S GROSS OUTPUT (1985$ 10**12/YR)	0.336	0.922	1.976	3.436	4.576	5.839	7.371
ROW GROSS OUTPUT (1984$ 10**12/YR)	1.049	3.049	6.425	11.578	17.008	23.784	32.587
WORLD GROSS OUTPUT (1985$ 10**12/YR)	1.091	3.166	6.682	12.006	17.504	24.332	33.191
CFC-11 Nonaerosols:							
RATIO OF CFC/GNP (US) (10**3 MT/YR)	3.642	7.327	10.589	14.133	18.260	23.066	28.706
US CFC CONSUMPTION (10**3 MT/YR)	18.599	50.918	99.508	174.904	263.278	384.038	555.135
ROW CFC CONSUMPTION (10**3 MT/YR)	45.190	138.286	330.046	721.560	1,281.422	2,230.666	3,930.552
WORLD CFC CONSUMPTION (10**3 MT/YR)	57.042	167.643	372.635	777.273	1,356.666	2,327.909	4,050.651
WORLD CFC BANK (10**3 MT)	221.859	606.510	1,353.727	2,838.618	5,165.273	8,840.082	15,249.957
WORLD CFC EMISSIONS (10**3 MT/YR)	32.897	115.892	274.083	587.715	1,084.152	1,865.854	3,231.867
WORLD CFC CONCENTRATIONS (10**3 MT)	193.966	845.606	2,6720.045	6,459.406	13,892.355	26,636.168	48,350.137
CFC-12 Nonaerosols:							
RATIO OF CFC/GNP (US) (10**3 MT/YR)	7.359	15.242	22.516	30.740	40.498	52.209	66.369
US CFC CONSUMPTION (10**3 MT/YR)	37.292	104.597	208.125	373.992	575.910	859.543	1,271.675
ROW CFC CONSUMPTION (10**3 MT/YR)	43.100	133.179	317.307	694.822	1,248.089	2,194.427	3,894.938
WORLD CFC CONSUMPTION (10**3 MT/YR)	71.635	209.456	443.787	881.720	1,508.547	2,541.875	4,341.871
WORLD CFC BANK (10**3 MT)	280.414	763.267	1,647.498	3,291.197	5,830.914	9,793.219	16,570.477
WORLD CFC EMISSION (10**3 MT/YR)	41.200	145.321	331.728	676.156	1,212.880	2,049.568	3,484.455
WORLD CFC CONCENTRAIONS (10**3 MT)	241.392	1,039.144	3,150.009	7,459.504	15,415.832	28,678.437	50,766.086
CFC-11 Aerosols:							
RATIO OF CFC/GNP (US) (10**3 MT/YR)	4.455	9.199	13.763	18.958	25.132	32.555	41.545
US CFC CONSUMPTION (10**3 MT/YR)	1.141	3.204	6.474	11.731	18.118	27.101	40.170
ROW CFC CONSUMPTION (10**3 MT/YR)	41.262	129.989	323.232	736.073	1,350.855	2,427.698	4,415.059
WORLD CFC CONSUMPTION (10**3 MT/YR)	41.831	131.388	325.117	738.389	1,354.089	2,432.022	4,420.520
WORLD CFC BANK (10**3 MT)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WORLD CFC EMISSIONS (10**3 MT/YR)	41.832	131.388	325.117	738.389	1,354.089	2,432.022	4,420.520
WORLD CFC CONCENTRATIONS (10**3 MT)	199.079	1,002.714	3,062.425	7,844.797	17,152.004	33,552.543	62,959.516
CFC-12 Aerosols:							
RATIO OF CFC/GNP (US) (10**3 MT/YR)	5.836	11.997	17.885	24.572	32.554	42.153	53.771
US CFC CONSUMPTION (10**3 MT/YR)	1.455	4.060	8.195	14.861	22.932	34.271	50.772
ROW CFC CONSUMPTION (10**3 MT/YR)	64.706	200.137	482.012	1,069.223	1,943.094	3,453.305	6,185.703
WORLD CFC CONSUMPTION (10**3 MT/YR)	65.565	202.298	485.095	1,073.188	1,948.455	3,460.241	6,194.250
WORLD CFC BANK (10**3 MT)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WORLD CFC EMISSIONS (10**3 MT/YR)	65.565	202.298	485.095	1,073.188	1,948.455	3,460.241	6,194.250

TABLE III-6

T-Statistics for Emissions and Consumption*

	1990	2000	2010	2020	2030	2040	2050
CFC-11 Nonaerosols							
World CFC Emissions	7.06	2.96	1.86	1.31	1.01	2.81	0.66
World CFC Consumption	4.82	2.42	1.62	1.18	0.92	0.75	0.61
CFC-12 Nonaerosols							
World CFC Emissions	7.22	2.95	1.91	1.41	1.11	0.91	0.76
World CFC Consumption	4.87	2.41	1.68	1.28	1.03	0.85	0.71

* Computed as the ratio of the mean estimates of Table III-1 and the standard deviations of Table III-5.

IV. Worldwide Regulation of Aerosol Consumption.

The results presented of the previous section do not reflect the effects of any CFC regulation beyond the U.S. ban on nonessential use of aerosols. They are advanced as benchmark projection against which the ability of further regulation can be judged. They do not, therefore, include the potential effects of either the voluntary cap on aerosol capacity currently in place throughout the EEC or of other voluntary restrictions on aerosol consumption now imposed by several other nations around the world.

The present section will report results for aerosols under an alternative assumption that all of the regulation presently in place throughout the world, be it voluntary or mandated by law, will remain in effect for the next seven decades regardless of economic circumstance. Future economic forces may, of course, cause some countries to weaken their restraint; serious future environmental damage may, on the other hand, drive more countries to impose stringent constraints upon themselves. The future regulatory environment is yet another source of uncertainty in projecting ranges of emissions and concentrations for CFCs, but we will make no attempt to endogenize the demand for regulation. A set of "worldwide status quo" results is, instead, reported in this section to provide some insight into the potential effectiveness of current worldwide efforts to control aerosol emissions.

More specifically, we first assume that 1980 aerosol consumption in the United States represents essential use. We apply, therefore, the frontier growth model described in Sections I and II directly to those initial levels. For the rest of the world, we assume (1) that the EEC capacity

constraint will hold nonessential aerosol use at observed 1980 levels, (2) that the EEC capacity constraint will allow essential aerosol use to grow and (3) that voluntary restrictions imposed by individual, non-EEC nations will hold their aerosol consumption fixed at 1980 levels (e.g., Japan: 25 percent reduction held fixed; Canada: 79 percent reduction held fixed; Norway and Sweden: total ban held fixed). Finally, essential EEC use was computed by applying the fraction of peak U.S. levels represented by 1980 U.S. consumption to the 1980 EEC consumption total.

The significance of these assumptions for the two aerosol compounds is displayed in Table IV-1. Voluntary restraint across the world, if it were to continue as is for the next 70 years, would effectively fix 73,400 metric tons of CFC-11 aerosol consumption at 1980 levels. The remaining 38,500 tons of 1980 CFC-11 aerosol consumption (35 percent of total) would thus be allowed to grow as a reflection of essential use in the U.S., essential use in the EEC, or unrestrained essential and nonessential use across the rest of the world. Similarly, existing regulation would fix 106,400 metric tons of CFC-12 aerosol consumption leaving 72,400 tons (41 percent of 1980 world consumption) to grow in one of the three categories just noted.

Table IV-2 reports the major results of incorporating these assumptions into the probabilistic scenario analysis. All of the statistics recorded there--the base cases, the mean trajectories, and the inner-quartile ranges--are all reduced by recognizing and projecting existing worldwide regulation. Annual growth rates of total world consumption over the 70 year time horizon fall, for the mean trajectory (e.g.), from 4.22 percent per year to 2.86 percent per year for CFC-11 aerosols and from 4.20 percent per year to 3.04 percent per year for CFC-12 aerosols.

TABLE IV-1

Distribution of 1980 CFC Aerosol Consumption
Between Constrained and Unconstrained Components*

	U.S. Essential	EEC Essential	Rest of World
CFC-11 Aerosols:			
Constrained	---	---	73.390
Unconstrained	4.100	6.170	32.340
CFC-12 Aerosols:			
Constrained	---	---	106.400
Unconstrained	5.400	10.730	61.670

*Measured in 10^3 M tons of consumption.

TABLE IV-2

Probabilistic Results—Consumption Responding to Voluntary Regulation Across the World[a]

		1980	2000	2020	2050
A. CFC-11 Aerosols					
United States:	25th	4.10(nc)[b]	5.71 (nc)	6.63 (nc)	6.53 (nc)
	Mean	4.10(nc)	8.11 (nc)	15.47 (nc)	34.02 (nc)
	75th	4.10(nc)	9.61 (nc)	19.17 (nc)	34.07 (nc)
	Median	4.10(nc)	7.17 (nc)	10.67 (nc)	15.43 (nc)
Rest of the World:	25th	111.90(nc)	127.63 (157.61)	140.62 (195.37)	141.63 (198.31)
	Mean	111.90(nc)	162.88 (260.07)	307.41 (680.14)	826.79 (2,189.74)
	75th	111.90(nc)	192.55 (346.31)	418.92 (1,004.24)	939.68 (2,517.84)
	Median	111.90(nc)	153.36 (229.49)	219.41 (424.39)	313.17 (696.89)
World:	25th	116.00(nc)	135.93 (166.61)	155.34 (201.61)	168.54 (220.32)
	Mean	116.00(nc)	170.99 (268.18)	322.88 (695.61)	860.81 (2,223.76)
	75th	116.00(nc)	200.43 (355.55)	429.59 (1,014.92)	993.32 (2,541.29)
	Median	116.00(nc)	159.53 (236.66)	230.09 (435.06)	328.60 (712.31)
B. CFC-12 Aerosols					
United States:	25th	5.40(nc)	7.29 (nc)	8.14 (nc)	8.42 (nc)
	Mean	5.40(nc)	10.02 (nc)	17.98 (nc)	38.08 (nc)
	75th	5.40(nc)	12.28 (nc)	22.64 (nc)	40.74 (nc)
	Median	5.40(nc)	9.34 (nc)	13.90 (nc)	20.09 (nc)
Rest of the World:	25th	178.80(nc)	217.43 (274.19)	260.43 (380.39)	283.31 (436.90)
	Mean	178.80(nc)	278.97 (426.18)	553.79 (1,104.89)	1,504.28 (3,452.26)
	75th	178.80(nc)	329.81 (551.75)	716.12 (1,505.76)	1,666.93 (3,853.91)
	Median	178.80(nc)	254.17 (364.94)	376.07 (665.99)	548.89 (1,092.79)
World:	25th	184.20(nc)	227.17 (283.74)	275.16 (395.12)	318.87 (475.29)
	Mean	184.20(nc)	288.99 (436.19)	571.77 (1,122.87)	1,542.36 (3,490.34)
	75th	184.20(nc)	339.16 (561.09)	719.43 (1,509.08)	1,752.06 (3,944.15)
	Median	184.20(nc)	263.51 (374.28)	389.97 (679.89)	568.99 (1,12.88

[a] Figures in parentheses are the comparable results in the absence of worldwide regulation (Section III).

[b] nc = no change.

Finally, to test the potential effectiveness of unilateral U.S. aerosol restriction, the model was manipulated to show that frontier growth rates (CFC per GNP intensity) of -3.00 percent per year, -1.95 percent per year, and -1.20 percent per year for the 1980-2000, 2000-2025, and 2025-2500 eras would be sufficient to hold CFC-12 aerosol consumption constant along the base trajectory for the entire 70 year time horizon. If these large reductions in essential CFC use intensity were the result of economically viable processes that were adopted by other producers around the world, then the base case would lead to consumption in the rest of the world equal to approximately 280,000 metric tons by the year 2050. World consumption would, as a result, be 50 percent lower than the regulatory base case recorded in Table IV-2, but still 50 percent higher than in 1980. Given that the mean of the probabilistic runs is generally an order of magnitude higher than the base case, even this extraordinary scenario does not allow us to expect that world aerosol consumption will not increase markedly over the next 70 years.

Appendix A: Specification and Estimation of the Demand for CFCs.

The demand for CFCs is divided into two components. The first, designed to depict experience in the United States, is driven by the CFC frontier described in Section I. The second, designed to depict experience outside the United States, is driven by U.S. demand and market development in a way that is also described in Section I. The precise specifications and supporting estimation procedures of these two modeling structures are recorded in this appendix.

A-1. Specification of Demand in the U.S. - the CFC Frontier.

The fundamental construction underlying the U.S. model centers around the specification of the potential frontier. An asymptotic CFC intensity, denoted by $Z^*(t)$, is assumed to grow over time at a constant growth rate plus a random error term reflecting changing technology, price trends, and incomes. Accordingly,

$$\text{(A-1)} \qquad \log [Z^*(t)] = a + gt + e(t)$$

where

$Z^*(t)$ = potential CFC consumption per dollar of real GNP in year t;

g = the growth rate of Z^* (positive or negative);

a = an initializing parameter; and

$e(t)$ = a random error term.

According to equation (A-1), the asymptotic frontier in Figure I-2 should be moving, on the average, at an annual rate of g. The estimate for this

average g is thus taken to be the middle value for the frontier growth rate in the scenario analysis. The high and low values are then simply the reflection of the imprecision with which we can estimate that average g given the uncertainty captured in (A-1) by the e(t).

The two stage estimation procedure employed in Stage I of this work turned out to be too sensitive to the initialization assumptions, and has been discarded. A second methodology based upon aggregate CFC proxies is, instead, employed to estimate both the most likely value for g and its surrounding range of uncertainty. More specifically, we consider, for each of the four chemicals (CFC-11 and -12, aerosols and nonaerosols), a time series of indexed proxies defined by

$$\text{(A-2)} \qquad CFC(t) = \sum_j a_j(1973)X_j(t),$$

where

$$a_j(1973) = [CFC_j(1973)/X_j(1973)]$$

are the CFC input/output coefficients for products X_j computed using 1973 data. The $a_j(1973)$ are, in other words, the product- specific CFC-usage intensities that were observed in 1973. Equation (A-2) uses these intensities as weights in constructing a total use time series of derived demand proxies based upon observed end product production levels recorded over several decades. Estimates of income elasticities for the various CFC chemicals can then be obtained by estimating the income elasticities of the constructed CFC(t) proxies over recent years. The result is a set of reliable estimates of frontier income elasticities as long as (1) future patterns of use for the products are close to historical ones and (2) there

is no systematic change in the CFC-usage intensities in future years. The desired estimates of frontier growth rates can, finally, be produced by subtracting 1 from the elasticity estimates.

The weights employed in this procedure are listed in Table A-1. They are expressed in terms of percent of total CFC use in each product category because the actual CFC(t) proxy series are index number series normalized for 1973 = 100. Note, too, that CFC-11 and CFC-12 are distinguishable only in nonaerosol form. The end product use time series for the 12 product groups listed are drawn from the U.S. National Income and Product Accounts; their precise sources are noted in Table A-2.

The resulting income elasticity estimates are recorded in Table A-3. They conform, reasonably well, to less precise estimates that can be obtained by computing the weighted average of end use income elasticities produced by Houthakker and Taylor in 1970 (using, again, the weights of Table A-1). The standard errors of the income elasticity estimates are, however, too small to be applicable as reasonable measures of the uncertainty with which we project into the future.

As a way of estimating uncertainty about the growth of the CFC frontier, we investigated the historical variation in growth rates of different materials; Table A-4 displays the results. The first line simply records the standard deviation of the growth rate of 13 major materials over the period 1900 to 1984: a dispersion of 3.29 percent per annum. A second measure is the same statistic for 24 resources (both fuel and nonfuel) studied by the Paley Commission. Smaller dispersions are noted, probably because the time period studied was one smaller structural change.

The most appropriate measure is the error of forecasts of 24 materials

TABLE A-1

Weights for Estimating
the Derived Demand for CFCs[a]

	Aerosols[b]		Nonaerosols	
	11	12	11	12
New Construction	0	0	36.8	19.8
Household Furniture	0	0	28.0	56.9
Motor Vehicles	2.7	2.7	19.5	3.9
Textiles	0	0	.9	0
Household Appliances	0	0	9.2	4.0
Marine Products	0	0	2.2	.1
Electrical Equipment	0	0	0	7.0
Health Services	0	0	0	8.3
Food Products	3.3	3.3	3.4	0
Household Products	38.3	38.3	0	0
Personal Products	52.2	52.2	0	0
Industrial Products	3.5	3.5	0	0
TOTAL	100.0	100.0	100.0	100.0

Notes:

[a] Expressed in percent of total in each category.

[b] Source: Exhibit 2-1 (1973 data), RAND, 1986.

TABLE A-2

Sources for Estimating
the Derived Demand for CFCs*

	Source	Series Name
New Construction	Table 1.2, 1.12	NC
Household Furniture	Table 2.5, 1.9	HF
Motor Vehicles	Table 2.5, 1.4	MV
Textiles	Table 2.5, 1.27	TX
Household Appliances	Table 2.5, 1.10	HA
Marine Products	Table 2.5, 1.82	MP
Electrical Equipment	Table 1.2, 1.10	EE
Health Services	Table 2.5, 1.71	HS
Food Products	Table 2.5, 1.20	FP
Household Products	Table 2.5, 1.37	CP
Personal Products	Table 2.5, 1.67	PP
Industrial Products	Table 1.4, 1.4	IP

*In each case, these refer to the U.S. National Income and Product Accounts, Standard Tables, as in Survey of Current Business, July 1985. Data are all in constant 1972 prices for the mentioned category.

TABLE A-3

Results for Estimates of Derived Demand for CFC's: 1948-84[a]

Dependent Variable	Output Elasticity[b]	Rho(ρ)	$\bar{R}^2$
Aerosols	1.02 (.065)	.45	.999
Nonaerosols-11	0.80 (.064)	.40	.926
Nonaerosols-12	1.09 (.041)	.37	.979

Notes:

a Equation took the form $\ln(C_{it}) = A + b\ln(GNP + \rho u_{t-1} + \varepsilon_t$ where C_{it} = weighted production of CFC-containing products; GNP = real GNP in 1972 prices; u_t and ε_t = error terms; ρ = estimated coefficient on first-order autoregressive error.

b Figures in parentheses under output elasticity are the standard error of the coefficient.

TABLE A-4

Standard Deviation in Growth Rates
for Different Materials

Source	Standard Deviation of Growth Rate (percent per year)
13 major materials, 1900-1984	3.29
Paley Commission (24 materials)	
Actual 1950 vs. Actual 1972	2.49
Forecast vs. Actual 1972	1.94

Sources: Data for the major materials were taken from U.S. Department of Commerce, Historical Statistics of the United States; data on the Paley Commission, from Richard cooper and Robert Lawrence, "The 1972-75 Commodity Boom," Brookings Papers on Economic Activity, 1975.

made by the Paley Commission for the period 1952 to 1972. It is conceptually closest to the uncertainty about the forecast of CFC use prepared for this study. We have rounded the figure to 2 percent per annum when using it as the most likely forecast error for our CFC frontier growth estimates.

A-2. Specification of Demand in the Rest of the World.

In order to estimate the growth of CFC consumption in the rest of the world, it is necessary to estimate the demand for CFCs in regions outside of the United States. This task poses formidable difficulties because of a lack of data on consumption throughout the rest of the world, but particularly outside of the OECD countries. Rough estimates are, nonetheless, obtained in the following manner.

The basic assumption, as stated in the text, is that the trajectory of consumption in the rest of the would will approach the U.S. experience as per capita incomes outside of the U.S. approach American levels. To represent this assumption formally, we consider

$$\text{(A-3)} \qquad \ln(C_k/C_1) = r \ln(Y_k/Y_1),$$

where

C_k = per capita consumption or production of CFCs in region k;

k = 1 for the U.S., 2 for the EEC, 3 for developed developed regions in the Pacific, 4 for the Eastern Block, 5 for Latin America, 6 for Africa, and 7 for all other countries;

Y_k = per capita GNP for the same country groupings; and

r = a coefficient to be estimated.

Data on CFC consumption, per capita incomes, and population are drawn from the RAND report (1985). The CFC consumption data is recorded in Table B-13. The unallocated totals, labeled "other used in developed countries," were allocated proportionally to CFC production identified for each region. We then estimated equation (A-3); the results are shown in Table A-5. Moving from the estimates of r to most likely middle values for the desired "relative intensity elasticities" recorded in Table II-2 of the text is again accomplished by subtracting 1 from the values recorded for the four chemicals in Table A-5. The ranges noted in II-2 are produced by assigning values to the two outside 25 percent likelihood cells of plus and minus /2 times the standard deviations of the estimates also noted in Table A-5.

The results confirm, in general, the initial impression that other countries lag far behind the U.S. in their use of CFCs. We may, therefore, witness very rapid growth in CFC production and consumption in the rest of the world if, in the absence of regulatory restraint, economic growth continues at historical levels in those countries.

Table A-5

Estimates of Cross Section Regression
--Per Capita Income Elasticities

Chemical	Elasticity (Standard Error of Coefficient)	R^2
11 Nonaerosols	2.27 (.25)	.848
12 Nonaerosols	2.15 (.20)	.868
11 Aerosols	2.30 (.37)	.729
12 Aerosols	1.93 (.27)	.806

Appendix B: The Data

This appendix begins with a review of the procedure used to construct the distributions for the exogenous variables identified in Section I of the report: the rate of growth of population and productivity in the U.S. and the rest of the world from 1980 through the year 2050. Each distribution is constructed to reflect not only statistical dispersion around published estimates, but also judgmental dispersion evidenced by disagreement across experts' best guesses. A brief description of the CFC data used to estimate the demand structure is also provided.

A. Population.

The population growth estimates for the U.S. and the rest of the world are both computed from a distribution of global growth rates deduced from the estimates recorded in Table B-1. The upper part of the table records the projected rates of growth of the world population reported in 9 separate studies published since 1980. The averages of these cited estimates are taken to be the maximum likelihood estimates for world population growth for the periods noted. For the years 1980 through 2000, for example, the published studies include estimates ranging from 1.3 percent per year up to 1.7 percent per year with an average value of 1.6 percent. The middle cell of a three cell distribution approximating the true distribution of our uncertainty about future population growth rates should therefore be assigned the value 1.6 percent.

For this study, however, we needed more than point estimates of the most likely growth estimates; we also needed measures of the uncertainty associated with each future projection. One possible source of these measure was the cited authors' own estimates of uncertainty, but few authors

Table B-1
Population Growth Estimates - World[a]

	1980-2000	2000-2025	2025-2050
N-Y (1983)	1.7 (.2)	1.1 (.36)	0.3 (.35)
EPA (1985)	1.6	0.9	0.4
UN (1985)	1.6 (.13)	1.3 (.41)	0.7 (.29)
World Bank (1984)	1.6	1.2	0.7
Population Reference Bureau (1985)	1.6	1.2	-
IIASA (1981)	1.7	0.9	-
Rotty and Marland (1980)	1.3	1.3	-
OECD (1981)	1.6	-	-
Keyfitz (1985)	1.4 (.3)	0.9 (.3)	0.4 (.3)
mean (disagreement dispersion)	1.6% (.13%)	1.1% (.18%)	0.5% (.15%)
judgemental dispersion (mean)	.21%	.36%	.32%

Note:

[a] The numbers in parentheses represent cited or deduced judgemental estimates of standard deviation contained in source.

provide these estimates. Indeed, only 3 authors cited in Table B-1 provided error bounds of any kind for their forecasts. For these three estimates, though, the average of the judgmental uncertainty ranges does provide one measure of dispersion. It is identified as judgmental dispersion in Table B-1 and elsewhere; for the period from 1980 through 2000, an average of .21 percent per year is obtained.

A second method of estimating the uncertainty around future trends involves looking at the extent to which experts disagree in their projections -- this measure is called the disagreement dispersion. According to this technique, we examine, in the case of population covered in Table B-1 for example, disagreement across the 9 published estimates. Taking these estimates as data and estimating the extent of uncertainty by computing the standard deviation, we find a value of .13 percent per year. This second estimate is of the same order of magnitude as the judgmental dispersion just noted.

Studies by behavioral psychologists and others have noted a nearly universal tendency of people to underestimate the uncertainty associated with many events. Even experts with knowledge of statistics display this tendency. In a preliminary paper designed to quantify this tendency, Nordhaus has considered the issue of translating disagreement across projections of the same event into a measure of the true uncertainty of the event. His results, rough but highly suggestive, imply that both measures of dispersion need to be increased by a factor of 50 percent before they can be considered reasonable indicators of the true uncertainty surrounding our knowledge about future forecast events such as population growth rates over the next 15 years. Table B-2 records this expansion in columns (D) and (F)

Table B-2
Population Growth Estimates - World [a]

years	mean estimate	disagreement dispersion	adjusted disagreement	judgemental dispersion	adjusted judgemental	deduced dispersion	one standard deviation range
(A)	(B)	(C)	(D)[b]	(E)	(F)[c]	(G)[d]	(H)
1980-2000	1.6%	.13%	.20%	.21%	.32%	.30%	1.3%/1.9%
2000-2025	1.1%	.18%	.27%	.36%	.54%	.40%	0.7%/1.5%
2025-2050	0.5%	.15%	.23%	.30%	.45%	.35%	0.2%/0.8%

Notes:

a Sources noted in Table B-1; based on 9, 8, and 5 published estimates for the three noted time periods respectively.

b Computed as 1.5 times column (C).

c Computed as 1.5 times column (E).

d Deduced estimation of standard deviation judged from the values noted in columns (D) and (F) adjusted in later eras to maintain consistency with the larger sample estimates of earlier eras. The associated t-stats decline as the estimates apply further into the future (5.33; 2.75; 1.42).

and ultimately proposes a deduced dispersion estimate for one standard deviation around the sample mean of .3 percent. The final assertion, representing a slight adjustment for the sake of consistency within and across time periods in the future, produces a one standard deviation range of possible population growth rates of 1.3 percent per year and 1.9 percent per year around a mean estimate of 1.6 percent. The very same process produces the recorded ranges for the other two time periods.

World population growth estimates are not, of course, estimates for the United States. To produce ranges of U.S. estimates, the well accepted Keyfitz projections of .68 percent, .42 percent and .08 percent per year are employed for the three time periods, respectively. Requiring that the ranges around these estimates have the same t-statistics as the world estimates recorded in Table B-2, the estimates recorded for the U.S. in Table B-3 are easily obtained. Notice, though, that the three possible values are labeled "high", "medium" and "low" instead of plus and minus one standard deviation. That is because the ranges recorded in Table B-3 represent the mean plus and minus the square root of 2 times the deduced dispersion estimate of one standard deviation. Why? Because a mean and a standard deviation fully specify a normal distribution for a random variable; and if that distribution is to be approximated by a three cell discrete distribution with 25 percent, 50 percent and 25 percent probability weights, then the values assigned to the two outside, 25 percent cells must be the mean plus and minus /2 times the standard deviation.

The rest of the world estimates recorded in Table B-3 were produced similarly, but have been adjusted slightly from the world estimates by a weighting process that makes them consistent with (1) the mean U.S.

Table B-3
Population Growth Ranges[a]

United States (percentage change per year)

Era	1980-2000	2000-25	2025-50
High	0.8	0.6	0.15
Middle	0.7	0.4	0.1
Low	0.6	0.3	0.0

Rest of World (percentage change per year)

Era	1980-2000	2000-25	2025-50
High	2.0	1.5	0.9
Middle	1.7	1.1	0.5
Low	1.3	0.7	0.2

[a] Source: Table B-2; see text for procedure.

estimates based on Keyfitz and reported in Table B-3, (2) the mean world estimates of Table B-2, (3) the standard deviations supporting the U.S. ranges of Table B-3, and (4) the standard deviations reported in Table B-3. The procedure that assures these consistencies is entirely algebraic. Given, for example, an aggregate random variable, Z, that is the weighted average of two other random variables, X and Y, according to

$$Z = aX + (1-a)Y,$$

knowledge about the distribution of Z and X can be translated into knowledge about the distribution of Y according to

$$\text{mean}(Y) = \{[\text{mean}(Z)]-a[\text{mean}(X)]\}/(1-a), \text{ and}$$

$$\text{var}(Y) = \{[\text{var}(Z)-a^2[\text{var}(X)]\}/(1-a)^2,$$

assuming that X and Y are uncorrelated. Knowledge about the distribution of population growth estimates for the world and the U.S. is thus sufficient to produce consistent estimates about the distribution of population growth across the rest of the world.

. Productivity Growth.

Productivity growth estimates for the U.S. and the rest of the world are based upon a similar procedure. There exists a collection of studies that report real GNP forecasts for the United States. A summary of their content is found on Table B-4, and its import for present purposes indicated in Table B-5. Assuming an independence between population growth and GNP growth that might not be justified, the estimates and ranges in Table B-5 for GNP and Table B-3 for population are combined in Table B-6 to produce productivity growth estimates and ranges for the U.S. Tables B-7 and B-8 display the results of repeating the process for world productivity growth projections so that Table B-9 records estimates and ranges for the rest of

Table B-4
GNP Growth Estimates - U.S.

	1980-2000	2000-2025	2025-2050
Exxon (1980)	2.7	-	-
USDOE (1980)	2.5	-	-
H-K (1979)	3.0	-	-
RFF (high) (1980)	2.7	-	-
RFF (low) (1980)	2.3	-	-
WEC (high) (1978)	3.5	3.1	-
WEC (low) (1978)	2.5	2.5	-
IIASA (high) (1980)	3.7	2.2	-
IIASA (low) (1980)	2.4	1.0	-
Mean	2.89	2.20	na
Judgmental dispersion	.49	.88	na

Table B-5
GNP Growth Estimates--U.S.[a]

Years (A)	mean estimate (B)	judgmental dispersion (C)	adjusted judgmental (D)[b]	deduced dispersion (E)[c]	one standard deviation range (F)
1980-2000	2.81%	.49%	.74%	.7%	2.1%/3.5%
2000-2025	2.20%	.88%	1.32%	1.3%	0.9%/3.5%
2025-2050	Data not available; world data used for both U.S. and rest of world.				

[a] Source: Table B-4 based on 9 and 4 published estimates.

[b] Computed at 1.5 times column (C).

[c] Deducted estimation based on column (D). The associated t-stats as the estimates apply further into the future (3.87 and 1.69).

Table B-6

Productivity Growth Rates - U.S.[a]

	1980-2000	2000-2025	2025-2050[b]
High	3.2	3.3	2.2
Middle	2.1	1.6	1.1
Low	1.0	0.0	0.0

[a] Source: Tables B-5 and B-3 assuming independence between population growth and GNP.

[b] The world figures are used for both the U.S. and the rest of the world because of data deficiencies.

Table B-7
Productivity Growth Estimates - World[a]

	1980-2000	2000-2025	2025-2050
N-Y (1983)	2.3 (0.7)	1.6 (0.5)	1.0
OECD (1981)	2.7 (.62)	-	-
IEW (1985)	1.47 (.67)	2.77 (.47)	-
IIASA (1981)	1.75 (.78)	1.4 (.71)	
Kahn (1977)	2.75	3.1	1.19
Lovins (1981)	1.29	0.9	0.5
E/R (1985)	2.67 (.67)	-	-
Rotty and Marland (1980)	1.49	1.50	-
RFF (1980)	2.0 (.57)	1.95 (.21)	-
EPA (1985)	1.60	1.68	1.67
WEL (1977)	1.74 (.76)	1.73 (.76)	-
Hudson	2.8	1.4	.98 (.32)
mean	2.0%	1.8%	1.1%
(disagreement dispersion)	(.59%)	(.70%)	(.49%)
judgemental dispersion (mean)	.68%	.54%	.32%

Notes:

a The numbers in parentheses represent cited or deduced judgemental estimates of standard deviation contained in source.

Table B-8
Productivity Growth Estimates - World[a]

years	mean estimate	disagreement dispersion	adjusted disagreement	judgmental dispersion	adjusted judgmental	deduced dispersion	one standard deviation range
(A)	(B)	(C)	(D)[b]	(E)	(F)[c]	(G)[d]	(H)
1980-2000	2.0%	.60%	.90%	.68%	1.02%	.95%	1.05%/2.95%
2000-2025	1.8%	.70%	1.35%	.54%	.81%	1.00%	.80%/2.80%
2025-2050	1.1%	.49%	.74%	.32%	.48%	.60%	.50%/1.70%

NOTES:

a Sources noted in Table B-7; based on 12, 10, and 5 published estimates for the three noted time periods respectively.

b Computed as 1.5 times column (C).

c Computed as 1.5 times column (E).

d Deduced estimation of standard deviation judged from the values noted in columns (D) and (F) adjusted in later eras to maintain consistency with the larger sample estimates of earlier eras. The associated t-stats decline as the estimates apply further into the future (2.11; 1.71; 1.38).

Table B-9

Productivity Growth Ranges - Rest of World[a]

Era	1980-2000	2000-2025	2025-2050
High	2.9	2.8	1.7
Middle	2.0	1.8	1.1
Low	1.1	0.9	0.5

[a] Source: Tables B-8 and B-6; see text.

the world that are consistent with both the world estimates of Table B-8 and the U.S. estimates of Table B-6. The ranges reported in Tables B-6 and B-9 are not expanded by the same multiplicative factor of /2 to preserve both the mean and the variance of the underlying normal distribution. The standard deviation estimates are used, instead, to reflect the effect of the likely negative correlation between population growth and productivity. The procedure that assures consistency in moving not only from the U.S. and the world estimates to the rest of the world, but also from growth in total GNP to growth in per capita GNP, is identical in spirit if not exact detail to the algebraic process described above.

C. CFC Data.

Two types of CFC emissions data are required to estimate the demand structure. The first, a time series of U.S. production for CFC-11 aerosols, CFC-12 aerosols, CFC-11 nonaerosols, and CFC-12 nonaerosols, was found in the ICF study. They are recorded here in Tables B-10 through B-12. It is important to note that these series were, to a significant degree, constructed on the basis of a wide range of assumptions recorded in the attached notes. They may be the best data available, but they are therefore far from perfect from a statistical perspective. They are also production data and not the consumption data that would usually be employed in demand analysis.

A second set of data, cross sectional production data for a specific year, was also required (although, again, consumption data would have been more appropriate). Table B-13 records the set that has been employed. The text surrounding its presentation as Table 4.1 in the January 1986 RAND study [Quinn, et. al. 1986] outlined a series of steps employed to construct

Table B-10
U.S. CFC Production - Total[a]

Year	CFC-11b	CFC-12b
1958	22.90	59.60
1959	27.40	71.30
1960	32.80	75.50
1961	41.20	78.70
1962	56.60	94.30
1963	63.60	98.60
1964	67.40	103.40
1965	77.30	123.10
1966	77.30	129.90
1967	82.70	140.50
1968	92.70	147.70
1969	108.20	166.80
1970	110.90	170.30
1971	117.00	176.70
1972	135.90	199.20
1973	151.40	221.70
1974	154.70	221.10
1975	122.30	178.30
1976	116.20	178.30
1977	96.40	162.50
1978	87.90	148.40
1979	75.80	133.30
1980	71.70	133.80
1981	73.80	147.60
1982	63.70	117.00
1983	73.10	134.30

Notes:

a Source: ICF Table A-1.

b U.S. ITC. Synthetic Organic Chemicals. Annual Series. These include CFC-22 used as an intermediate. Approximately 28 percent of CFF-22 is used in the production of teflon and other products.

Table B-11
U.S. CFC Production - Aerosals[a]

Year	CFC-11	CFC-12
1958	19.90[b]	35.80[c]
1959	23 10	42.80
1960	26.70	45.30
1961	32.40	47.20
1962	43.20	56.60
1963	46.60	59.10
1964	47.50	62.00
1965	52.40	73.90
1966	50.20	77.90
1967	51.50	84.30
1968	55.20	88.60
1969	61.40	100.00
1970	60.00[d]	102.10[d]
1971	63.10	106.20
1972	72.10	117.50
1973	83.40	135.20
1974	86.70	123.90
1975	73.30	94.50
1976	64.00	80.30
1977	36.50	47.30
1978	32.90[e]	41.90[e]
1979	9.50	5.30
1980	9.50	5.80
1981	9.50	5.60

Notes:

a Source: ICF Table A-2

b Estimates for 1958-1969: based on the assumption that in 1958 the U.S. dominates the OECD market as CFC-11. In 1958, the CMA data (CMA. Production, Sales, and Calculated Release of CFC-11 and 12 through 1982; Expanded Data) show a market share of open cell, aerosol, and all other production to be 87 percent of total CFC-11 production. Thus, the U.S. aerosol share of total CFC production is assumed to be 87 percent in 1958, declining smoothly to 54 percent in 1970, where 54 percent is the aerosol proportion in 1970 described in footnote C. Total CFC-11 production is bsed on U.S. ITC data.

c Estimates for 1958-1969: Based on the assumption that CFC-12 aerosol production was 60 percent of total CFC-12 production, as it was in 1970.

d Data for 1970-1977: U.S. EPA. Regulation Chlorofluorocarbon Emissions: Effects on Chemical Production. (EPA-560/12-80-0016) October 1980, pp. 73, 74, 80. Reports production figures from pp. 73-74, using aerosol/nonaerosol proportions from p. 80.

e Estimates for 1978 and 1981 computed by subtracting usage in non-aerosol applications from total CFC usage. See Tables 10 and 12.

Table B-12
U.S. CFC Production - Nonaerosals[a]

Year	CFC-11	CFC-12
1958	3.00[b]	23.80[c]
1959	4.30	28.50
1960	6.10	30.20
1961	8.80	31.50
1962	13.40	37.70
1963	17.00	39.50
1964	19.90	41.40
1965	24.90	49.20
1966	27.10	52.00
1967	31.20	56.20
1968	37.50	59.10
1969	46.80	66.80
1970	50.80[d]	68.00[d]
1971	54.00	70.80
1972	64.00	81.70
1973	68.00	86.60
1974	68.00	97.10
1975	49.00	83.90
1976	52.20	98.00
1977	59.90	115.20
1978	55.00[e]	106.50[e]
1979	66.30	128.00
1980	62.20	128.00
1981	64.30	142.00
1982	63.70[f]	117.00[f]
1983	73.10	134.30

Notes:

a Source: ICF Table A-3

b Estimates for 1958-1969: CFC-aa non-aerosols are defined as CFC-11 total minus CFC-11 aerosol (see table A-2).

c Estimates for 1958-1969: based on the assumption that CFC-12 nonaerosol production was 40 percent of total CFC-12 production, as it was in 1970.

d Data for 1970-1977: U.S. EPA. Regulation Chlorofluorocarbon Emissions: Effects on Chemical Production. (EPA-560/12-80-0016) October 1980, pp. 73, 74, 80. Reports production figures from pp. 73-74, using aerosol/nonaerosol proportions from p. 80.

e Estimates for 1978-1981: OECD. Economic Aspects of CFC Emission Scenarios prepared by the Chemical Groups and Management Committee, 15 September 1982, p. 32. Based on the assumption that the split between CFC-11 and cFC-12 in these years was the same as it was in 1977.

f Estimates for 1982-1982: based on the assumption that production for aerosol applications is zero, which makes nonaerosol production equal to total production.

Table B-13
1980 Worldwide CFC Production[a]

Region	CFC-11 Aerosol	CFC-11 Nonaerosol	CFC-12 Aerosol	CFC-12 Nonaerosol
Developing Nations	102.1	181.9	131.8	207.3
U.S.	4.1	67.6	5.4	128.4
European Community	56.4	57.6	74.1	33.9
Pacific	8.2	35.7	10.8	36.9
Other Uses in Developed Nations	33.4	21.0	42.6	8.1
East Bloc	10.7	8.8	45.2	36.9
Developing Nations	3.2	2.6	6.2	5.0
Latin America	1.7	1.4	3.4	2.7
Africa	1.4	1.1	2.2	1.8
Other	0.1	0.1	0.6	0.5
Total	116.0	193.3	184.2	249.2
GRAND TOTAL	309.3		433.4	

[a] Source: Rand Table 4.1.

(8304b)

even this one year cross section from a variety of sources. Of particular note is the row labeled "Other Uses in Developed Nations" into which many apparent discrepancies were collected. Production listed there was, for the purposes of estimation in this study, assumed to be distributed proportionately across the non-U.S. developed countries.

Appendix C: The Complete Model.

The complete set of equations for the CFC projections produced in this report is recorded here. The form of the equations is identical for all four chemicals, but the parameters differ according to the statistical estimates.

Equations (a) through (d) represent the exogenous projections of populations (P) and per capita GNP (A) in the United States (US) and the rest of the world (ROW):

(a) PUS(t) exogenous {3 paths}:

(b) PROW(t) exogenous {3 paths};

(c) AUS(t) exogenous {3 paths}; and

(d) AROW(t) exogenous {3 paths}.

Equation (e) represents the growth in the CFC frontier in the United States, where Z* is potential use of CFCs per unit GNP.

(e) $\log [Z^*(t)] = a + gt$. {3 frontier paths}

The ratio of actual to potential CFC consumption in the U.S. [Z/Z*] is given by a logistics curve for each frontier:

(f) $W(t) = -b-ct$ {1 for each frontier}

where the definition of W(t) is

(g) $Z(t) = Z^*(t)/(1 + \exp[W(t)])$ {identity}

Total CFC consumption in the U.S. is given by:

$$\text{(h)}\quad CFCUS(t) = Z(t)\ PUS(t)\ AUS(t) \qquad \text{\{identity\}}$$

Total CFC consumption in the rest of the world is:

$$\text{(i)}\quad CFCROW(t) = Z(t)\ \left(\frac{AROW(t)}{AUS(t)}\right)^{E}\ AROW(t)\ PROW(t)$$

with 3 values of E. Finally, the emissions of CFCs into the atmosphere, ECFC(t), and the volume of the banks, BCFC(t), are be determined by Koyck lag equations of the form

$$\text{(j)}\quad ECFC(t) = (1-d)\ BCFC(t-1) + .1\ CFCN(t) \text{ and}$$

{3 sets of equations defined by 3 d parameters}

$$\text{(k)}\quad BCFC(t) = d\ BCFC(t-1) + .9\ CFCN(t)$$

for nonaerosols and

$$\text{(j')}\quad ECFC(t) = CFCA(t) \text{ and}$$

$$\text{(k')}\quad BCFC(t) = 0$$

{1 set of equations}

References

Camm, Frank, and James K. Hammitt, An Analytic Method for Constructing Scenarios from a Subjective Joint Probability Distribution, The Rand Corporation, N-2442-EPA, May 1986.

Chemical Manufacturers Association, Fluorocarbon Program Panel, World Production and Sales of Chlorofluorocarbons CFC-11 and CFC-12, various years.

Exxon Corporation, World Energy Outlook, New York, 1980.

Gibbs, Michael, ICF, "Scenarios of CFC Use: 1985-2075," presented at "Protecting the Ozone Layer: Workshop on Demand and Control Technologies," U.S. EPA, Washington, D.C., March 6, 1986.

Gibbs, Michael, ICF, "Summary of Historical Chlorofluorocarbon Production," ICF, presented at "Protecting the Ozone Layer: Workshop on Demand and Control Technologies," U.S. EPA, Washington, D.C., March 6, 1986.

Hafele, W., Energy In a Finite World, IIASA, Ballinger Publishing Co., Cambridge, Massachusetts, 1981.

Keyfitz, Nathan, et al., "Global Population 91975-2075) and Labor Force (1975-2050)," Institute for Energy Analysis, Oak Ridge Associate Universities, Oak Ridge, Tennessee, 1983.

Lovins, A.B., L.H. Lovins, F. Crause, and W. Bach, Energy Strategies for Low Climate Risks, prepared for the German Federal Environmental Agency, San Francisco International Project for Soft-Energy Paths, June 1981.

My T. Vu, World Population Projections 1984, World Bank, Washington, D.C., 1984.

National Academy of Sciences, Causes and Effects of Changes in Stratospheric Ozone: Update 1983, Washington, D.C., 1984.

National Academy of Sciences, Causes and Effects in Stratospheric Ozone: An Update, Washington, D.C., 1982.

National Academy of Sciences, Halocarbons: Effects on Stratospheric Ozone, Washington, D.C., 1976.

National Academy of Sciences, Protection against Depletion of Stratospheric Ozone, Washington, D.C., 1979.

Nordhaus, W.D. and G. Yohe, "Future Carbon Dioxide Emissions From Fossil Fuels," Changin Climate, National Academy of Sciences, Washington, D.C., 1983.

Palmer, Adele R., William E. Mooz, Timothy H. Quinn, and Kathleen A. Wolf, Economic Implications of Regulating Chlorofluorocarbon Emissions from Nonaerosol Applications, The Rand Corporation, R-2524-EPA, June 1980.

Population Reference Bureau, 1985 World Population Data Sheet, Washington, D.C., 1985.

Quinn, Timothy, Kathleen A. Wolf, William E. Mooze, James K. Hammitte, Thomas W. Chesnutt, and Syam Sarma, Projected Use, Emissions, and Banks of Potential Ozone Depleting Substances, The Rand Corporation, N-2282-EPA, January 1986.

Reilly, John, Rayola Dougher, and Jae Edmonds, Determinants of Global Energy Supply to the Year 2050, Institute for Energy Analysis, Washington, D.C. 1981.

Ridker, R.G. and W.D. Watson, To Choose a Future, Baltimore, Maryland, The Johns Hopkins University Press, 1980.

Rotty, R.M. and G. Marland, Constraints on Carbon Dioxide Production From Fossil Fuel Use, ORAU/IEA-80-9(M), Institute for Energy Analysis, 1980.

Seidel, Stephen, and Dale Keyes, Can We Delay a Greenhouse Warming?, U.S. Environmental Protection Agency, EPA-230-10-84-001, Washington, D.C., 1983.

Tversky, Amos and Daniel Kahneman, "Judgment Under Uncertainty: Heuristics and Biases," Science, September 1974.

U.S. Department of Energy, Annual Report to Congress, DOE/EIA-0173(80), U.S. Department of Energy, Washington, D.C., 1980.

United Nations, World Population Prospects: Estimates and Projections as Assessed in 1982, New York, New York, 1985.

Wolf, Kathleen A., Regulating Chlorofluorocarbon Emissions: Effects on Chemical Production, The Rand Corporation, N-1483-EPA, August 1980.

World Energy Conference (WEC), The Full Report to the Conservation Commission of the World Energy Conference: World Energy Demand, New York, IPC Science and Technology Press, 1981.

SCENARIOS OF CFC USE: 1985-2075

by
Michael J. Gibbs

Prepared for

Strategic Studies Staff
Office of Policy Analysis
Office of Policy, Planning and Evaluation
U.S. Environmental Protection Agency
401 M Street, S.W.
Washington, D.C. 20460

February 1986

EXECUTIVE SUMMARY

Using recent historical trends as a guide, potential future use and emissions of chlorofluorocarbons (CFCs) are projected in a series of scenarios. The total use of CFCs 11, 12, 22, and 113 worldwide is likely to increase between 1985 and 2075 at an annual rate of approximately 2.4 percent to 3.5 percent per year. Use per capita is likely to increase at a rate of 1.7 percent to 2.7 percent per year. At these potential growth rates, total use of these CFCs may grow from the current annual level of approximately 1.2 million metric tons to between 10.0 and 27.5 million metric tons by 2075.

The size of this range is driven by the uncertainties regarding the primary determinants of future CFC consumption: population growth and economic growth. A range of projections of global and regional population and Gross National Product (GNP) was used to develop the CFC use scenarios. Additionally, assumptions about the roles of CFCs in future economies were varied.

TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY	1
1. INTRODUCTION	2
2. DATA AND METHODS	3
2.1 Data Sources for CFC Use and Emissions	4
2.2 Statistical Analysis	5
2.3 Implementation of the Scenarios	7
3. RESULTS	14
4. LIMITATIONS	18
4.1 Limitations in Data	18
4.2 Limitations in Methods	19
4.3 Next Steps	20
ANNEX A	A-1
ANNEX B	B-1
ANNEX C	C-1
ANNEX D	D-1
ANNEX E	E-1

I. INTRODUCTION

This paper presents scenarios of the potential future use of chlorofluorocarbons (CFCs). CFCs are a non-toxic, non-flammable class of chemicals used as propellants in aerosol cans and for a variety of non-aerosol applications (such as in making plastic foams and as the coolant in refrigerators, air conditioners, and freezers). In 1974, it was hypothesized that CFCs emitted to the atmosphere will reduce the amount of ozone in the stratosphere,[1] thereby allowing greater amounts of ultraviolet radiation to reach the earth's surface. Since that time, considerable experimentation, data collection, atmospheric monitoring, and modeling have been used to investigate the potential for CFCs to induce stratospheric ozone depletion, and the implications of such depletion. In response to concerns over ozone depletion, public use of CFCs as an aerosol propellant decreased in the United States and abroad between 1974 and 1978 by two-thirds. In 1978 the use of CFCs in nonessential aerosol propellant applications was banned in the United States. Norway, Sweden, and Canada have adopted similar restrictions and the European Economic Community has adopted a 30 percent cutback in the use of CFCs as aerosol propellants.

Due to concerns about potential ozone depletion that may be caused by CFC emissions, the United States and other countries have initiated multilateral negotiations regarding future uses and restrictions of CFCs. Cooperation among all countries is required in order to control the effects of CFC emissions because the impacts of concern are global in nature; i.e., the emissions have the same effects on stratospheric ozone regardless of their point of origin. In support of these negotiations, this analysis presents potential future scenarios of CFC use and emissions worldwide through the year 2075.

The effects of today's CFC use will be felt for a long time because the chlorine released from CFCs remains in the stratosphere for a very long time, up to hundreds of years. If the chlorine that today's CFCs put into the stratosphere cause problems in the future (e.g., by causing ozone depletion after 2000), the only method we will have to correct those problems will be to reduce CFC use <u>at that time</u>, i.e., in the future. We will be unable to remove from the stratosphere the chlorine put there by today's uses of CFCs. Therefore, to evaluate the potential implications of policies to reduce CFC use now or in the future, scenarios of CFC use into the fairly far off future are required.

---

[1] M.J. Molina and F.S. Rowland, "Stratospheric Sink for Chlorofluoromethanes: Chlorine Atom Catalysed Destruction of Ozone," <u>Nature</u>, 1974, pp. 810-812.

This need to have long range scenarios poses a challenge to policy analysts. Most factors that will influence the use of CFCs after 2000 can be projected only with great uncertainty. Describing the potential changes in the economies and populations of developed and developing countries beyond 2000 is inherently uncertain. Adding to this demographic and economic uncertainty is uncertainty regarding the roles that CFCs will continue to play in the economies of various countries around the world. Within the next 90 years unforeseen technologies may develop that replace today's major uses of CFCs or require additional use of CFCs. The approaches developed here reflect the key uncertainties in the analysis. All the assumptions that influence the scenarios are presented, and a range of possible scenarios is described.

Even with the most advanced methods, however, scenarios into the far-off future must be considered somewhat speculative. The later years of the scenarios can only identify what could possibly occur, but cannot say with any definitiveness what will actually occur.

This paper first describes in section 2 the approach used to develop the scenarios. Section 3 presents results of the analysis and section 4 summarizes the limitations of the scenarios.

2. DATA AND METHODS

This section summarizes the data and methods used to project scenarios of CFC use and emissions worldwide. The general approach is in three parts:

- collect data on the historical use of CFCs;
- analyze the data statistically to identify relationships between CFC use and population, GNP per capita, and the prices of CFCs; and
- use the results of the statistical analysis to project future use and emissions, also using assumptions about future population and economic growth.

First the availability of historical CFC use data is described. Then the statistical analysis is summarized. Finally, the manner in which the results of the statistical analysis are used to generate the scenarios of CFC use and emissions is presented.

2.1 Data Sources for CFC Use and Emissions

Data describing historical CFC use and emissions were collected from U.S. Environmental Protection Agency (EPA) reports, U.S. International Trade Commission (ITC) publications, Chemical Manufacturers Association (CMA) reports, and Organisation for Economic Cooperation and Development (OECD) reports. A list of the data used and their sources are presented in Annex A.

Data were generally available for the use of:

- CFC-11, CFC-12, and CFC-22 in the U.S. from 1958 to 1982;
- CFC-113 in the United States from 1958 to 1979;
- CFC-11, and CFC-12 in the OECD countries from 1958 to 1982; and
- CFC-22 in the OECD countries from 1958 to 1975.

However, the division of total CFC use for CFC-11 and CFC-12 between aerosol and non-aerosol applications was not available for the U.S. between 1958 and 1969 and not available for the other OECD countries between 1958 and 1975. The distinction between aerosol and non-aerosol uses is important in order to project separate scenarios of future aerosol and non-aerosol uses. The separate scenarios are needed because different control policies exist for the two types of applications (and because different future control policies may be contemplated). The assumptions made regarding the aerosol/non-aerosol division are described in Annex A.

Data were generally not available or not reliable for the following:

- CFC-113 in the OECD countries other than the U.S.; and
- CFC-11, CFC-12, CFC-22 and CFC-113 in countries outside the OECD.

This lack of data is particularly troublesome because: (1) the use of CFC-113 is expected to grow significantly (because it is used in the production of electronic components); and (2) the countries outside the OECD have the overwhelming majority of the world's population, and their population and per capita GNP are projected to grow at a faster rate than in the developed world. Consequently these countries may represent potentially large future users of CFCs. As described below, alternative approaches (that are not based on statistical analyses of historical data) were used to project scenarios of potential use for these CFCs and portions of the world for which historical data were not available.

*

Data were also collected on the rate of emissions of CFCs. Emissions do not equal use for some CFC applications because the CFCs remain in some products for many years (e.g., refrigerators). Annex C describes the data collected on emissions rates. The emissions rates were used along with the scenarios of future use to develop scenarios of future emissions.

2.2 Statistical Analysis

The objective of the statistical analysis was to describe the historical behavior of CFC use over time using common economic and demographic variables such as population and Gross National Product (GNP). These variables were used because CFC use can be shown to be related to them and because there are a variety of projections for them that stretch far into the future.

Basing the analysis on population and GNP is appropriate because the use of most products and commodities in our modern economies is generally related to the size of the economy and its wealth, or standard of living. For example, in various developed countries the use of products such as cars, refrigerators, and housing is related to the number of people in the country, and the average wealth per person. The more people there are, the greater the use. The wealthier the people, also the greater the use. Cultural and other local geographic and climatic factors are also important, but population and wealth explain much of the observed differences between countries.

This general idea of a product's use being related to population and wealth applies not only to easily observable products such as cars and refrigerators, but also to the things that are used to make these products. For example, steel is used to make a large number of products, including cars and refrigerators. The amount of steel used in different countries is therefore related to the population and wealth of the country.

The use of CFCs, like steel, can also be thought of as being related to the population and wealth of a country. Using a statistical technique call "regression analysis," the manner in which the use of CFCs has varied in the past with population and wealth can be estimated in the form of an equation. These estimated equations can then be used to identify how CFC use may change in the future as population and wealth change.

The equations estimated in this analysis relate historical CFC use per person on the one hand to GNP per person and the price of CFCs on the other. These equations are used with scenarios of future rates of growth in GNP per person, the number of people, and the real price of CFCs to project the future use of CFCs.

The advantages of this method are that it is simple and straightforward, it can be implemented with the type of data that exist, and it can use standard projection variables (population and GNP) to generate scenarios. The primary shortcoming of this approach is that it does not describe the underpinnings of the demand for CFCs. Instead, it implicitly assumes that the structure of the demand for CFCs remains constant through time. If the factors affecting demand change substantially, then the relationships estimated using this approach will no longer be appropriate for projecting future scenarios of CFC use. Examples of important changes in the factors affecting demand include: changes in the relative prices of CFCs and their

substitutes due to changes in the prices of the raw materials used to make the products or changes in the technologies used to make the products; and changes in the ability to use or handle substitutes due to findings regarding their toxicity. Although it would be preferred to have available a rigorous demand analysis that can reflect these potential changes, it was not undertaken because:

- the data needed to perform the analysis was not readily available; and

- for the variables needed to project demand, established scenarios or estimates far into the future are not unavailable, and would have had to be developed.

The lack of good estimates of the future values of the detailed determinants of CFC demand is particularly important because projections of CFC use will only be as good as the projections of the variables used to derive CFC use.

Using historical data on GNP, population, and prices (see Annex A for the sources of the data) along with the historical data on CFC use, regression analysis was used to estimate relationships for the following 10 combinations of regions of the world; CFC type; and aerosol/non-aerosol application:

1. U.S.; CFC-11; aerosol
2. U.S.; CFC-11; non-aerosol
3. U.S.; CFC-12; aerosol
4. U.S.; CFC-12; non-aerosol
5. U.S.; CFC-22; total
6. U.S.; CFC-113; total
7. OECD-U.S.; CFC-11; aerosol
8. OECD-U.S.; CFC-11; non-aerosol
9. OECD-U.S.; CFC-12; aerosol
10. OECD-U.S.; CFC-12; non-aerosol.

Of note is that the analysis of U.S. aerosol applications only used data through 1974. The post-1974 use was assumed to be influenced by the rising concern over ozone depletion and the subsequent U.S. ban on the use of CFCs as aerosol propellants. Similarly, the OECD-U.S. aerosol analysis only used data through 1977. By truncating the time series in this manner, the resulting relationships reflect the level of CFC aerosol use in these locations in the absence of existing restrictions. Consequently, these relationships can be used to assess whether the current restrictions are binding (i.e., the extent to which use would be expected to have exceed the current levels absent the attention given to the ozone-depletion issue and the subsequent regulations) and to project scenarios of use in the absence of existing restrictions. Results of the regression analysis are displayed in Annex B.

Due to a lack of data, relationships could <u>not</u> be developed for the following region of the world, CFC combinations:

- Non-OECD use of all CFCs (CFC-11; CFC-12; CFC-113; CFC-22);

- OECD-U.S. use of CFC-22 and CFC-113.

The next section describes how the relationships estimated in the regression analysis are used to generate the scenarios. Also described are the methods used to project potential use for the portions of the world for which historical relationships could not be estimated.

2.3 Implementation of the Scenarios

Five scenarios of potential future use of CFCs were generated. Three scenarios, Low, Medium, and High, report the likely range of future CFC use. In addition, two bounding scenarios were generated: (1) "Limits to Growth," a very low scenario; and (2) "No Limits to Growth," a very high scenario. Although it is possible, it is unlikely that future use will fall outside these bounding scenarios in the absence of government regulatory intervention. For total CFC use in the U.S., and for CFC-11 and CFC-12 use in the OECD, the scenarios were generated by inserting projections of population and GNP per capita into the equations developed using the regression analysis. However, as described in the previous section, equations could not be developed for CFC-22 and CFC-113 use in the the non-U.S. OECD countries and for all the CFC use in the countries outside the OECD. Therefore, alternative approaches were used to project scenarios for these areas.

All the approaches use population and GNP per capita as the basis for the projections. Consequently, these data are described first. Then the manner in which the regression equations were used is described. Finally, the alternative approaches are presented.

Population and GNP Per Capita Projections

The potential future use of CFCs will be driven by the growth in the world population and the expected wealth of that population. A variety of projections have been published that provide estimates of potential future population and GNP per capita through 2075. These estimates were reviewed along with information describing historical rates of growth. Annex E describes the data reviewed, and the assumptions used to create five projections of population and GNP per capita through 2075.

Exhibit 2 summarizes the population projections for the world. The highest projection, 13.6 billion people by 2075, is nearly double the low projection of 7.1 billion by 2075. The growth rates implied in the projections are also shown in the exhibit. Of note is that all the projections have the general trend of slowing growth rates over time. Relative to the historical rate of population growth from 1925 to 1975 (1.9 percent), all the projections start out with slower growth.

Not displayed in Exhibit 2 are regional differences in the population projections. The developing countries are expected to grow more rapidly than the developed countries in all the projections. Zero population growth (ZPG) is assumed to be achieved in all regions in the Limits to Growth scenario by

EXHIBIT 2

SUMMARY OF POPULATION PROJECTIONS
(Billions of people -- rates of growth in percent per year)

	SCENARIO				
	Limits to Growth	Low	Medium	High	No Limits to Growth
1985	4.6 (1.1%)	4.7 (1.5%)	4.7 (1.5%)	4.8 (1.6%)	5.0 (1.8%)
2000	5.4 (0.8%)	5.9 (0.9%)	5.9 (0.9%)	6.1 (1.1%)	6.5 (1.5%)
2025	6.5 (0.5%)	7.4 (0.2%)	7.4 (0.4%)	8.2 (0.6%)	9.5 (1.0%)
2050	7.3 (-0.1%)	7.7 (0.1%)	8.2 (0.1%)	9.5 (0.2%)	12.1 (0.5%)
2075	7.1 (--)	7.9 (--)	8.5 (--)	10.0 (--)	13.6 (--)

Source: See Annex E.

2050. The U.S. and other OECD countries achieve ZPG by 2075 in the Low and Medium scenarios. Annex E presents the regional breakdowns of the projections.

Exhibit 3 displays the diversity among the GNP per capita projections. By 2075, the highest projection is over five times larger than the lowest projection. The range of uncertainty in the economic growth projections is larger than the range for the population projections. Compared to the historical rate of growth from 1925 to 1975 (2.1 percent per year), the projections start out slower.

Scenarios Based on the Statistical Analysis

The statistical analysis produced 10 equations that were used to generate scenarios for 10 region, compound, end use combinations (see Section 2.2 and Annex B). The scenarios were developed from each of the 10 equations by: (1) varying the population and GNP per capita projections; and (2) modifying the regression coefficients to reflect uncertainty.

The population and GNP per capita projections discussed above were used. For example, the Low CFC scenario is based on the low population and low GNP per capita projections. The differences among the population and GNP per capita projections account for the majority of the differences in the CFC use projections across the scenarios (over 80 percent).

EXHIBIT 3

SUMMARY OF GNP PER CAPITA PROJECTIONS
(1975 U.S. $ -- rates of growth in percent per year)

	SCENARIO				
	Limits to Growth	Low	Medium	High	No Limits to Growth
1985	1,900 (1.0%)	1,900 (1.5%)	1,900 (1.7%)	1,950 (1.9%)	1,950 (2.3%)
2000	2,200 (0.5%)	2,400 (1.2%)	2,450 (1.7%)	2,550 (2.0%)	2,750 (2.5%)
2025	2,500 (0.5%)	3,200 (1.0%)	3,750 (1.7%)	4,200 (2.0%)	5,100 (2.5%)
2050	2,850 (0.3%)	4,100 (1.0%)	5,700 (1.7%)	6,883 (2.0%)	9,450 (2.5%)
2075	3,050 (--)	5,250 (--)	8,650 (--)	11,242 (--)	17,550 (--)

Source: See Annex E.

The uncertainty in the estimates of the regression coefficients was also reflected in the scenarios. Regression analysis provides estimates of the expected coefficients in the equations. There is uncertainty in these estimates, which is expressed as the standard error of the estimated regression coefficient. The larger the standard error relative to the size of the coefficient, the more uncertain the estimate of the coefficient (and hence the relationship).[2] To reflect this uncertainty, the coefficient on GNP per capita was varied across each of the scenarios. Changing the coefficient by plus and minus one standard error of the estimate changed the scenarios by approximately 10 to 20 percent in each direction. These changes are small relative to the differences caused by the alternative population and GNP per capita projection. The Low, Medium, and High scenarios presented below are based on the estimate of the coefficient that is produced by the regression analysis. The Limits to Growth scenario is based in this estimate

---

[2] It should be noted that the estimates of the standard errors are probably biased downward as the result of serial correlation of the data. Consequently, the relationships are more uncertain than indicated by the regression results. For more information on the influence of serial correlation on uncertainty estimates in regression analysis see: Pindyck, R.S. and D.L. Rubinfeld, Econometric Models and Economic Forecasts, McGraw/Hill (New York), 1976, pp. 106-108.

minus one standard error of the estimate. The No Limits to Growth scenario is based on this estimate plus one standard error of the estimate.

Several additional adjustments were performed for all the scenarios. To reflect the current ban on the use of CFCs as an aerosol propellant in non-essential applications in the U.S., the annual aerosol use of CFC-11 and CFC-12 was not permitted to exceed 4.5 million kilograms each. Because the aerosol use in the U.S. would exceed this level without the ban, this adjustment sets U.S. aerosol use throughout the period examined at this level. Similarly, the aerosol use restrictions in other OECD countries were reflected. Because the European Economic Community (EEC) countries have agreed to reduce their aerosol use to 70 percent of their 1976 use, the EEC use had to be projected separately. To do so, the non-U.S. OECD estimates were divided into an EEC portion and a non-EEC portion using a constant proportion. The EEC portion is set at approximately 71 percent of the aerosol uses of CFC-11 and CFC-12 in the non-U.S. OECD (based on data from the 1970s). To reflect the EEC aerosol restrictions, the annual EEC use of these CFCs in aerosol applications is limitted to 54.5 million kilograms and 69.4 million kilograms, respectively.

Other non-EEC countries have also instituted controls on the use of CFCs in aerosol applications. Exhibit 4 shows the countries and the percent reductions achieved to date. As shown in the exhibit, the controls reduced total use by approximately 40 percent. This reduction is reflected in the scenarios by assuming that future use would only be 60 percent of what it would be estimated to be without the controls.

EXHIBIT 4

REDUCTIONS IN CFC-11 AND CFC-12 USE IN AEROSOL APPLICATION IN NON-U.S., NON-EEC OECD COUNTRIES

Country	Percent Reduction	CFC Use as Percent of Non-U.S., Non-EEC OECD	Weighted Percent Reduction[1]
Australia	35	16	6
Austria	30	5	1
Canada	79	21	16
Finland	20	5	1
Japan	25	21	5
New Zealand	49	5	2
Norway	100	2	2
Sweden	100	5	5
Switzerland	23	11	2
		TOTAL:	40 percent

[1] Derived by multiplying first two columns.

Source: Derived from: Report on Chlorofluorocarbons, OECD, April 1982.

Scenarios Based on Alternative Approaches

Because equations based on historical data could not be devloped for some CFC uses in portions of the world, alternative approaches were used to generate scenarios for these regions. The scenarios for CFC-22 and CFC-113 use in the non-U.S. OECD countries were developed by assuming that the use of these CFCs in the U.S. would remain a constant fraction of the total use in the OECD. For example, recent data indicate that the U.S. share of total CFC-113 use in the OECD is approximately 65 percent.[3] From the regression equations, scenarios of the potential future U.S. use of CFC-113 are generated. To generate the scenarios for CFC-113 in the other OECD countries, it is assumed that the 65 percent U.S. share remains constant, meaning that the use of CFC-113 in the non-U.S. OECD countries is approximately 54 percent of the estimated U.S. use.[4] The U.S. share of OECD use of CFC-22 is approximately 80 percent.

The implications of this approach is that the scenarios for non-U.S. CFC-22 and CFC-113 use are based on projections for the U.S. To the extent that the U.S. data reflect the likely growth rate of the total use of these CFCs in the OECD, the method provides a reasonable estimate of future OECD use. However, the share of OECD use accounted for by the U.S. may change in the future, probably becoming smaller as the other OECD countries capture larger shares of the electronics markets. Consequently, even if the total OECD CFC scenarios are reasonable, the U.S. share of this use may be biased upward.

Scenarios could not be based on historical data for the non-OECD countries. Instead, for purposes of projecting this use, it was assumed that per-capita use would increase over time at a rate described by an "S-shaped" curve. This type of curve, shown in Exhibit 5, reflects the hypothesis that as wealth per capita grows over time, the use of CFCs will also grow, but not in a linear fashion. Instead, once market penetration reaches a threshold (in the exhibit shown as time T_1 to T_2) the growth in CFC use may exceed the growth in wealth. Thereafter, the rate of increase in the use of CFCs decreases relative to increases in wealth, as CFCs are used more efficiently or as markets become saturated.

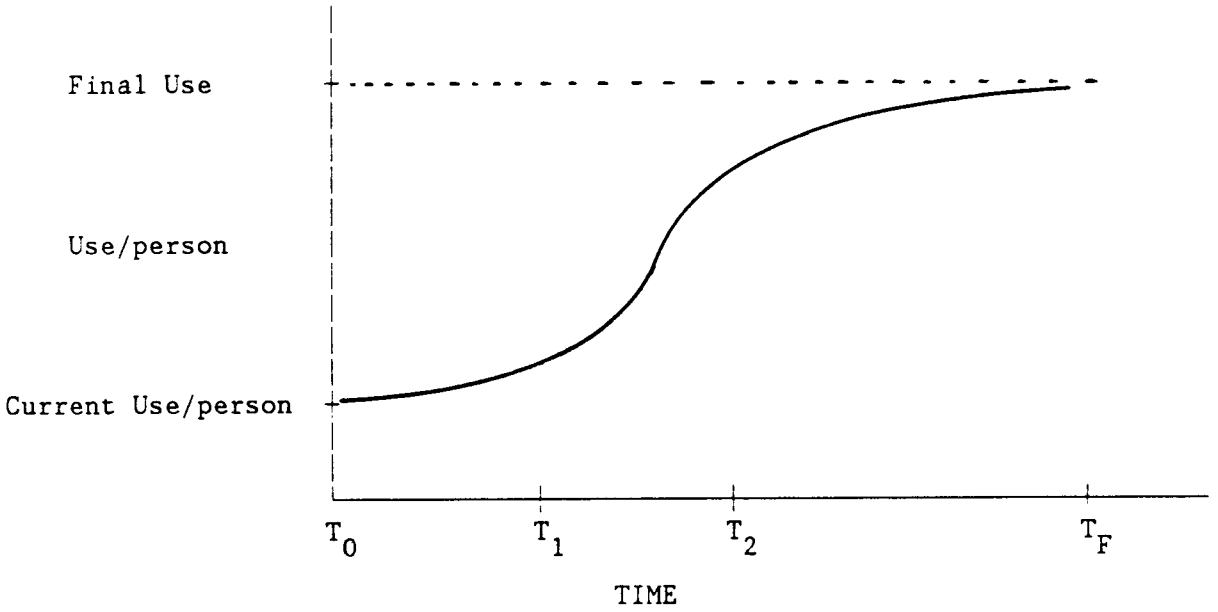
---

[3] Based on a comparison of U.S. data with OECD data. U.S. data from: A.D. Little, Preliminary Economic Impact Assessment of Possible Regulatory Actions to Control Emissions of Selected Halocarbons, September 1976. OECD data from: OECD (1981), Summary of the Conclusions Regarding Scenarios of the Ad Hoc Meeting, ENV/Chem/PJC/81.79.

[4] The non-U.S. OECD share of the OECD use is 35 percent. This quantity is 35 ÷ 65 = 54 percent of the projected U.S. use.

EXHIBIT 5

EXAMPLE OF AN S-SHAPED CURVE



To specify this S-shaped curve, the logistic function was used.[5] The shape of the curve is fully defined by specifying the current use per capita at time T_0 and the final use per capita at time T_F. Current use per capita estimates are shown in Exhibit 6. For example, in the non-U.S. OECD, current use per capita of CFC-11 is approximately 0.58 kilograms. In the non-OECD countries, use per capita is currently approximately 1.2 percent of this value (or about 0.007 kilograms). Using the logistic function, this fraction of 1.2 percent will grow over time to the final fraction specified for 2075.

---

[5] The logistic function is $f = \frac{1}{1+\exp(-a-bt)}$; where "t" is time and "a" and "b" are parameters defining the shape of the curve. The value for "f" computed for each time, t, is multiplied by the expected final use to compute the use at time t. For example, the final (i.e., ending year) use is defined as the use per capita expected to be achieved in 2075. To estimate the use per capita in 2050, the value of "f" in 2050 (which will be less than 1.0) is multiplied by the final per-capita use.

EXHIBIT 6

CURRENT PER-CAPITA USE OF CFCs

CFC	Annual Per-Capita Use in OECD Countries Other than the U.S.[1] (kg/person)	Annual Per-Capita Use in Non-OECD Countries as a Percentage of Annual Per-Capita Use in OECD Countries (%)
CFC-11	0.58	1.2[2]
CFC-12	0.58	5.3[2]
CFC-22	0.06	3.8[3]
CFC-113	0.04	3.8[3]

[1] Estimated by taking the most current estimate of the total use available (1982 or 1983) and dividing by the total number of people in the OECD.

[2] Current total use for CFC-11 and CFC-12 was taken from "Production, Sales, and Calculated Release of CFC-11 and CFC-12 through 1982," Chemical Manufacturers Association (1983). The CMA cautions that these estimates are uncertain because they are based on extrapolation of data reported for earlier years. However, estimates of the current use in the non-OECD countries do not influence the overall scenarios significantly.

[3] Current total use of CFC-22 and CFC-113 was derived using estimates of the share of total world use calculated for these countries from data in OECD (1976), Fluorocarbons: An Assessment of Worldwide Production, Use and Environmental Issues, pp. 30-35.

The final fraction was estimated using the projected GNP per capita in the non-OECD countries, and the current relationship between per capita use and per capita GNP in the non-U.S. OECD countries. For example, in the medium population and GNP per capita projection, the GNP per capita in the non-OECD countries reaches approximately 85 percent of the 1980 GNP per capita in the non-U.S. OECD countries. Consequently, it was assumed that by 2075, CFC use per capita in the non-OECD countries would reach this same fraction (85 percent) of the 1980 use per capita in the non-U.S. OECD. The estimate for the low and high projections were 53 percent and 111 percent.

Exhibit 7 summarizes the assumptions in the scenarios.

3. RESULTS

This section presents five scenarios of future CFC use and emissions worldwide. These scenarios incorporate the current restrictions on CFC use in aerosol applications in the U.S. and elsewhere.

Exhibit 8 summarizes the results for the scenarios.[6] For example, the Medium scenario for CFC-11 shows world use growing from approximately 400 million kilograms in 1985 to about 7,600 million kilograms by 2075. This is an average rate of growth of 3.3 percent per year. The growth rate in the Medium scenario is not constant, however. The early years have nearly a 4.5 percent annual rate of growth, and the later years have growth at 2.0 percent per year.

The annual use of CFC-11 in the Low scenario in Exhibit 8 grows on average at only 2.6 percent per year throughout the entire period examined, resulting in 4.3 billion kilograms of use by 2075. The High scenario has larger use of CFC-11 over time, with an average annual growth rate of 3.7 percent.

The growth in use per capita is smaller than the growth in total use because population also increases over time. For the total of all four CFCs examined, world per capita use reaches the following levels in the five scenarios (smallest to largest): (1) 0.65 kilograms; (2) 1.3 kilograms; (3) 2.1 kilograms; (4) 2.8 kilograms; and (5) 4.6 kilograms. Current per capita use in the non-U.S. OECD countries is approximately 1.3 kilograms, and in the U.S. is approximately 1.6 kilograms (both these estimates reflect existing restrictions on aerosol applications). Consequently, per capita use in the 1.3 to 2.8 kilograms range from the Low, Medium, and High scenarios seems plausible. The Limits to Growth scenario has per capita use well below current rates in the developed world. Non-OECD countries would be required to have very low economic and population growth over the next 90 years to achieve the per capita use estimates in the Limits to Growth scenario. Similarly, the No Limits to Growth Scenario has very high per capita as rates, requiring both large population growth and excellent economic performance to be achieved.

---

[6] Annex D presents scenario results for each of the major regions of the world.

EXHIBIT 7

SUMMARY OF SCENARIO ASSUMPTIONS

	Limits to Growth Scenario	Low Scenario	Medium Scenario	High Scenario	No limits to Growth Scenario
Population Projection	Grows at an average rate of 0.5 percent (1985-2075)	Grows at an average rate of 0.58 percent (1985-2075)	Grows at an average rate of 0.65 percent (1985-2075)	Grows at an average rate of 0.8 percent (1985-2075)	Grows at an average rate of 1.1 percent (1985-2075)
GNP Per Capita Projection	Grows at average real rate of 0.5 percent (1985-2075)	Grows at average real rate of 1.1 percent (1985-2075)	Grows at an average real rate of 1.7 percent (1985-2075)	Grows at average real rate of 2.0 percent (1985-2075)	Grows at average real rate of 2.5 percent (1985-2075)
Growth of Use in OECD Countries	Historical relationship reduced to reflect uncertainty (minus one standard error)	Based on historical relationship	Based on historical relationship	Based on historical relationship	Historical relationship increased to reflect uncertainty (plus one standard error)
Growth of Use in Non-OECD Countries	Follows an S-shaped curve. Reaches 30 percent of current per capita use in non-U.S. OECD countries	Follows an S-shaped curve. Reaches 53 percent of current per capita use in non-U.S. OECD countries	Follows an S-shaped curve. Reaches 85 percent of current per capita use in non-U.S. OECD countries	Follows an S-shaped curve. Reaches 111 percent of current per capita use in non-U.S. OECD countries	Follows an S-shaped curve. Reaches 172 percent of current per capita use in non-U.S. OECD countries
Restrictions	Performed with current aerosol use restrictions	Performed with current aerosol use restrictions	Performed with current aerosol use restrictions	Performed with current aerosol use restrictions	Performed with current aerosol use restrictions

EXHIBIT 8

SUMMARY OF CFC SCENARIOS

	LOW SCENARIO				MEDIUM SCENARIO				HIGH SCENARIO			
	CFC-11	CFC-12	CFC-22	CFC-113	CFC-11	CFC-12	CFC-22	CFC-113	CFC-11	CFC-12	CFC-22	CFC-113
Potential Future Use (millions of kilograms)												
1985	400	550	110	95	400	560	110	95	430	600	115	95
2000	725	950	220	200	785	1,065	235	210	980	1,450	280	250
2025	1,475	1,775	380	340	2,035	2,525	500	450	3,850	4,620	790	675
2050	2,550	2,750	540	475	4,625	4,825	930	820	8,240	8,130	1,480	1,280
2075	4,325	4,175	830	725	7,650	7,350	1,550	1,380	11,680	11,240	2,425	2,170
Average Growth Rate (%)												
1985-2000	4.0	3.7	4.7	5.0	4.5	4.4	5.1	5.4	5.6	6.0	6.2	6.4
2000-2025	2.9	2.6	2.2	2.2	3.9	3.5	3.1	3.1	5.6	4.7	4.2	4.1
2025-2050	2.2	1.7	1.4	1.4	3.3	2.6	2.5	2.5	3.1	2.8	2.6	2.6
2050-2075	2.2	1.7	1.7	1.7	2.0	1.7	2.1	2.1	1.4	1.3	2.0	2.1

Source: ICF Incorporated Estimate.

EXHIBIT 8 (continued)

SUMMARY OF CFC SCENARIOS

	LIMITS TO GROWTH SCENARIO				NO LIMITS TO GROWTH SCENARIO			
	CFC-11	CFC-12	CFC-22	CFC-113	CFC-11	CFC-12	CFC-22	CFC-113
Potential Future Use (millions of kilograms)								
1985	350	460	75	75	500	800	160	125
2000	550	700	135	130	1,325	2,120	420	345
2025	860	1,040	180	175	6,550	8,020	1,400	1,150
2050	1,400	1,520	250	230	16,100	16,075	3,100	2,570
2075	2,050	2,000	320	290	25,850	25,250	5,885	5,075
Average Growth Rate (%)								
1985-2000	3.2	2.8	4.1	4.1	6.5	6.7	6.7	7.0
2000-2025	1.9	1.6	1.2	1.1	6.6	5.5	5.0	4.9
2025-2050	1.9	1.5	1.3	1.1	3.7	2.8	3.2	3.3
2050-2075	1.6	1.0	1.0	1.0	1.9	1.8	2.6	2.8

Source: ICF Incorporated Estimate.

Also of interest is the projected "intensity of use" in each of the scenarios. Intensity of use measures the contribution that CFCs are expected to make to overall economic activity, measured in kilograms per 1,000 dollars of GNP (1975 U.S. dollars). In 2075 the intensity of use in each of the five scenarios is estimated as: (1) 0.21 kilograms; (2) 0.24 kilograms; (3) 0.24 kilograms; (4) 0.25 kilograms; and (5) 0.26 kilograms. The current intensity of use in the U.S. and in the non-U.S. OECD countries is approximately 0.2 kilograms. The scenarios, therefore, do not reflect an unreasonably large intensity of use of CFCs over the next 90 years.

4. LIMITATIONS

This section discusses the major limitations of the data and methods used to project scenarios of CFC use and emissions. Many of these limitations are inherent in all projections far into the future. Others, however, relate to the lack of historical data describing CFC use in many parts of the world and the simple methods used to generate the scenarios. Individuals considering using the scenarios should be fully aware of the limitations presented here.

4.1 Limitations in Data

Historical data on CFC use and emissions form the basis for the projections of the CFC scenarios. The data are most detailed and complete for the United States, from 1970 to the present. Aggregate data (not differentiated by CFC or use) are available for the OECD for CFC-11, CFC-12, and CFC-22. However, data are particularly sketchy in the following areas:

- Prior to 1970, the division of CFC-11 and CFC-12 between aerosol and nonaerosol uses in the United States is not documented. The division was made by assumption for purposes of this study.

- Data describing the historical use of CFC-113 outside the United States have not been developed. Rough estimates of the current U.S. share of OECD use of CFC-113 were the only data available to describe the use of CFC-113 outside the U.S.

- The mix of uses of CFC-11 and CFC-12 in the OECD is only documented for selected years (i.e., the fraction used in foams, air conditioners, aerosol propellants, etc.). The mix of uses in the United States was assumed to apply to the entire OECD for purposes of developing emissions rates from use.

- Data for non-OECD countries are unreliable or nonexistent.

These data difficulties were overcome by adopting reasonable assumptions. However, alternative assumptions are plausible that may influence the scenarios.

4.2 Limitations in Methods

The methods used in this study to project scenarios of future CFC use are simple and straightforward. Historical data are used to develop relationships between CFC use and population and GNP. These relationships are then used as the basis for projecting future scenarios. The limitations of this method include:

- The structural underpinnings of demand are not estimated. The method assumes that the determinants of demand, in relation to the variables used to make projections (population and GNP), remain unchanged.

- The relationships are based on a fairly narrow range of experience, from a unique history. In the future, population and GNP will be far outside the historical range for the OECD countries. Therefore, even if the relationships among the variables are estimated correctly, there is considerable uncertainty surrounding estimates of future use.

- Estimates of population and GNP far into the future are inherently uncertain. The range of estimates used may understate the full range of possible future outcomes.

- Non-OECD use of each CFC was projected by assuming that per-capita use in these countries would reach a portion of current per-capita use in the non-U.S. OECD. Of note is that the OECD experience may not be applicable to these non-OECD countries due to differences in culture, economies, climate, and other factors.

- By using historical data, the scenarios reflect the historical rate of the introduction of new uses for CFCs. However, the method does not explicitly explore the potential for new uses, nor does it address the potential for new substitutes or more efficient use of CFCs in existing uses.

- Constraints in the future production of CFCs were not explored.

These limitations can be addressed by performing additional research and analysis. However, scenarios that project far into the future will always be fairly uncertain. The next section provides recommendations for next steps.

4.3 Next Steps

To improve the scenarios reported here, analysis should focus on potential natural or man-made constraints to future CFC production and use. This analysis could first explore the implications of the scenarios of future CFC use in termes of demand for complementary products (e.g., automobiles, housing, furniture). Other issues include:

- the likely future availability of the raw materials needed to make CFCs;
- the capital investment required in plant and equipment needed to produce CFCs at the projected rate;
- the potential elimination of CFC substitutes in certain applications due to their toxicity (e.g., carbon tetrachloride used as a solvent in developing nations);
- increased refrigeration and space-cooling requirements as global warming occurs; and
- differences in potential future use among countries developing at different rates (e.g., rapidly developing countries like Taiwan, Brazil, Korea), and among countries that may follow very different development paths (e.g., Tanzania).

By examining these factors, the potential constraints on future CFC use can be explored.[7] These constraints may indicate when important turning points in the scenarios occur, i.e., when use cannot grow at rates indicated by the analysis of the historical data.

If constraints are found to be important, the structural underpinning of demand should also be explored. This information will be required to assess how the future constrained amounts of CFCs will be divided among potential competing uses. Additionally, this information may be useful for improving estimates of future uses in the non-OECD countries by identifying important differences between these countries and the OECD countries.

---

[7] Of note is that as recently as 1976 it was reported that the projected supply of fluorine in the world is "immense and provides no practical limit to CFM [CFC] production," in Halocarbons: Effects on Stratospheric Ozone, National Academy of Sciences, 1976, p. 174. Consequently, the availability and/or price of this raw material may not pose a constraint on the future production of CFCs. More recent analyses confirm this conclusion, see: Mooz, William E., Kathleen A. Wolf, Frank Camm, "Potential Constraints on Cumulative Global Production of Chlorofluorocarbons," The RAND Corporation, WD-2864-EPA, December 1985, and Gibbs, Michael J. and Robin Weiner, "Assessment of the Availability of Fluorine for the Production of Chlorofluorocarbons," ICF Incorporated, February 1986.

ANNEX A

This Annex presents the historical data used to project scenarios of future CFC use. The data are presented in a series of tables. Each table is followed by a description and the footnotes that list the sources of the data. Exhibit A-1 lists the tables presented.

EXHIBIT A-1

LIST OF TABLES IN ANNEX A

Table	Title	Page
A-1	U.S. CFC Production Data - Total	A-3
A-2	U.S. CFC Production Data - Aerosols	A-5
A-3	U.S. CFC Production Data - Non-Aerosols	A-7
A-4	Nominal and Real CFC Prices	A-9
A-5	U.S. Economic Data	A-11
A-6	OECD CFC Production Data	A-13
A-7	OECD Economic Data	A-17
A-8	Projections of GNP and Population Relative to 1975	A-19

TABLE A-1

U.S. CFC PRODUCTION DATA - TOTAL
(Millions of Kilograms)

YEAR	CFC-11 a/	CFC-12 a/	CFC-22 a/	CFC-113 c/
1958	22.90	59.60	15.10 b/	0.00
1959	27.40	71.30	16.60	0.00
1960	32.80	75.50	18.20	2.00
1961	41.20	78.70	20.50	3.00
1962	56.60	94.30	22.30	4.00
1963	63.60	98.60	24.50	4.50
1964	67.40	103.40	26.80	5.40
1965	77.30	123.10	29.10	6.40
1966	77.30	129.90	31.80	7.30
1967	82.70	140.50	35.50	9.50
1968	92.70	147.70	39.10	11.40
1969	108.20	166.80	42.70	13.60
1970	110.90	170.30	45.50	16.40
1971	117.00	176.70	50.90	19.50
1972	135.90	199.20	55.90	22.70
1973	151.40	221.70	61.80	26.80
1974	154.70	221.10	64.10	29.00
1975	122.30	178.30	59.80	31.00
1976	116.20	178.30	77.00	37.10
1977	96.40	162.50	81.40	45.20
1978	87.90	148.40	93.30	51.20
1979	75.80	133.30	95.60	58.80
1980	71.70	133.80	103.20	45.90
1981	73.80	147.60	114.20	48.20
1982	63.70	117.00	79.00	50.00
1983	73.10	134.30	106.90	52.70

---

a/ See attached footnotes.

TABLE A-1: U.S. CFC PRODUCTION DATA - TOTAL

Description: Table A-1 presents time series data on the total U.S. production of CFC-11, CFC-12, CFC-22, and CFC-113 for the years 1958 to 1983. The primary source of these data is the U.S. International Trade Commission. It was necessary to estimate some values using assumptions based on actual data. The footnotes which accompany the table describe these assumptions.

Footnotes:

a) U.S. ITC. Synthetic Organic Chemicals. Annual Series. These include CFC-22 used as an intermediate. Approximately 28 percent of CFC-22 is used in the production of teflon and other products.

b) Estimates for 1958-59 for CFC-22 are based on average annual percent changes over the period 1960-65.

c) For 1958 to 1962, U.S. production is assumed to be 100 percent of total world production reported in: OECD, 1981, Summary of the Conclusions Regarding Scenarios of the Ad Hoc Meeting, ENV/CHEM/PJC/81.79, p. D.1. U.S. production in 1963 was assumed to be 90 percent of the world total reported in the OECD document. Data for 1964 to 1974 are from: A.D. Little, Preliminary Economic Impact Assessment of Possible Regulatory Actions to Control Emissions of Selected Halocarbons, September 1976. Data for 1975 to 1979 are estimated by taking the portion of world CFC-113 production accounted for by the U.S. in 1974 (64.6 percent) and multiplying by the world production reported in the OECD document. The years 1980 to 1983 are projections reported in U.S. EPA, Economic Implications of Regulating Chlorofluorocarbon Emissions from Nonaerosol Applications, (EPA-560/12-80-001), October 1980, pp. 67-68.

TABLE A-2

U.S. CFC PRODUCTION DATA - AEROSOLS
(Millions of Kilograms)

YEAR	CFC-11	CFC-12
1958	19.90 a/	35.80 b/
1959	23.10	42.80
1960	26.70	45.30
1961	32.40	47.20
1962	43.20	56.60
1963	46.60	59.10
1964	47.50	62.00
1965	52.40	73.90
1966	50.20	77.90
1967	51.50	84.30
1968	55.20	88.60
1969	61.40	100.00
1970	60.00 c/	102.10 c/
1971	63.10	106.20
1972	72.10	117.50
1973	83.40	135.20
1974	86.70	123.90
1975	73.30	94.50
1976	64.00	80.30
1977	36.50	47.30
1978	32.90 d/	41.90 d/
1979	9.50	5.30
1980	9.50	5.80
1981	9.50	5.60

a/ See attached footnotes.

TABLE A-2: U.S. CFC PRODUCTION DATA - AEROSOLS

Description: Table A-2 presents time series data on the total U.S. CFC production of CFC-11 and CFC-12 for aerosol applications. The statistical analyses performed to project potential aerosol applications in the absence of government regulation used data for the years 1958 to 1974. Use in the years following 1974 may be influenced by expectations regarding government regulation.

Footnotes:

a) Estimates for 1958-1969: based on the assumption that in 1958 the U.S. dominates the OECD market as CFC-11. In 1958, the CMA data (CMA. Production, Sales, and Calculated Release of CFC-11 and 12 through 1982; Expanded Data) show a market share of open cell, aerosol, and all other production to be 87 percent of total CFC-11 production. Thus, the U.S. aerosol share of total CFC production is assumed to be 87 percent in 1958, declining smoothly to 54 percent in 1970, where 54 percent is the aerosol proportion in 1970 described in footnote C. Total CFC-11 production is based on U.S. ITC data.

b) Estimates for 1958-1969: based on the assumption that CFC-12 aerosol production was 60 percent of total CFC-12 production, as it was in 1970.

c) Data for 1970-1977: U.S. EPA. Regulating Chlorofluorocarbon Emissions: Effects on Chemical Production. (EPA-560/12-80-0016) October 1980, pp. 73, 74, 80. Reports production figures from pp. 73-74, using aerosol/nonaerosol proportions from p. 80.

d) Estimates for 1978 to 1981 computed by subtracting usage in non-aerosol applications from total CFC usage. See Tables A-1 and A-3.

TABLE A-3

U.S. CFC PRODUCTION DATA - NON-AEROSOLS
(Millions of Kilograms)

YEAR	CFC-11	CFC-12	CFC-22 f/	CFC-113 h/
1958	3.00 a/	23.80 b/	15.10 g/	0.00
1959	4.30	28.50	16.60	0.00
1960	6.10	30.20	18.20	2.00
1961	8.80	31.50	20.50	3.00
1962	13.40	37.70	22.30	4.00
1963	17.00	39.50	24.50	4.50
1964	19.90	41.40	26.80	5.40
1965	24.90	49.20	29.10	6.40
1966	27.10	52.00	31.80	7.30
1967	31.20	56.20	35.50	9.50
1968	37.50	59.10	39.10	11.40
1969	46.80	66.80	42.70	13.60
1970	50.80 c/	68.00 c/	45.50	16.40
1971	54.00	70.80	50.90	19.50
1972	64.00	81.60	55.90	22.70
1973	68.00	86.60	61.80	26.80
1974	68.00	97.10	64.10	29.00
1975	49.00	83.90	59.80	31.00
1976	52.20	98.00	77.00	37.10
1977	59.90	115.20	81.40	45.20
1978	55.00 d/	106.50 d/	93.30	51.00
1979	66.30	128.00	95.60	58.80
1980	62.20	128.00	103.20	45.90
1981	64.30	142.00	114.20	48.20
1982	63.70 e/	117.00 e/	79.00	50.00
1983	73.10	134.30	106.90	52.70

---

a/ See attached footnotes.

TABLE A-3: U.S. CFC PRODUCTION DATA - NON-AEROSOLS

Description: Table A-3 presents time series data on U.S. CFC production for non-aerosol applications. The table contains actual data for CFC-11 and CFC-12 for the years 1970-1977; CFC-22 for the years 1960-1983; and CFC-113 for the years 1965-1974. The remaining estimates are based on assumptions detailed in the footnotes.

Footnotes:

a) Estimates for 1958-1969: CFC-11 non-aerosols are defined as CFC-11 total minus CFC-11 aerosol (see Table A-2).

b) Estimates for 1958-1969: based on the assumption that CFC-12 nonaerosol production was 40 percent of total CFC-12 production, as it was in 1970.

c) Data for 1970-1977: U.S. EPA. Regulating Chlorofluorocarbon Emissions: Effects on Chemical Production. (EPA-560/12-80-0016) October 1980, pp. 73, 74, 80. Reports production figures from pp. 73-74, using aerosol/nonaerosol proportions from p. 80.

d) Estimates for 1978-1981: OECD. Economic Aspects of CFC Emission Scenarios prepared by the Chemical Groups and Management Committee, 15 September 1982, p. 32. Based on the assumption that the split between CFC-11 and CFC-12 in these years was the same as it was in 1977.

e) Estimates for 1981-1982: based on the assumption that production for aerosol applications is zero, which makes nonaerosol production equal to total production.

f) U.S. ITC. Synthetic Organic Chemicals. Annual Series.

g) Estimates for 1958-1959: based on the average annual percent change for CFC production for the period 1960-1965.

h) For 1958 to 1962, U.S. production is assumed to be 100 percent of total world production reported in: OECD, 1981, Summary of the Conclusions Regarding Scenarios of the Ad Hoc Meeting, ENV/CHEM/PJC/81.79, p. D.1. U.S. production in 1963 was assumed to be 90 percent of the world total reported in the OECD document. Data for 1964 to 1974 are from: A.D. Little, Preliminary Economic Impact Assessment of Possible Regulatory Actions to Control Emissions of Selected Halocarbons, September 1976. Data for 1975 to 1979 are estimated by taking the portion of world CFC-113 production accounted for by the U.S. in 1974 (64.6 percent) and multiplying by the world production reported in the OECD document. The years 1980 to 1983 are projections reported in U.S. EPA, Economic Implications of Regulating Chlorofluorocarbon Emissions from Nonaerosol Applications, (EPA-560/12-80-001), October 1980, pp. 67-68.

TABLE A-4

NOMINAL AND REAL CFC PRICES
(cents/kg)

YEAR	CFC-11 Nominal	CFC-11 Real	CFC-12 Nominal	CFC-12 Real	CFC-22 Nominal	CFC-22 Real	CFC-113 Nominal	CFC-113 Real
1958	46.20 a/	69.96 b/	66.00 a/	199.94 b/	156.20 a/	236.52 b/	NA	NA
1959	NA	NA	68.20	100.89	151.80	224.56	NA	NA
1960	48.80	71.03	66.00	96.07	154.00	224.16	NA	NA
1961	48.80	70.39	66.00	95.20	154.00	222.13	NA	NA
1962	46.20	65.43	63.80	90.36	147.40	208.75	NA	NA
1963	44.00	61.39	63.80	89.02	145.20	202.60	NA	NA
1964	44.00	60.46	63.80	87.67	136.40	187.44	NA	NA
1965	44.00	59.17	61.60	82.84	134.20	180.47	NA	NA
1966	44.06	57.40	61.60	80.25	138.60	180.56	NA	NA
1967	41.80	52.87	59.40	75.13	136.40	172.53	NA	NA
1968	41.80	50.64	57.20	69.30	132.00	159.92	NA	NA
1969	39.60	45.63	55.00	63.37	123.20	141.95	NA	NA
1970	41.80	45.71	57.20	62.55	112.20	122.69	88.0 c/	96.2 b/
1971	41.80	43.54	55.00	57.29	112.20	116.86	88.0	91.7
1972	39.60	39.60	52.80	52.80	107.80	107.80	88.0	88.0
1973	41.80	39.53	52.80	49.93	99.00	93.62	85.0	80.4
1974	52.80	45.88	68.20	59.26	123.20	107.06	95.0	82.5
1975	74.80	59.46	90.20	71.71	173.80	138.17	107.0	85.0
1976	74.80	56.52	90.20	68.16	156.20	118.03	114.0	86.1
1977	74.80	53.41	88.00	62.83	149.60	106.82	123.0	87.8
1978	NA	NA	NA	NA	NA	NA	NA	NA
1979	86.00 d/	52.63	94.00 d/	57.52	135.00 d/	82.61	134.0 d/	82.0
1980	92.00	51.56	105.00	58.85	170.00	95.28	152.0	85.2
1981	104.00	53.30	119.00	60.98	192.00	98.39	159.0	81.5
1982	NA	NA	NA	NA	NA	NA	NA	NA
1983	NA	NA	NA	NA	NA	NA	NA	NA

a/ See attached footnotes.

NA = Not available.

TABLE A-4: NOMINAL AND REAL CFC PRICES

Description: Table A-4 presents time series data on the nominal and real prices of CFC-11, CFC-12, CFC-22 and CFC-113. The primary source of this data is the SRI Chemical Economics Handbook.

Footnotes:

a) Data for 1958-1977: SRI. Chemical Economics Handbook.

b) Real prices computed using implicit GNP deflator.

c) Data for 1970-1977: U.S. EPA. Economic Implications of Regulating Chlorofluorocarbon Emissions from Nonaerosol Applications. (EPA-560/12-80-001) October 1980, p. 79.

d) 1979-1982: List prices from the Chemical Marketing Reporter.

TABLE A-5

U.S. ECONOMIC DATA a/

Year	GNP (bill. 1972 $)	Population (1000s)	GNP Per Capita (1972 $/person)	Annual Growth Rate of GNP Per Capita (%)
1958	680.9	174,882	3,890	--
1959	721.7	177,830	4,060	4.4
1960	737.2	180,671	4,080	0.4
1961	756.6	183,691	4,120	1.0
1962	800.3	186,538	4,290	4.1
1963	832.5	189,242	4,400	2.6
1964	876.4	191,889	4,570	3.9
1965	929.3	194,303	4,780	4.6
1966	984.8	196,560	5,010	4.8
1967	1011.4	198,712	5,090	1.6
1968	1058.1	200,706	5,270	3.5
1969	1087.6	202,677	5,370	1.9
1970	1085.6	205,052	5,295	-1.4
1971	1122.4	207,661	5,405	2.1
1972	1185.9	209,896	5,650	4.5
1973	1254.3	211,909	5,920	4.8
1974	1246.3	213,854	5,830	-1.5
1975	1231.6	215,973	5,700	-2.2
1976	1298.2	218,035	5,940	4.2
1977	1369.7	220,239	6,220	3.8
1978	1438.6	222,585	6,465	3.9
1979	1479.4	225,055	6,575	3.0
1980	1475.0	227,704	6,480	-2.7
1981	1513.8	229,849	6,587	1.6
1982	1485.4	232,057	6,400	-2.8
1983	1534.8	234,249	6,550	2.3

a/ See attached footnotes.

TABLE A-5: U.S. ECONOMIC DATA

Description: Table A-5 presents time series data on U.S. GNP (in billions of 1972 dollars) and population (in thousands)

Footnotes: a) Economic Report of the President, 1984. pp. 222, 253

TABLE A-6

OECD CFC PRODUCTION DATA
(Millions of Kg)

YEAR	Total Production CFC-11	Total Production CFC-12	Total Production CFC-22	Aerosol Production CFC-11	Aerosol Production CFC-12* Assumption 1	Aerosol Production CFC-12* Assumption 2	Aerosol Production CFC-12* Assumption 3	Aerosol Production CFC-22
1958	29.50 a/	73.40 a/	7.60 b/	25.70 d/	42.40 d/	34.40 e/	44.00 g/	-
1959	35.60	87.60	11.30	30.70	50.60	45.50	52.60	-
1960	49.70	99.40	12.20	42.18	57.50	53.70	59.60	-
1961	60.50	108.50	12.20	50.52	62.70	59.00	65.10	-
1962	78.10	128.10	15.50	63.40	74.00	74.20	76.90	-
1963	93.30	146.40	17.60	73.63	84.60	87.20	87.80	-
1964	111.10	170.10	22.40	85.90	98.30	104.80	102.10	-
1965	122.80	190.10	25.10	92.50	109.90	115.30	114.10	-
1966	141.00	216.20	31.60	102.70	125.00	132.00	129.70	-
1967	159.80	242.80	37.40	114.53	140.30	150.40	145.70	-
1968	183.10	267.50	45.70	127.50	154.60	168.80	160.50	-
1969	217.30	297.30	56.00	147.46	171.80	187.00	178.40	-
1970	238.10	321.10	58.80	159.33	185.60	201.70	192.70	-
1971	263.20	341.60	64.60	168.81	197.40	214.30	205.00	-
1972	306.90	379.90	70.10	191.81	219.60	236.60	224.10	-
1973	349.10	423.30	76.60	211.42	244.70	263.00	258.20	-
1974	369.70	442.80	87.90	222.53	255.90	276.10	248.00	-
1975	314.10	381.00	73.70	183.79	220.20	229.80	201.90	-
1976	339.80	410.70	80.70 c/	195.10 f/				237.30 f/
1977	320.50	382.80	88.40	164.70				186.30
1978	308.90	372.10	96.80	143.60				163.70
1979	289.50	357.20	106.00	111.60				143.00
1980	289.60	350.20	116.10	105.10				138.20
1981	286.90	351.30	127.10	94.00				127.60
1982	282.60	328.00	139.20	92.50				116.10

* Estimates of the aerosol/non-aerosol division of CFC-12 for 1958 to 1975 were performed using three sets of assumptions. See footnotes, d, e, and g for details.

TABLE A-6 (continued)

OECD CFC PRODUCTION DATA
(Millions of Kg)

YEAR	Non-Aerosol Production					
		CFC-12*				
	CFC-11	Assumption 1	Assumption 2	Assumption 3		CFC-22
1958	3.80 d/	31.00 d/	39.00 e/	29.40 g/	-	7.60 b/
1959	4.90	37.00	42.10	35.00	-	11.30
1960	7.60	41.90	45.70	39.80	-	12.20
1961	9.98	45.80	49.50	43.40	-	12.20
1962	14.70	54.10	53.90	51.20	-	15.50
1963	19.67	61.80	59.20	58.40	-	17.60
1964	25.20	71.80	65.30	68.00	-	22.40
1965	30.30	80.20	74.80	76.00	-	25.10
1966	38.30	91.20	84.20	86.50	-	31.60
1967	45.27	102.50	92.40	97.10	-	37.40
1968	55.60	112.90	98.70	107.00	-	45.70
1960	69.84	125.50	110.30	118.90	-	56.00
1970	78.77	135.50	119.40	128.40	-	58.80
1971	94.39	144.20	127.30	136.60	-	64.60
1972	115.09	160.30	143.30	155.80	-	70.10
1973	137.68	178.60	160.30	165.10	-	76.60
1974	147.17	186.90	166.70	194.80	-	87.90
1975	130.31	160.80	151.20	152.40	-	73.70
1976	144.70				173.50 f/	80.70 c/
1977	155.90				196.70	88.40
1978	165.40				208.40	96.80
1979	177.90				214.20	106.00
1980	184.60				212.20	116.10
1981	193.00				223.80	127.10
1982	190.20				212.10	139.20

a/ See attached footnotes.

* Estimates of the aerosol/non-aerosol division of CFC-12 for 1958 to 1975 were performed using three sets of assumptions. See footnotes, d, e, and g for details.

TABLE A-6: OECD CFC PRODUCTION DATA

Description: Table A-6 presents time series data on OECD CFC production for 1958 to 1982. The principal source for these data are the Chemical Manufacturers Association (CMA) estimates based on the reports of 21 companies involved in CFC production throughout the world. The assumption underlying the estimates is that production by CMA reporting companies is used almost entirely in the OECD countries. The procedures for dividing total production of CFC-11 and CFC-12 into aerosol and nonaerosol use are described in footnotes d, e and g.

Footnotes:

a) CMA. Production, Sales, and Calculated Release of CFC-11 and CFC-1[illegible] Through 1982. 12 August 1983, Schedules 2, 3.

b) 1958-197[illegible] OECD. Fluorocarbons: An Assessment of Worldwid[illegible] roduction, Use, and Environmental Issues. 1976, Schedule 4. CFC-22 data are end use only and do not include CFC-22 produced as an intermediate.

c) Estimates for 1976-1982: based on the assumption that the percent change remains constant at 9.5 percent, which is equal to the average of the annual percent changes over the period 1970-1975.

d) CMA. 12 August 1983. Estimates for 1958-1975: based on the 1976 proportions for aerosol/nonaerosol reported in schedules 5 and 6:

- CFC-11 production for aerosol is based on CMA estimates assuming that all of the open cell, aerosols, and all other production category was used for aerosols in 1958. It is also assumed that in 1976, aerosols make up 76 percent of this category, based on 1976 proportions for aerosols found in schedules 5 and 6. The aerosol share of total CFC-11 production in this time period (1958-1976) is thus 87 percent in 1958, declining smoothly to 57 percent of total CFC-11 in 1976. The non-aerosol share of CFC-11 is assumed to be total production minus aerosol production.

- CFC-12 production for aerosol = 57.8 percent of total CFC-12 production for nonaerosol = 42.2 percent.

e) CMA. 12 August 1983. Estimates for 1958-1975: based on the 1976 proportions for aerosol/nonaerosol reported in schedules 5 and 6:

- CFC-12 for aerosol = 82.8 percent of CFC-12 for aerosol + open cell + all other

f) CMA. 12 August 1983. Estimates for 1976-1982: based on assumption that aerosol sales = aerosol production.

g) Estimates for 1958-1975: based on the assumption that OECD division between aerosol and nonaerosol use will follow the U.S. experience (until the time of the U.S. ban on aerosol production).

TABLE A-7

OECD ECONOMIC DATA a/

YEAR	GDP (Billions of 1975 $)	Population (1000s)	GDP/Population (1975 $/person)	Annual Growth Rate of GDP/Population (%)
1960	2150.38	NA	NA	NA
1961	2251.52	NA	NA	NA
1962	2372.62	656,444	3614.3	--
1963	2485.74	664,384	3741.4	3.5
1964	2641.22	672,171	3929.4	5.0
1965	2781.35	679,749	4091.7	4.1
1966	2931.17	686,837	4267.6	4.3
1967	3039.67	693,529	4382.9	2.7
1968	3213.59	699,995	4590.9	4.7
1969	3385.03	706,919	4788.4	4.3
1970	3501.64	714,281	4902.3	2.3
1971	3635.82	723,180	5027.5	2.6
1972	3830.22	730,617	5242.4	4.3
1973	4061.50	737,699	5505.6	5.0
1974	4094.72	744,409	5500.6	-0.1
1975	4080.64	750,860	5434.6	-1.2
1976	4284.42	756,724	5661.8	4.2
1977	4449.49	762,476	5835.6	3.1
1978	4618.97	768,355	6011.5	3.0
1979	4776.08	774,275	6168.4	2.6
1980	4835.22	780,643	6193.9	0.4

a/ See attached footnotes.

NA = not available.

TABLE A-7: OECD ECONOMIC DATA

Description: Table A-7 presents time series data on OECD GDP (measured at 1975 exchange rates and in billions of constant 1975 U.S. dollars), population, and GDP/population. Data are only available for the period 1960 to 1980.

Footnotes: a) OECD. National Accounts: Volume 1, Main Aggregates 1951-1980. 1982.

TABLE A-8

PROJECTIONS OF GNP AND POPULATION RELATIVE TO 1975 a/

OECD REGIONS

UNITED STATES		CANADA AND WESTERN EUROPE		OECD PACIFIC		
POPULA	GNP	POPULA	GNP	POPULA	GNP	YEAR
1.0000	1.000	1.0000	1.000	1.0000	1.000	1975
1.1890	1.877	1.1760	1.978	1.2010	2.701	2000
1.3170	3.021	1.3030	3.534	1.2790	5.432	2025
1.3470	4.505	1.3650	5.709	1.3050	9.121	2050 b/
1.3664	6.537	1.3872	8.283	1.3176	13.234	2075
1.3664	9.484	1.3872	12.019	1.3176	19.202	2100

CENTRALLY PLANNED AND MIDEAST REGIONS

EASTERN EUROPE AND USSR		CENTRALLY PLANNED ASIA		MIDDLE EAST		
POPULA	GNP	POPULA	GNP	POPULA	GNP	YEAR
1.0000	1.000	1.0000	1.000	1.0000	1.000	1975
1.1960	1.815	1.3700	2.665	1.8030	3.649	2000
1.3080	2.943	1.6450	5.468	2.4480	8.959	2025
1.3510	4.442	1.7700	10.335	2.8470	18.044	2050 b/
1.3720	6.445	1.8081	14.996	2.9595	26.181	2075
1.3720	9.351	1.8081	21.758	2.9595	37,987	2100

DEVELOPING COUNTRY REGIONS

AFRICA		CENTRALLY LATIN AMERICA		SOUTH AND EAST ASIA		
POPULA	GNP	POPULA	GNP	POPULA	GNP	YEAR
1.0000	1.000	1.0000	1.000	1.0000	1.000	1975
1.7450	3.069	1.7280	3.475	1.6850	3.079	2000
2.3610	7.327	2.2980	9.005	2.2260	7.169	2025
2.7580	13.806	2.6310	16.395	2.5560	13.502	2050 b/
2.8807	20.032	2.7144	23.788	2.6504	19.591	2075
2.8807	29.065	2.7144	34.515	2.6504	28.425	2100

a/ See attached footnotes.

TABLE A-8: PROJECTIONS OF GNP AND POPULATION RELATIVE TO 1975

Description: Table A-8 presents projections of GNP and population for the nine regions of the world: 1) U.S.; 2) Canada and Western Europe; 3) OECD Pacific; 4) Eastern Europe and USSR; 5) Centrally Planned Asia; 6) the Middle East; 7) Africa; 8) Latin America; and 9) South and East Asia.

Footnotes:

a) Institute for Energy Analysis, Oak Ridge Associated Universities. The values in the table are relative to 1975. For example, in the U.S., population is projected to be 1.3664 times the 1975 population by 2100.

b) The post-2050 GNP annual growth rates were assumed to be 1.5 percent in all parts of the world.

ANNEX B

REGRESSION ANALYSIS RESULTS

The equations used to project scenarios of CFC use were estimated using least squares regression. The equations were evaluated using t-statistics and adjusted R-squared values (R^2). Most importantly, the variable coefficients were examined to see whether their signs and sizes conformed to theoretical and intuitive expectations.

The regression equations estimated are presented in Exhibit B-1. The t-statistics were used to determine whether the coefficients are statistically significant at the 5% level. (The t-statistics are shown in parentheses below their corresponding coefficients.) The R^2, also presented in Exhibit B-1, measures the proportion of variation in the dependent variable explained by the right hand side variable(s), while controlling for the numbers of explanantory variables.

In general, the regression equations explain a large portion of the variation in the dependent variables. For example, in equation 1, the variation in U.S. GNP per person explains 90 percent of the variation in the U.S. use per person of CFC-11 in aerosol applications. The coefficient on the U.S. GNP per person variable implies that a one unit increase in this quantity will correspond to a 1.2E-07 unit increase in CFC use per person (in millions of kilograms).[1]

---

[1] The format "1.2E-07" shown in Exhibit B-1 means 1.2 times 10 raised to the -07 power.

EXHIBIT B-1

ESTIMATED RELATIONSHIPS BETWEEN CFC USE
AND EXPLANATORY VARIABLES 1/

	Dependent Variable	Explanatory Variables and Coefficients	Adjusted R-Squared
1.	U.S. CFC-11 aerosol use/person	-3.1E-04 + 1.2E-07 × U.S. GNP/POP (-6.4) (11.76)	0.90
2.	U.S. CFC-11 nonaerosol use/person	-1.7E-05 + 8.5E-08 × U.S. GNP/POP (-0.2) (9.0) + -1.7E-06 × Price of CFC-11 (-6.4)	0.97
3.	U.S. CFC-12 aerosol use/person	7.7E-05 + 1.2E-07 × U.S. GNP/POP (0.4) (4.2) + -2.0E-06 Price of CFC-12 (-3.0)	0.98
4.	U.S. CFC-12 nonaerosol use/person	-7.4E-04 + 2.0E-07 × U.S. GNP/POP (-4.8) (7.5)	0.89
5.	U.S. CFC-22 use/person	-6.2E-04 + 1.6E-07 × U.S. GNP/POP (-5.0) (7.3)	0.88
6.	U.S. CFC-113 use/person	-3.7E-04 + 8.9E-08 × U.S. GNP/POP (-10.3) (12.8)	0.89
7.	OECD-U.S. CFC-11 aerosol use/person	-2.9E-04 + 1.1E-07 × OECD-U.S. GNP/POP (-23.6) (36.0)	0.99
8.	OECD-U.S. CFC-11 nonaerosol use/person	-2.9E-04 + 9.2E-08 × OECD-U.S. GNP/POP (-12.5) (16.8)	0.94
9.	OECD-U.S. CFC-12 aerosol use/person	-2.6E-04 + 1.1E-07 × OECD-U.S. GNP/POP (-20.1) (31.4)	0.99
10.	OECD-U.S. CFC-12 nonaerosol use/person	-6.0E-06 + 4.3E-03 × OECD-U.S. GNP/POP (-0.2) (12.2) + -5.07E-07 Price of CFC-12 (-4.7)	0.98

1/ CFC use/person in thousands of kilograms per person. U.S. GNP/POP is in 1972 dollars per person. OECD-U.S. GNP/POP in 1975 dollars per person. Prices of CFC-11 and CFC-12 expressed as an index with 1972 = 100.

ANNEX C

THE RELATIONSHIPS AMONG CFC USE, CFC EMISSIONS, AND BANKED CFCs

Annual CFC use and emissions are not equivalent. Some portion of the use may be released immediately (e.g., emissions from solvent use). However, a large portion may remain in the product for many years (e.g., the refrigerant trapped in the appliance). The CFCs remaining in products are referred to as "banked." Banked CFCs are emitted slowly over time (e.g., when a refrigerator compressor is repaired or disposed of, the CFCs in the refrigerator may be released). Exhibit C-1 displays the manner in which CFC use, emissions, and the CFC bank interact and are treated in this analysis.

In year 1 of the analysis (e.g., 1985) there is an existing amount of banked CFCs from past uses of products containing these chemicals. These CFCs contribute to emissions in year 1. Also in year 1, there is some level of CFC use. Some portion of these CFCs are emitted promptly, and become part of the year 1 emissions. The remaining portion is banked, and becomes part of the bank in year 2. These banked CFCs are then slowly emitted from year 2 onward. This procedure repeats year after year.

From the schematic in Exhibit C-1 it is clear that the following three components must be specified in order to project scenarios of emissions:

- the future rate of CFC use;
- current reservoir of banked CFCs; and
- the rate of prompt emissions directly from use (e.g., from CFC use as aerosol propellants) and the rate of emissions from the banked CFCs (e.g., the rate of releases of CFCs trapped in appliances).

The future rates of use are developed as scenarios. Estimates of the current CFC bank and the rates of emissions from use and the bank were developed. The total world quantity of currently banked CFC-11 and CFC-12 was estimated as 768.9 and 880.7 million kilograms respectively.[1] No estimate was available for the amount of CFC-22 banked. Because CFC-113 is only used in a prompt emitting applications, there is no CFC-113 bank.

The release rates from the existing CFC-11 and CFC-12 banks are displayed in Exhibit C-2. For example, the exhibit shows that over the next ten years, 27.5 percent of the banked CFC-11 is expected to be released. Of note is that a fairly large fraction of CFC-11 (22.8 percent) is expected to take a very long time to be released. These CFCs are banked in insulating foams.

---

[1] "Production, Sales ...", CMA, op. cit. These data are for 1982.

EXHIBIT C-I

SCHEMATIC OF CFC USE, EMISSIONS, AND BANKS

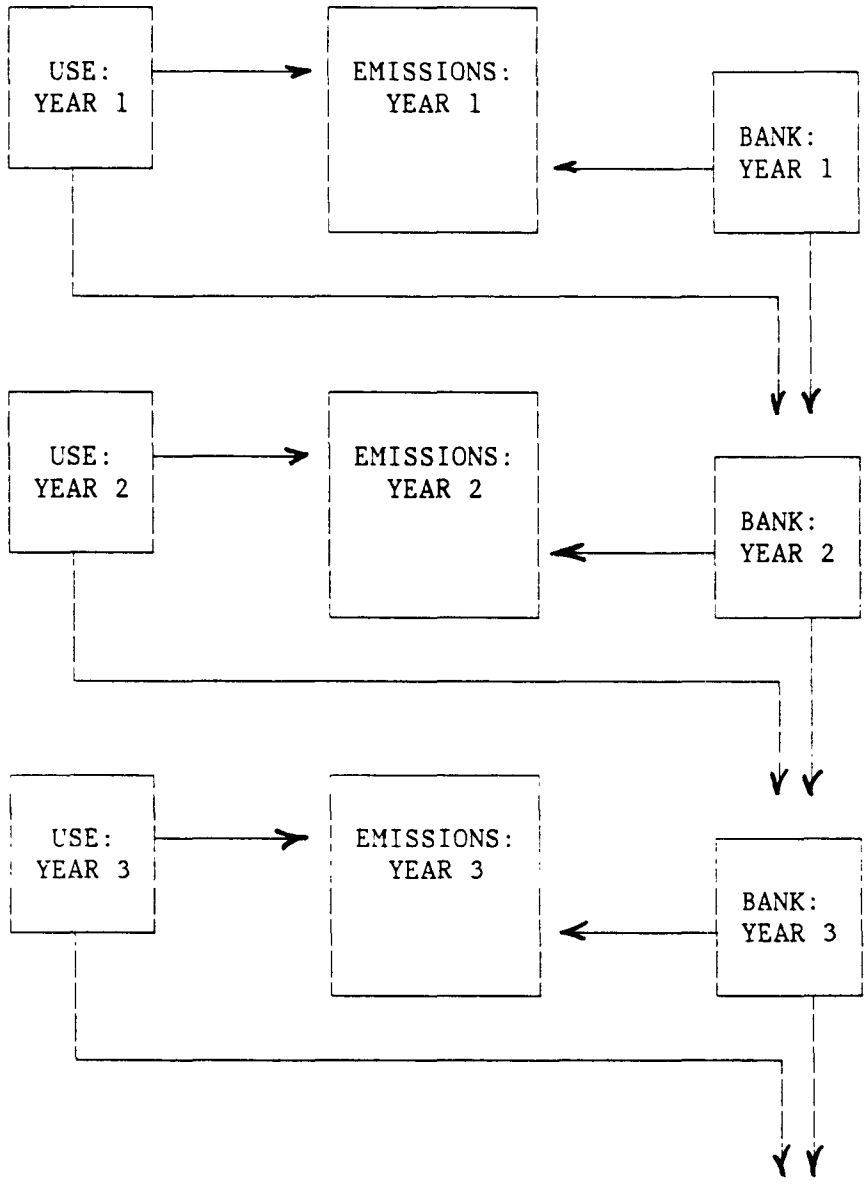


EXHIBIT C-2

EMISSIONS FROM EXISTING BANKS
(percentage)

Years from Now	CFC-11	CFC-12
1-10	27.5	85.0
11-20	27.0	6.3
21-30	6.2	7.5
31-40	3.9	0.1
41-50	3.8	0.1
51-60	3.3	0.1
61-70	2.8	0.1
71-80	2.7	0.1
81-150	22.8	0.7
Total	100.0	100.0

Source: See text.

Exhibit C-3 shows the rate of release after the use of CFCs in non-aerosol applications.[2] For example, 66.4 percent of the use of CFC-11 in non-aerosol applications is estimated to be released promptly, i.e., in the year of use (the exhibit shows this 66.4 percent being released zero years after use). Again, CFC-11 shows a substantial fraction being banked over a long period of time.

These release rates were derived by: (1) identifying the mix of applications of each CFC (i.e., the fraction going to air conditioners, foams, refrigerators, etc.); (2) identifying the rate of emissions from each of these applications; and (3) weighting the rates of emissions by the mix of the applications to estimate release rates for the CFC type. The data describing the rates of release by application and the mix of applications are presented in Exhibit C-4. These release rate estimates were developed from Environment Committee Report on Chlorofluorocarbons by OECD (1982). The mix of uses is for the U.S. in 1976 as reported in Economic Implications of Regulating Chlorofluorocarbon Emissions from Nonaerosol Applications, by The Rand Corporation (June 1980). The emissions rates reported in Exhibits 3 and 4 were used for all parts of the world, throughout the entire period examined.

---

[2] The release rate for the aerosol applications of CFC-11 and CFC-12 as well as all the use of CFC-113 is assumed to be 100 percent in the year of use.

EXHIBIT C-3

EMISSIONS FROM USE
(percentage)

Years After Use	CFC-11 Non-Aerosol	CFC-12 Non-Aerosol	CFC-22 Non-Aerosol
0	66.4	45.0	45.0
1-10	7.6	46.5	23.9
11-20	7.2	3.7	23.4
21-30	3.6	4.4	7.7
31-40	2.5	0.1	0.0
41-50	2.4	0.1	0.0
51-60	2.1	0.1	0.0
61-70	1.8	0.1	0.0
71-80	1.7	0.0	0.0
81-150	4.7	0.0	0.0
Total	100.0	100.0	100.0

Source: See text.

EXHIBIT C-4

PROMPT VS. BANKED EMISSION DATA BY END USE

CFC Product	Principal End Use and Percent of Product Use	Emissions % Prompt	Emissions % Banked	Life of End-Use	Year of Release of Banked CFCs After Initial Use: 1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100	greater than 100
CFC-11	Flexible Foam: 34%	100%	0%												
	Rigid Foams Urethane: 35%	26.5	73.5	1/2 life of emissions = 60 years	11%	10%	9%	7%	7%	6%	5%	5%	4%	4%	32%
	Nonurethane: 2%	100.0	0												
	Chillers: 8%	2.0	98.0	20 years	47.5 (46.5)[1]	47.5 (46.5)	5.0								
	Other: 20%	100.0	0												
CFC-12	Rigid Foams Urethane: 1%	26.5	73.5	1/2 life of emissions = 60 years	11	10	9	7	7	6	5	5	4	4	32
	Nonurethane: 11%	100.0	0												
	MACS[2]: 48%	11.0	89.0	7 years	100 (89)										
	Chillers: 3%	2.0	98.0	20 years	47.5 (46.5)	47.5 (46.5)	5.0								
	Home Refrig. & Freezer: 3%	7.0	93.0	20 years	16.0 (14.5)	16.0 (14.5)	69.0 (64)								
	Retail Food Refrig.: 6%	3.0	97.0	20 years	31.0 (30)	31.0 (30)	38.0 (37)								
	Other: 28%	100.0	0	--	--	--	--								
CFC-22	Chillers: 3%	2.0	98.0	20 years	47.5 (46.5)	47.5 (46.5)	5.0								
	Retail Food Refrig.: 1%	3.0	97.0	20 years	31.0 (30)	31.0 (30)	38.0 (37)								
	Other: 96%	100.0	0	--	--	--	--								
CFC-113	Solvents: 100%	100.0	0	--	--	--	--								

[1] Numbers in parentheses refer to the rate of release of total CFCs emitted (i.e. Prompt and banked emissions).

[2] Mobile Air Conditioners.

Source: ICF analysis of data in: Environment Committee Report on Chlorofluorocarbons, OECD, 1982, and Economic Implications of Regulating Chlorofluorocarbon Emissions from Non-Aerosol Applications, The Rand Corporation, June 1980.

ANNEX D

SCENARIOS BY TYPE OF CFC

This annex presents a series of tables that describe the potential future use and emission of CFC-11, CFC-12, CFC-22, and CFC-113 in five scenarios: Limits to Growth; Low; Medium; High; and No Limits to Growth. These estimates are based on the assumption that current aerosol use restrictions remain in force.

For each CFC type in each scenario the following information is provided for the world total:

- annual use and the annual percent growth in use;
- total annual emissions;
- portions of emissions that come:
  - -- directly from use
  - -- from the banked CFCs created due to projected use (referred to as the "simulated use bank" and labelled "UBANK")
  - -- from the banked CFCs that already exist today (referred to as the "other bank" and labelled "OBANK");
- total banked CFCs, labelled "TBANK;"
- banked CFCs from simulated future use, labelled "UBANK;" and
- banked CFCs that already exist today, labelled "OBANK."

RESULTS FOR LIMITS TO GROWTH SCENARIO

WORLD TOTAL: CFC-11

COMPONENTS INCLUDED :
UNITED STATES NON-AEROSOL USE OF CFC-11: LINEAR MODEL 2
UNITED STATES AEROSOL USE OF CFC-11: LINEAR MODEL + AEROSOL REST = 4.5
EEC NON-AEROSOL USE OF CFC-11: LINEAR MODEL 2
EEC AEROSOL USE OF CFC-11: LINEAR MODEL 2 + CURRENT AEROSOLS RESTR.
OECD - US - EEC NON-AEROSOL USE OF CFC-11: LINEAR MODEL 2
OECD - US - EEC AEROSOL USE OF CFC-11: LINEAR MODEL 2
NON-OECD NON-AEROSOL USE OF CFC-11: LOGIT/POPULATION MODEL
NON-OECD AEROSOL USE OF CFC-11: LOGIT/POPULATION MODEL
EMISSION FROM WORLD BANK OF CFC-11: BEST ESTIMATE - NO RESTRICTIONS

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	USE	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	342.3	294.6	273.5	0.0	21.1	795.5	68.8	726.6
1990	3.3	406.8	351.7	322.0	8.5	21.1	1056.8	435.9	620.9
1995	3.0	474.6	412.9	373.3	18.8	20.8	1352.3	836.4	515.9
2000	2.8	546.1	479.1	427.7	30.6	20.8	1677.5	1265.3	412.1
2005	1.8	598.2	517.0	468.3	44.0	4.8	2039.2	1698.9	340.3
2010	1.8	655.1	572.3	513.0	54.5	4.8	2449.6	2133.1	316.5
2015	1.9	717.9	631.2	562.6	65.6	3.0	2873.3	2577.1	296.2
2020	1.9	787.5	696.9	618.0	75.9	3.0	3318.2	3037.0	281.2
2025	1.9	865.4	770.0	680.2	86.8	2.9	3785.2	3518.9	266.3
2030	1.9	948.0	848.0	746.7	98.5	2.9	4275.6	4023.8	251.7
2035	1.9	1040.8	935.2	821.7	110.9	2.5	4791.7	4553.8	237.9
2040	2.0	1145.3	1033.3	906.6	124.1	2.5	5338.5	5113.3	225.2
2045	2.0	1263.2	1143.5	1003.0	138.4	2.2	5920.9	5707.6	213.3
2050	2.0	1396.3	1267.9	1112.2	153.6	2.2	6544.9	6342.4	202.5
2055	1.5	1505.4	1375.0	1203.0	169.9	2.1	7192.3	7000.4	191.9
2060	1.6	1625.5	1492.2	1303.4	186.7	2.1	7852.8	7671.3	181.5
2065	1.6	1757.0	1620.1	1413.6	204.0	2.5	8530.3	8360.0	170.3
2070	1.6	1899.5	1756.7	1533.2	221.0	2.5	9232.2	9074.4	157.8
2075	1.5	2052.2	1902.6	1661.6	238.6	2.5	9966.5	9821.2	145.3

ANNUAL AVERAGE GROWTH RATES:

	2.011	2.010	2.094	2.025	0.0	-2.342	2.849	5.666	-1.773

WORLD TOTAL: CFC-12

COMPONENTS INCLUDED :
UNITED STATES NON-AEROSOL USE OF CFC-12: LINEAR MODEL 2
UNITED STATES AEROSOL USE OF CFC-12: LINEAR MODEL + AEROSL REST = 4.5
EEC NON-AEROSOL USE OF CFC-12: LINEAR MODEL 2
EEC AEROSOL USE OF CFC-12: LINEAR MODEL 2 + CURRENT AEROSOL RESTR.
OECD - US - EEC NON-AEROSOL USE OF CFC-12: LINEAR MODEL 2
OECD - US - EEC AEROSOL USE OF CFC-12: LINEAR MODEL 2
NON-OECD NON-AEROSOL USE OF CFC-12: LOGIT/POPULATION MODEL
NON-OECD AEROSOL USE OF CFC-12: LOGIT/POPULATION MODEL
EMISSIONS FROM WORLD BANK OF CFC-12: BEST ESTIMATE - NO RESTRICTIONS

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	U S E	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	460.2	409.9	335.1	0.0	74.9	856.1	125.2	731.0
1990	2.9	535.1	516.5	384.4	57.2	74.9	1016.6	659.9	356.7
1995	2.7	613.7	567.7	436.9	125.3	5.5	1126.6	1005.6	121.0
2000	2.5	696.5	650.2	492.7	151.9	5.5	1357.9	1264.7	93.3
2005	1.6	754.5	720.2	535.7	177.9	6.6	1552.4	1489.0	63.4
2010	1.6	817.2	790.0	582.5	200.9	6.6	1700.5	1670.1	30.4
2015	1.6	885.2	855.8	633.3	222.4	0.1	1836.7	1826.3	10.4
2020	1.6	959.0	929.0	688.6	240.3	0.1	1985.2	1975.2	10.0
2025	1.6	1039.1	1007.8	748.6	259.1	0.1	2138.7	2129.2	9.5
2030	1.5	1120.6	1087.9	809.2	278.6	0.1	2299.3	2290.2	9.1
2035	1.5	1208.6	1173.7	874.5	299.1	0.1	2469.5	2460.8	8.6
2040	1.5	1303.6	1266.2	945.1	321.0	0.1	2651.6	2643.4	8.2
2045	1.5	1406.1	1365.8	1021.1	344.7	0.1	2847.1	2839.4	7.7
2050	1.5	1516.4	1473.2	1102.9	370.2	0.1	3057.2	3049.9	7.3
2055	1.0	1597.2	1558.2	1161.9	396.2	0.1	3259.5	3252.7	6.9
2060	1.0	1681.5	1643.8	1223.4	420.3	0.1	3449.5	3443.1	6.4
2065	1.0	1769.3	1730.8	1287.4	443.3	0.1	3640.4	3634.4	6.0
2070	1.0	1860.4	1821.1	1353.7	467.3	0.1	3835.4	3829.9	5.5
2075	1.0	1954.5	1914.2	1422.2	491.9	0.1	4035.1	4030.0	5.1

ANNUAL AVERAGE GROWTH RATES:

	1.622	1.620	1.727	1.619	0.0	-7.221	1.737	3.933	-5.366

WORLD TOTAL: CFC-22

COMPONENTS INCLUDED :
UNITED STATES TOTAL USE OF CFC-22: LINEAR MODEL 2
NON-US OECD USE OF CFC-22: LINEAR MODEL 2 DERIVED FROM U.S. USE
NON-OECD NON-AEROSOL USE OF CFC-22: LOGIT/POPULATION MODEL

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	U S E	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	73.9	33.3	33.3	0.0	0.0	40.7	40.7	0.0
1990	4.5	93.9	52.1	42.3	9.8	0.0	248.5	248.5	0.0
1995	3.7	114.1	73.3	51.4	22.0	0.0	455.5	455.5	0.0
2000	3.2	134.6	97.2	60.6	36.6	0.0	650.3	650.3	0.0
2005	1.1	142.4	117.1	64.1	53.0	0.0	801.4	801.4	0.0
2010	1.2	150.8	131.5	67.9	63.6	0.0	909.5	909.5	0.0
2015	1.2	159.8	145.4	71.9	73.5	0.0	990.7	990.7	0.0
2020	1.2	169.4	156.2	76.2	79.9	0.0	1058.4	1058.4	0.0
2025	1.2	179.8	166.4	80.9	85.5	0.0	1124.9	1124.9	0.0
2030	1.3	191.3	177.0	86.1	91.0	0.0	1194.2	1194.2	0.0
2035	1.3	203.6	188.2	91.6	96.5	0.0	1269.0	1269.0	0.0
2040	1.3	216.7	200.1	97.5	102.6	0.0	1349.7	1349.7	0.0
2045	1.3	230.8	213.0	103.9	109.1	0.0	1436.5	1436.5	0.0
2050	1.3	245.9	226.8	110.7	116.1	0.0	1529.5	1529.5	0.0
2055	1.1	259.3	240.2	116.7	123.5	0.0	1625.1	1625.1	0.0
2060	1.0	273.1	254.0	122.9	131.1	0.0	1720.6	1720.6	0.0
2065	1.0	287.2	268.0	129.2	138.8	0.0	1816.2	1816.2	0.0
2070	1.0	301.6	282.2	135.7	146.5	0.0	1912.6	1912.6	0.0
2075	0.9	316.3	296.6	142.3	154.3	0.0	2010.3	2010.3	0.0
ANNUAL AVERAGE GROWTH RATES:									
	1.634	1.628	2.460	1.628	0.0	0.0	4.429	4.429	0.0

WORLD TOTAL: CFC-113

COMPONENTS INCLUDED :
UNITED STATES TOTAL USE OF CFC-113: LINEAR MODEL 2
NON-US OECD USE OF CFC-113: LINEAR MODEL 2 DERIVED FROM U.S. USE
NON-OECD NON-AEROSOL USE OF CFC-113: LOGIT/POPULATION MODEL

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	USE	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	72.2	72.2	72.2	0.0	0.0	0.0	0.0	0.0
1990	4.5	92.1	92.1	92.1	0.0	0.0	0.0	0.0	0.0
1995	3.7	112.1	112.1	112.1	0.0	0.0	0.0	0.0	0.0
2000	3.2	132.3	132.3	132.3	0.0	0.0	0.0	0.0	0.0
2005	1.1	139.3	139.3	139.3	0.0	0.0	0.0	0.0	0.0
2010	1.1	146.9	146.9	146.9	0.0	0.0	0.0	0.0	0.0
2015	1.1	154.8	154.8	154.8	0.0	0.0	0.0	0.0	0.0
2020	1.1	163.3	163.3	163.3	0.0	0.0	0.0	0.0	0.0
2025	1.1	172.3	172.3	172.3	0.0	0.0	0.0	0.0	0.0
2030	1.1	182.3	182.3	182.3	0.0	0.0	0.0	0.0	0.0
2035	1.1	193.0	193.0	193.0	0.0	0.0	0.0	0.0	0.0
2040	1.1	204.2	204.2	204.2	0.0	0.0	0.0	0.0	0.0
2045	1.1	216.2	216.2	216.2	0.0	0.0	0.0	0.0	0.0
2050	1.1	228.9	228.9	228.9	0.0	0.0	0.0	0.0	0.0
2055	1.0	240.3	240.3	240.3	0.0	0.0	0.0	0.0	0.0
2060	0.9	251.9	251.9	251.9	0.0	0.0	0.0	0.0	0.0
2065	0.9	263.6	263.6	263.6	0.0	0.0	0.0	0.0	0.0
2070	0.9	275.5	275.5	275.5	0.0	0.0	0.0	0.0	0.0
2075	0.8	287.5	287.5	287.5	0.0	0.0	0.0	0.0	0.0
ANNUAL AVERAGE GROWTH RATES:									
	1.554	1.547	1.547	1.547	0.0	0.0	0.0	0.0	0.0

RESULTS FOR LOW SCENARIO

WORLD TOTAL: CFC-11

COMPONENTS INCLUDED :
UNITED STATES NON-AEROSOL USE OF CFC-11: LINEAR MODEL 2
UNITED STATES AEROSOL USE OF CFC-11: LINEAR MODEL + AEROSOL REST = 4.5
EEC NON-AEROSOL USE OF CFC-11: LINEAR MODEL 2
EEC AEROSOL USE OF CFC-11: LINEAR MODEL 2 + CURRENT AEROSOLS RESTR.
OECD - US - EEC NON-AEROSOL USE OF CFC-11: LINEAR MODEL 2
OECD - US - EEC AEROSOL USE OF CFC-11: LINEAR MODEL 2
NON-OECD NON-AEROSOL USE OF CFC-11: LOGIT/POPULATION MODEL
NON-OECD AEROSOL USE OF CFC-11: LOGIT/POPULATION MODEL
EMISSION FROM WORLD BANK OF CFC-11: BEST ESTIMATE - NO RESTRICTIONS

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	U S E	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	400.7	336.5	315.3	0.0	21.1	812.0	85.4	726.6
1990	4.3	499.2	421.0	389.1	10.8	21.1	1175.5	554.6	620.9
1995	3.8	607.0	515.4	470.2	24.4	20.8	1606.8	1090.9	515.9
2000	3.5	725.5	621.2	559.9	40.6	20.8	2103.2	1691.1	412.1
2005	3.0	844.8	715.9	651.3	59.8	4.8	2682.9	2342.6	340.3
2010	2.9	976.3	834.5	752.7	77.1	4.8	3365.7	3049.2	316.5
2015	2.8	1122.5	965.6	866.2	96.3	3.0	4117.8	3821.6	296.2
2020	2.7	1286.3	1113.7	994.5	116.2	3.0	4949.0	4667.9	281.2
2025	2.7	1471.4	1281.4	1140.4	138.1	2.9	5863.7	5597.4	266.3
2030	2.2	1642.9	1442.0	1277.2	161.9	2.9	6846.2	6594.5	251.7
2035	2.2	1832.7	1619.5	1429.7	187.3	2.5	7886.7	7648.8	237.9
2040	2.2	2043.2	1816.7	1600.0	214.2	2.5	8992.2	8767.0	225.2
2045	2.2	2276.4	2034.7	1789.7	242.8	2.2	10169.7	9956.4	213.3
2050	2.1	2533.2	2275.0	1999.7	273.2	2.2	11427.5	11224.9	202.5
2055	2.4	2855.2	2568.4	2259.9	306.5	2.1	12804.1	12612.2	191.9
2060	2.3	3199.7	2884.9	2539.3	343.5	2.1	14322.3	14140.8	181.5
2065	2.1	3563.0	3221.7	2834.7	384.5	2.5	15976.7	15806.4	170.3
2070	2.0	3939.5	3571.9	3141.3	428.1	2.5	17762.7	17604.9	157.8
2075	1.8	4322.7	3931.0	3453.5	475.0	2.5	19673.9	19528.7	145.3

ANNUAL AVERAGE GROWTH RATES:

	2.680	2.678	2.769	2.695	0.0	-2.342	3.605	6.222	-1.773

WORLD TOTAL: CFC-12

COMPONENTS INCLUDED :
UNITED STATES NON-AEROSOL USE OF CFC-12: LINEAR MODEL 2
UNITED STATES AEROSOL USE OF CFC-12: LINEAR MODEL + AEROSL REST = 4.5
EEC NON-AEROSOL USE OF CFC-12: LINEAR MODEL 2
EEC AEROSOL USE OF CFC-12: LINEAR MODEL 2 + CURRENT AEROSOL RESTR.
OECD - US - EEC NON-AEROSOL USE OF CFC-12: LINEAR MODEL 2
OECD - US - EEC AEROSOL USE OF CFC-12: LINEAR MODEL 2
NON-OECD NON-AEROSOL USE OF CFC-12: LOGIT/POPULATION MODEL
NON-OECD AEROSOL USE OF CFC-12: LOGIT/POPULATION MODEL
EMISSIONS FROM WORLD BANK OF CFC-12: BEST ESTIMATE - NO RESTRICTIONS

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	U S E	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	545.3	457.2	382.4	0.0	74.9	893.9	162.9	731.0
1990	3.9	666.5	612.0	461.2	75.9	74.9	1239.5	882.8	356.7
1995	3.6	799.8	724.8	548.9	170.3	5.5	1510.5	1389.5	121.0
2000	3.3	946.5	866.9	646.7	214.6	5.5	1899.6	1806.3	93.3
2005	2.7	1083.3	1010.0	742.0	261.4	6.6	2278.3	2214.9	63.4
2010	2.6	1233.6	1163.5	847.8	309.1	6.6	2633.8	2603.4	30.4
2015	2.5	1399.0	1323.7	965.0	358.6	0.1	2993.6	2983.2	10.4
2020	2.5	1581.1	1500.9	1095.0	405.8	0.1	3384.3	3374.4	10.0
2025	2.4	1781.6	1695.5	1238.9	456.5	0.1	3802.6	3793.1	9.5
2030	1.8	1952.1	1871.0	1362.1	508.8	0.1	4216.6	4207.5	9.1
2035	1.8	2133.4	2052.6	1493.6	558.9	0.1	4619.4	4610.7	8.6
2040	1.7	2325.8	2242.2	1633.5	608.5	0.1	5031.6	5023.4	8.2
2045	1.7	2529.0	2442.3	1781.6	660.6	0.1	5458.9	5451.1	7.7
2050	1.6	2742.8	2652.7	1937.6	715.0	0.1	5902.7	5895.4	7.3
2055	1.9	3013.0	2900.7	2125.1	775.5	0.1	6423.4	6416.5	6.9
2060	1.7	3292.5	3167.0	2319.4	847.5	0.1	7028.5	7022.0	6.4
2065	1.6	3579.7	3447.3	2519.2	928.0	0.1	7677.4	7671.4	6.0
2070	1.5	3872.5	3734.6	2723.0	1011.5	0.1	8356.7	8351.2	5.5
2075	1.4	4168.5	4026.8	2929.1	1097.6	0.1	9058.5	9053.4	5.1
ANNUAL AVERAGE GROWTH RATES:									
	2.288	2.286	2.447	2.288	0.0	-7.221	2.607	4.565	-5.366

WORLD TOTAL: CFC-22

COMPONENTS INCLUDED :
UNITED STATES TOTAL USE OF CFC-22: LINEAR MODEL 2
NON-US OECD USE OF CFC-22: LINEAR MODEL 2 DERIVED FROM U.S. USE
NON-OECD NON-AEROSOL USE OF CFC-22: LOGIT/POPULATION MODEL

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	U S E	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	109.5	49.3	49.3	0.0	0.0	60.2	60.2	0.0
1990	5.1	143.7	79.4	64.7	14.7	0.0	374.9	374.9	0.0
1995	4.3	180.2	114.7	81.1	33.6	0.0	701.3	701.3	0.0
2000	3.8	218.9	155.5	98.5	57.0	0.0	1024.0	1024.0	0.0
2005	2.4	246.9	195.5	111.1	84.4	0.0	1305.8	1305.8	0.0
2010	2.3	276.7	229.6	124.5	105.1	0.0	1549.7	1549.7	0.0
2015	2.2	308.6	265.3	138.9	126.4	0.0	1773.7	1773.7	0.0
2020	2.1	342.8	298.5	154.3	144.2	0.0	1992.7	1992.7	0.0
2025	2.0	379.5	332.8	170.8	162.0	0.0	2221.5	2221.5	0.0
2030	1.5	409.1	364.2	184.1	180.1	0.0	2449.3	2449.3	0.0
2035	1.4	439.7	395.9	197.9	198.0	0.0	2670.2	2670.2	0.0
2040	1.4	471.5	428.0	212.2	215.9	0.0	2888.0	2888.0	0.0
2045	1.3	504.5	460.5	227.0	233.5	0.0	3106.4	3106.4	0.0
2050	1.3	538.6	493.5	242.4	251.2	0.0	3329.4	3329.4	0.0
2055	1.9	594.9	537.8	267.7	270.2	0.0	3591.5	3591.5	0.0
2060	1.8	652.3	585.7	293.5	292.1	0.0	3906.5	3906.5	0.0
2065	1.7	710.7	637.1	319.8	317.2	0.0	4261.9	4261.9	0.0
2070	1.6	769.8	691.9	346.4	345.4	0.0	4644.2	4644.2	0.0
2075	1.5	829.3	749.2	373.2	376.0	0.0	5040.9	5040.9	0.0
ANNUAL AVERAGE GROWTH RATES:									
	2.282	2.275	3.070	2.275	0.0	0.0	5.042	5.042	0.0

WORLD TOTAL: CFC-113

COMPONENTS INCLUDED :
UNITED STATES TOTAL USE OF CFC-113: LINEAR MODEL 2
NON-US OECD USE OF CFC-113: LINEAR MODEL 2 DERIVED FROM U.S. USE
NON-OECD NON-AEROSOL USE OF CFC-113: LOGIT/POPULATION MODEL

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	U S E	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	93.2	93.2	93.2	0.0	0.0	0.0	0.0	0.0
1990	5.5	125.1	125.1	125.1	0.0	0.0	0.0	0.0	0.0
1995	4.6	158.9	158.9	158.9	0.0	0.0	0.0	0.0	0.0
2000	3.9	194.7	194.7	194.7	0.0	0.0	0.0	0.0	0.0
2005	2.4	220.0	220.0	220.0	0.0	0.0	0.0	0.0	0.0
2010	2.3	246.8	246.8	246.8	0.0	0.0	0.0	0.0	0.0
2015	2.2	275.3	275.3	275.3	0.0	0.0	0.0	0.0	0.0
2020	2.1	305.6	305.6	305.6	0.0	0.0	0.0	0.0	0.0
2025	2.0	337.8	337.8	337.8	0.0	0.0	0.0	0.0	0.0
2030	1.5	363.6	363.6	363.6	0.0	0.0	0.0	0.0	0.0
2035	1.4	390.1	390.1	390.1	0.0	0.0	0.0	0.0	0.0
2040	1.3	417.3	417.3	417.3	0.0	0.0	0.0	0.0	0.0
2045	1.3	445.2	445.2	445.2	0.0	0.0	0.0	0.0	0.0
2050	1.2	473.9	473.9	473.9	0.0	0.0	0.0	0.0	0.0
2055	1.9	523.4	523.4	523.4	0.0	0.0	0.0	0.0	0.0
2060	1.8	573.9	573.9	573.9	0.0	0.0	0.0	0.0	0.0
2065	1.7	624.9	624.9	624.9	0.0	0.0	0.0	0.0	0.0
2070	1.6	676.5	676.5	676.5	0.0	0.0	0.0	0.0	0.0
2075	1.4	728.4	728.4	728.4	0.0	0.0	0.0	0.0	0.0
ANNUAL AVERAGE GROWTH RATES:									
	2.319	2.311	2.311	2.311	0.0	0.0	0.0	0.0	0.0

RESULTS FOR MEDIUM SCENARIO

WORLD TOTAL: CFC-11

COMPONENTS INCLUDED :
UNITED STATES NON-AEROSOL USE OF CFC-11: LINEAR MODEL 2
UNITED STATES AEROSOL USE OF CFC-11: LINEAR MODEL + AEROSOL REST = 4.5
EEC NON-AEROSOL USE OF CFC-11: LINEAR MODEL 2
EEC AEROSOL USE OF CFC-11: LINEAR MODEL 2 + CURRENT AEROSOLS RESTR.
OECD - US - EEC NON-AEROSOL USE OF CFC-11: LINEAR MODEL 2
OECD - US - EEC AEROSOL USE OF CFC-11: LINEAR MODEL 2
NON-OECD NON-AEROSOL USE OF CFC-11: LOGIT/POPULATION MODEL
NON-OECD AEROSOL USE OF CFC-11: LOGIT/POPULATION MODEL
EMISSION FROM WORLD BANK OF CFC-11: BEST ESTIMATE - NO RESTRICTIONS

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	U S E	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	408.4	342.5	321.3	0.0	21.1	813.7	87.1	726.6
1990	4.7	519.0	436.8	404.5	11.1	21.1	1192.8	571.9	620.9
1995	4.2	643.5	545.0	498.9	25.4	20.8	1652.5	1136.6	515.9
2000	4.0	785.4	670.9	607.5	42.6	20.8	2193.0	1780.8	412.1
2005	4.1	966.9	816.0	747.4	63.8	4.8	2859.0	2518.7	340.3
2010	3.9	1174.8	998.5	909.2	84.5	4.8	3689.5	3373.0	316.5
2015	3.8	1416.5	1211.0	1099.1	108.9	3.0	4656.1	4359.9	296.2
2020	3.7	1700.1	1463.1	1324.2	135.9	3.0	5776.9	5495.7	281.2
2025	3.6	2034.7	1762.2	1592.0	167.2	2.9	7066.9	6800.5	266.3
2030	3.7	2456.2	2134.9	1928.4	203.6	2.9	8575.3	8323.5	251.7
2035	3.5	2930.6	2558.4	2309.5	246.3	2.5	10333.8	10095.9	237.9
2040	3.2	3455.6	3031.4	2733.4	295.5	2.5	12350.7	12125.5	225.2
2045	3.0	4022.3	3546.4	3192.7	351.5	2.2	14627.2	14413.9	213.3
2050	2.7	4616.3	4091.0	3674.9	413.9	2.2	17156.4	16953.9	202.5
2055	2.6	5277.8	4687.9	4202.6	483.2	2.1	19980.7	19788.7	191.9
2060	2.2	5920.2	5275.9	4713.9	559.9	2.1	23097.6	22916.1	181.5
2065	1.9	6531.0	5843.7	5198.2	643.1	2.5	26452.8	26282.5	170.3
2070	1.6	7103.6	6382.1	5649.6	730.0	2.5	29995.8	29838.0	157.8
2075	1.4	7636.6	6889.9	6067.2	820.2	2.5	33681.7	33536.5	145.3
ANNUAL AVERAGE GROWTH RATES:									
	3.312	3.307	3.391	3.319	0.0	-2.342	4.224	6.838	-1.773

WORLD TOTAL: CFC-12

COMPONENTS INCLUDED :
UNITED STATES NON-AEROSOL USE OF CFC-12: LINEAR MODEL 2
UNITED STATES AEROSOL USE OF CFC-12: LINEAR MODEL + AEROSL REST = 4.5
EEC NON-AEROSOL USE OF CFC-12: LINEAR MODEL 2
EEC AEROSOL USE OF CFC-12: LINEAR MODEL 2 + CURRENT AEROSOL RESTR.
OECD - US - EEC NON-AEROSOL USE OF CFC-12: LINEAR MODEL 2
OECD - US - EEC AEROSOL USE OF CFC-12: LINEAR MODEL 2
NON-OECD NON-AEROSOL USE OF CFC-12: LOGIT/POPULATION MODEL
NON-OECD AEROSOL USE OF CFC-12: LOGIT/POPULATION MODEL
EMISSIONS FROM WORLD BANK OF CFC-12: BEST ESTIMATE - NO RESTRICTIONS

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	USE	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	558.7	467.9	393.1	0.0	74.9	896.7	165.7	731.0
1990	4.6	704.5	643.9	491.1	78.0	74.9	1266.2	909.5	356.7
1995	4.2	871.6	788.4	606.0	176.8	5.5	1574.4	1453.4	121.0
2000	4.0	1064.3	973.5	741.0	226.9	5.5	2013.4	1920.1	93.3
2005	3.8	1287.5	1189.7	899.8	283.2	6.6	2489.9	2426.5	63.4
2010	3.6	1541.9	1437.5	1083.0	347.9	6.6	2998.8	2968.4	30.4
2015	3.4	1831.2	1714.2	1293.2	420.9	0.1	3552.0	3541.6	10.4
2020	3.3	2158.6	2028.5	1532.6	495.8	0.1	4175.6	4165.7	10.0
2025	3.1	2525.8	2381.2	1802.0	579.1	0.1	4869.2	4859.7	9.5
2030	3.0	2944.8	2774.8	2100.9	673.8	0.1	5671.1	5662.0	9.1
2035	2.8	3390.8	3202.2	2419.3	782.8	0.1	6579.6	6570.9	8.6
2040	2.5	3858.4	3656.0	2752.6	903.4	0.1	7564.7	7556.5	8.2
2045	2.3	4340.1	4126.6	3095.1	1031.3	0.1	8611.3	8603.5	7.7
2050	2.1	4828.0	4606.5	3441.0	1165.4	0.1	9704.3	9697.0	7.3
2055	2.0	5372.6	5115.0	3804.7	1310.3	0.1	10928.8	10921.9	6.9
2060	1.8	5900.4	5628.1	4155.1	1473.0	0.1	12268.9	12262.5	6.4
2065	1.6	6407.6	6134.1	4489.5	1644.5	0.1	13635.6	13629.6	6.0
2070	1.4	6892.2	6620.7	4806.6	1814.0	0.1	14998.4	14992.9	5.5
2075	1.2	7354.2	7087.2	5106.5	1980.6	0.1	16343.4	16338.2	5.1

ANNUAL AVERAGE GROWTH RATES:

2.910	2.905	3.066	2.890	0.0	-7.221	3.278	5.234	-5.366

WORLD TOTAL: CFC-22

COMPONENTS INCLUDED :
UNITED STATES TOTAL USE OF CFC-22: LINEAR MODEL 2
NON-US OECD USE OF CFC-22: LINEAR MODEL 2 DERIVED FROM U.S. USE
NON-OECD NON-AEROSOL USE OF CFC-22: LOGIT/POPULATION MODEL

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	USE	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	110.9	49.9	49.9	0.0	0.0	61.0	61.0	0.0
1990	5.6	149.3	82.2	67.2	15.1	0.0	385.3	385.3	0.0
1995	4.7	190.6	120.6	85.8	34.8	0.0	730.6	730.6	0.0
2000	4.1	235.5	165.7	106.0	59.7	0.0	1081.3	1081.3	0.0
2005	3.4	280.3	216.1	126.1	90.0	0.0	1414.7	1414.7	0.0
2010	3.2	329.1	263.3	148.1	115.2	0.0	1740.4	1740.4	0.0
2015	3.0	382.5	315.4	172.1	143.3	0.0	2073.4	2073.4	0.0
2020	2.8	440.9	368.2	198.4	169.8	0.0	2425.4	2425.4	0.0
2025	2.7	504.6	425.4	227.1	198.4	0.0	2808.0	2808.0	0.0
2030	2.8	583.6	492.5	262.6	229.9	0.0	3240.2	3240.2	0.0
2035	2.6	666.5	565.1	299.9	265.2	0.0	3727.2	3727.2	0.0
2040	2.4	752.7	643.0	338.7	304.3	0.0	4259.8	4259.8	0.0
2045	2.2	841.4	725.6	378.6	347.0	0.0	4827.4	4827.4	0.0
2050	2.0	931.5	811.7	419.2	392.5	0.0	5419.2	5419.2	0.0
2055	2.5	1060.3	918.9	477.1	441.7	0.0	6086.1	6086.1	0.0
2060	2.2	1187.1	1030.9	534.2	496.7	0.0	6840.2	6840.2	0.0
2065	1.9	1311.5	1146.7	590.2	556.6	0.0	7649.4	7649.4	0.0
2070	1.7	1433.2	1265.6	644.9	620.6	0.0	8484.0	8484.0	0.0
2075	1.5	1552.1	1385.6	698.4	687.1	0.0	9319.5	9319.5	0.0
ANNUAL AVERAGE GROWTH RATES:									
	2.981	2.975	3.762	2.975	0.0	0.0	5.747	5.747	0.0

WORLD TOTAL: CFC-113

COMPONENTS INCLUDED :
UNITED STATES TOTAL USE OF CFC-113: LINEAR MODEL 2
NON-US OECD USE OF CFC-113: LINEAR MODEL 2 DERIVED FROM U.S. USE
NON-OECD NON-AEROSOL USE OF CFC-113: LOGIT/POPULATION MODEL

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	U S E	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	94.5	94.5	94.5	0.0	0.0	0.0	0.0	0.0
1990	5.9	130.0	130.0	130.0	0.0	0.0	0.0	0.0	0.0
1995	4.9	168.0	168.0	168.0	0.0	0.0	0.0	0.0	0.0
2000	4.2	208.9	208.9	208.9	0.0	0.0	0.0	0.0	0.0
2005	3.5	249.3	249.3	249.3	0.0	0.0	0.0	0.0	0.0
2010	3.2	292.9	292.9	292.9	0.0	0.0	0.0	0.0	0.0
2015	2.9	340.0	340.0	340.0	0.0	0.0	0.0	0.0	0.0
2020	2.8	390.9	390.9	390.9	0.0	0.0	0.0	0.0	0.0
2025	2.6	445.9	445.9	445.9	0.0	0.0	0.0	0.0	0.0
2030	2.8	515.2	515.2	515.2	0.0	0.0	0.0	0.0	0.0
2035	2.6	587.5	587.5	587.5	0.0	0.0	0.0	0.0	0.0
2040	2.3	662.2	662.2	662.2	0.0	0.0	0.0	0.0	0.0
2045	2.1	738.9	738.9	738.9	0.0	0.0	0.0	0.0	0.0
2050	2.0	816.9	816.9	816.9	0.0	0.0	0.0	0.0	0.0
2055	2.5	933.1	933.1	933.1	0.0	0.0	0.0	0.0	0.0
2060	2.2	1048.0	1048.0	1048.0	0.0	0.0	0.0	0.0	0.0
2065	2.0	1161.2	1161.2	1161.2	0.0	0.0	0.0	0.0	0.0
2070	1.8	1272.5	1272.5	1272.5	0.0	0.0	0.0	0.0	0.0
2075	1.6	1381.8	1381.8	1381.8	0.0	0.0	0.0	0.0	0.0
ANNUAL AVERAGE GROWTH RATES:									
	3.033	3.026	3.026	3.026	0.0	0.0	0.0	0.0	0.0

RESULTS FOR HIGH SCENARIO

*

WORLD TOTAL: CFC-11

COMPONENTS INCLUDED :
UNITED STATES NON-AEROSOL USE OF CFC-11: LINEAR MODEL 2
UNITED STATES AEROSOL USE OF CFC-11: LINEAR MODEL + AEROSOL REST = 4.5
EEC NON-AEROSOL USE OF CFC-11: LINEAR MODEL 2
EEC AEROSOL USE OF CFC-11: LINEAR MODEL 2 + CURRENT AEROSOLS RESTR.
OECD - US - EEC NON-AEROSOL USE OF CFC-11: LINEAR MODEL 2
OECD - US - EEC AEROSOL USE OF CFC-11: LINEAR MODEL
NON-OECD NON-AEROSOL USE OF CFC-11: LOGIT/POPULATION MODEL
NON-OECD AEROSOL USE OF CFC-11: LOGIT/POPULATION MODEL
EMISSION FROM WORLD BANK OF CFC-11: BEST ESTIMATE - NO RESTRICTIONS

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	U S E	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	430.2	359.7	338.5	0.0	21.1	818.3	91.6	726.6
1990	5.7	574.2	481.2	448.2	11.9	21.1	1237.8	616.9	620.9
1995	5.4	751.5	633.7	585.1	27.9	20.8	1775.7	1259.7	515.9
2000	5.4	977.5	831.3	762.3	48.2	20.8	2447.8	2035.7	412.1
2005	6.0	1315.2	1108.8	1029.2	74.8	4.8	3340.9	3000.6	340.3
2010	5.8	1751.8	1487.9	1378.9	104.1	4.8	4541.3	4224.8	316.5
2015	5.6	2314.3	1979.5	1834.6	141.9	3.0	6066.9	5770.7	296.2
2020	5.3	3017.7	2600.4	2409.1	188.3	3.0	7984.1	7702.9	281.2
2025	4.8	3849.6	3341.0	3092.1	245.9	2.9	10342.3	10076.0	266.3
2030	4.2	4802.6	4187.2	3868.2	316.1	2.9	13209.2	12957.5	251.7
2035	3.4	5757.3	5046.9	4644.8	399.5	2.5	16577.2	16339.3	237.9
2040	2.7	6661.5	5874.2	5377.7	493.9	2.5	20367.7	20142.5	225.2
2045	2.2	7489.7	6643.9	6044.7	597.0	2.2	24486.8	24273.5	213.3
2050	1.8	8241.2	7353.0	6645.2	705.6	2.2	28848.7	28646.2	202.5
2055	1.7	9004.1	8054.3	7233.4	818.9	2.1	33480.4	33288.5	191.9
2060	1.4	9713.1	8714.8	7775.0	937.7	2.1	38379.1	38197.5	181.5
2065	1.3	10386.7	9349.8	8285.8	1061.5	2.5	43490.2	43320.0	170.3
2070	1.2	11039.0	9968.6	8777.6	1188.5	2.5	48777.6	48619.9	157.8
2075	1.1	11679.3	10580.5	9258.6	1319.4	2.5	54216.2	54070.9	145.3

ANNUAL AVERAGE GROWTH RATES:

	3.753	3.736	3.829	3.745	0.0	-2.342	4.770	7.346	-1.773

WORLD TOTAL: CFC-12

COMPONENTS INCLUDED :
UNITED STATES NON-AEROSOL USE OF CFC-12: LINEAR MODEL 2
UNITED STATES AEROSOL USE OF CFC-12: LINEAR MODEL + AEROSL REST = 4.5
EEC NON-AEROSOL USE OF CFC-12: LINEAR MODEL 2
EEC AEROSOL USE OF CFC-12: LINEAR MODEL 2 + CURRENT AEROSOL RESTR.
OECD - US - EEC NON-AEROSOL USE OF CFC-12: LINEAR MODEL 2
OECD - US - EEC AEROSOL USE OF CFC-12: LINEAR MODEL 2
NON-OECD NON-AEROSOL USE OF CFC-12: LOGIT/POPULATION MODEL
NON-OECD AEROSOL USE OF CFC-12: LOGIT/POPULATION MODEL
EMISSIONS FROM WORLD BANK OF CFC-12: BEST ESTIMATE - NO RESTRICTIONS

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	U S E	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	IBANK	UBANK	OBANK
1985	0.0	608.1	509.0	434.1	0.0	74.9	904.9	174.0	731.0
1990	6.1	824.5	747.2	588.7	83.7	74.9	1341.5	984.8	356.7
1995	5.8	1100.1	992.1	791.3	195.3	5.5	1757.8	1636.8	121.0
2000	5.6	1451.3	1323.6	1055.0	263.1	5.5	2355.5	2262.3	93.3
2005	5.5	1915.4	1757.2	1404.0	346.6	6.6	3086.2	3022.8	63.4
2010	5.1	2476.2	2287.3	1827.5	453.2	6.6	3969.3	3939.0	30.4
2015	4.6	3128.9	2903.1	2318.9	584.1	0.1	5018.0	5007.6	10.4
2020	4.0	3853.5	3592.1	2860.4	731.7	0.1	6254.8	6244.8	10.0
2025	3.5	4618.2	4326.8	3426.4	900.4	0.1	7654.9	7645.4	9.5
2030	3.0	5403.4	5074.9	3985.2	1089.7	0.1	9232.3	9223.2	9.1
2035	2.4	6154.2	5811.0	4513.5	1297.4	0.1	10927.2	10918.6	8.6
2040	2.0	6858.7	6515.9	5003.8	1512.0	0.1	12645.3	12637.1	8.2
2045	1.7	7516.1	7180.0	5456.5	1723.4	0.1	14341.1	14333.3	7.7
2050	1.5	8132.9	7806.0	5876.7	1929.3	0.1	15994.4	15987.1	7.3
2055	1.5	8795.4	8427.5	6287.8	2139.6	0.1	17762.9	17756.0	6.9
2060	1.3	9429.2	9046.2	6676.3	2369.8	0.1	19657.7	19651.3	6.4
2065	1.2	10043.7	9659.7	7049.2	2610.4	0.1	21575.9	21570.0	6.0
2070	1.1	10646.1	10260.6	7411.9	2848.6	0.1	23500.5	23495.0	5.5
2075	1.1	11241.5	10854.7	7768.4	3086.2	0.1	25432.3	25427.2	5.1
ANNUAL AVERAGE GROWTH RATES:									
	3.311	3.294	3.458	3.257	0.0	-7.221	3.776	5.695	-5.366

WORLD TOTAL: CFC-22

COMPONENTS INCLUDED :
UNITED STATES TOTAL USE OF CFC-22: LINEAR MODEL 2
NON-US OECD USE OF CFC-22: LINEAR MODEL 2 DERIVED FROM U.S. USE
NON-OECD NON-AEROSOL USE OF CFC-22: LOGIT/POPULATION MODEL

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	U S E	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	115.2	51.8	51.8	0.0	0.0	63.3	63.3	0.0
1990	6.6	163.6	89.7	73.6	16.0	0.0	412.9	412.9	0.0
1995	5.7	219.1	136.7	98.6	38.1	0.0	808.8	808.8	0.0
2000	5.1	283.4	194.9	127.6	67.3	0.0	1240.1	1240.1	0.0
2005	4.8	360.4	266.9	162.2	104.7	0.0	1698.7	1698.7	0.0
2010	4.4	449.8	343.2	202.4	140.8	0.0	2205.2	2205.2	0.0
2015	4.1	552.4	432.4	248.6	183.8	0.0	2778.6	2778.6	0.0
2020	3.7	666.6	530.0	300.0	230.0	0.0	3428.8	3428.8	0.0
2025	3.3	789.3	637.8	355.2	282.7	0.0	4157.6	4157.6	0.0
2030	3.2	933.4	762.1	420.0	342.1	0.0	4977.4	4977.4	0.0
2035	2.7	1076.2	892.6	484.3	408.3	0.0	5873.8	5873.8	0.0
2040	2.3	1215.4	1026.5	547.0	479.5	0.0	6810.4	6810.4	0.0
2045	2.0	1350.9	1161.8	607.9	553.9	0.0	7757.4	7757.4	0.0
2050	1.8	1483.0	1296.8	667.4	629.5	0.0	8694.7	8694.7	0.0
2055	2.3	1674.9	1461.1	753.7	707.4	0.0	9711.8	9711.8	0.0
2060	2.1	1863.9	1630.3	838.8	791.6	0.0	10842.9	10842.9	0.0
2065	1.9	2051.4	1804.7	923.1	881.6	0.0	12052.6	12052.6	0.0
2070	1.7	2238.0	1984.8	1007.1	977.7	0.0	13308.3	13308.3	0.0
2075	1.6	2424.6	2169.1	1091.1	1078.0	0.0	14581.8	14581.8	0.0
ANNUAL AVERAGE GROWTH RATES:									
	3.456	3.444	4.236	3.444	0.0	0.0	6.230	6.230	0.0

WORLD TOTAL: CFC-113

COMPONENTS INCLUDED :
UNITED STATES TOTAL USE OF CFC-113: LINEAR MODEL 2
NON-US OECD USE OF CFC-113: LINEAR MODEL 2 DERIVED FROM U.S. USE
NON-OECD NON-AEROSOL USE OF CFC-113: LOGIT/POPULATION MODEL

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	U S E	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	98.0	98.0	98.0	0.0	0.0	0.0	0.0	0.0
1990	7.0	142.2	142.2	142.2	0.0	0.0	0.0	0.0	0.0
1995	5.8	192.0	192.0	192.0	0.0	0.0	0.0	0.0	0.0
2000	5.1	248.7	248.7	248.7	0.0	0.0	0.0	0.0	0.0
2005	4.7	315.5	315.5	315.5	0.0	0.0	0.0	0.0	0.0
2010	4.3	391.8	391.8	391.8	0.0	0.0	0.0	0.0	0.0
2015	3.9	477.9	477.9	477.9	0.0	0.0	0.0	0.0	0.0
2020	3.6	573.1	573.1	573.1	0.0	0.0	0.0	0.0	0.0
2025	3.2	674.9	674.9	674.9	0.0	0.0	0.0	0.0	0.0
2030	3.2	798.6	798.6	798.6	0.0	0.0	0.0	0.0	0.0
2035	2.7	921.9	921.9	921.9	0.0	0.0	0.0	0.0	0.0
2040	2.4	1043.6	1043.6	1043.6	0.0	0.0	0.0	0.0	0.0
2045	2.1	1163.2	1163.2	1163.2	0.0	0.0	0.0	0.0	0.0
2050	1.9	1281.2	1281.2	1281.2	0.0	0.0	0.0	0.0	0.0
2055	2.5	1460.5	1460.5	1460.5	0.0	0.0	0.0	0.0	0.0
2060	2.2	1638.2	1638.2	1638.2	0.0	0.0	0.0	0.0	0.0
2065	2.0	1815.0	1815.0	1815.0	0.0	0.0	0.0	0.0	0.0
2070	1.8	1991.6	1991.6	1991.6	0.0	0.0	0.0	0.0	0.0
2075	1.7	2168.4	2168.4	2168.4	0.0	0.0	0.0	0.0	0.0
ANNUAL AVERAGE GROWTH RATES:									
	3.513	3.501	3.501	3.501	0.0	0.0	0.0	0.0	0.0

RESULTS FOR NO LIMITS TO GROWTH SCENARIO

WORLD TOTAL: CFC-11

COMPONENTS INCLUDED :
UNITED STATES NON-AEROSOL USE OF CFC-11: LINEAR MODEL 2
UNITED STATES AEROSOL USE OF CFC-11: LINEAR MODEL + AEROSOL RESE - 4.5
EEC NON-AEROSOL USE OF CFC-11: LINEAR MODEL 2
EEC AEROSOL USE OF CFC-11: LINEAR MODEL 2 + CURRENT AEROSOLS RESTR.
OECD - US - EEC NON-AEROSOL USE OF CFC-11: LINEAR MODEL 2
OECD - US - EEC AEROSOL USE OF CFC-11: LINEAR MODEL 2
NON-OECD NON-AEROSOL USE OF CFC-11: LOGIT/POPULATION MODEL
NON-OECD AEROSOL USE OF CFC-11: LOGIT/POPULATION MODEL
EMISSION FROM WORLD BANK OF CFC-11: BEST ESTIMATE - NO RESTRICTIONS

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	U S E	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	IBANK	UBANK	OBANK
1985	0.0	518.7	426.3	405.1	0.0	21.1	840.1	113.5	726.6
1990	6.6	723.5	597.6	561.5	15.0	21.1	1401.2	780.3	620.9
1995	6.2	984.3	820.2	763.6	35.8	20.8	2142.6	1626.7	515.9
2000	6.1	1327.2	1117.6	1033.7	63.1	20.8	3096.1	2684.0	412.1
2005	7.3	1906.8	1596.6	1491.3	100.5	4.8	4424.2	4083.9	340.3
2010	6.9	2676.6	2257.6	2107.3	145.6	4.8	6292.7	5976.3	316.5
2015	6.5	3690.9	3137.5	2928.1	206.4	3.0	8779.0	8482.8	296.2
2020	6.0	4983.9	4270.8	3983.1	284.7	3.0	12015.7	11734.5	281.2
2025	5.3	6540.6	5647.9	5259.8	385.2	2.9	16113.9	15847.6	266.3
2030	4.9	8479.3	7346.6	6832.0	511.6	2.9	21300.3	21048.5	251.7
2035	4.0	10485.8	9128.5	8457.8	668.2	2.5	27646.6	27408.7	237.9
2040	3.2	12455.7	10902.2	10047.8	851.8	2.5	35034.5	34809.2	225.2
2045	2.6	14329.8	12612.7	11551.6	1059.0	2.2	43305.4	43092.1	213.3
2050	2.2	16096.5	14244.7	13958.8	1283.8	2.2	52304.6	52102.0	202.5
2055	2.2	18110.7	16036.7	14508.0	1526.7	2.1	62241.8	62049.9	191.9
2060	2.0	20065.0	17794.8	15999.9	1792.8	2.1	73209.2	73027.7	181.5
2065	1.8	21992.1	19546.2	17462.7	2081.0	2.5	85094.5	84924.2	170.3
2070	1.6	23917.3	21309.5	18917.9	2389.2	2.5	97815.4	97657.7	157.8
2075	1.5	25858.8	23100.4	20380.8	2717.1	2.5	111309.1	111163.9	145.3
ANNUAL AVERAGE GROWTH RATES:									
	4.460	4.439	4.536	4.450	0.0	-2.342	5.580	7.952	-1.773

WORLD TOTAL: CFC-12

COMPONENTS INCLUDED :
UNITED STATES NON-AEROSOL USE OF CFC-12: LINEAR MODEL 2
UNITED STATES AEROSOL USE OF CFC-12: LINEAR MODEL + AEROSL REST = 4.5
EEC NON-AEROSOL USE OF CFC-12: LINEAR MODEL 2
EEC AEROSOL USE OF CFC-12: LINEAR MODEL 2 + CURRENT AEROSOL RESTR.
OECD - US - EEC NON-AEROSOL USE OF CFC-12: LINEAR MODEL 2
OECD - US - EEC AEROSOL USE OF CFC-12: LINEAR MODEL 2
NON-OECD NON-AEROSOL USE OF CFC-12: LOGIT/POPULATION MODEL
NON-OECD AEROSOL USE OF CFC-12: LOGIT/POPULATION MODEL
EMISSIONS FROM WORLD BANK OF CFC-12: BEST ESTIMATE - NO RESTRICTIONS

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	U S E	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	798.2	648.2	573.3	0.0	74.9	955.9	224.9	731.0
1990	6.9	1128.3	996.8	812.0	109.9	74.9	1658.8	1302.1	356.7
1995	6.5	1559.2	1399.3	1132.1	261.6	5.5	2341.7	2220.7	121.0
2000	6.2	2119.2	1924.5	1555.9	363.0	5.5	3242.6	3149.4	93.3
2005	6.5	2943.3	2675.2	2173.6	495.0	6.6	4437.5	4374.1	63.4
2010	5.9	3962.6	3623.8	2940.7	676.5	6.6	5991.7	5961.4	30.4
2015	5.2	5173.3	4759.7	3849.4	910.2	0.1	7902.6	7892.2	10.4
2020	4.5	6543.7	6053.8	4870.6	1183.1	0.1	10201.0	10191.0	10.0
2025	3.9	8017.7	7460.3	5958.6	1501.7	0.1	12858.6	12849.1	9.5
2030	3.6	9695.0	9017.8	7144.4	1873.3	0.1	16026.0	16017.0	9.1
2035	3.0	11359.4	10616.4	8308.2	2308.0	0.1	19630.8	19622.2	8.6
2040	2.5	12980.8	12210.5	9429.6	2780.7	0.1	23434.6	23426.4	8.2
2045	2.2	14550.2	13766.4	10503.6	3262.7	0.1	27330.9	27323.1	7.7
2050	1.9	16073.9	15284.4	11535.6	3748.8	0.1	31269.2	31261.9	7.3
2055	2.1	17907.5	16945.3	12673.3	4272.0	0.1	35769.2	35762.3	6.9
2060	1.9	19726.8	18675.2	13790.9	4884.2	0.1	40880.6	40874.2	6.4
2065	1.7	21548.1	20456.3	14900.8	5555.4	0.1	46259.9	46254.0	6.0
2070	1.6	23384.5	22254.1	16012.7	6241.3	0.1	51835.8	51830.3	5.5
2075	1.5	25245.4	24079.5	17133.7	6945.6	0.1	57596.2	57591.1	5.1
ANNUAL AVERAGE GROWTH RATES:									
	3.931	3.912	4.098	3.847	0.0	-7.221	4.659	6.356	-5.366

WORLD TOTAL: CFC-22

COMPONENTS INCLUDED :
UNITED STATES TOTAL USE OF CFC-22: LINEAR MODEL 2
NON-US OECD USE OF CFC-22: LINEAR MODEL 2 DERIVED FROM U.S. USE
NON-OECD NON-AEROSOL USE OF CFC-22: LOGIT/POPULATION MODEL

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	U S E	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	159.0	71.6	71.6	0.0	0.0	87.5	87.5	0.0
1990	7.2	231.7	126.6	104.3	22.4	0.0	578.5	578.5	0.0
1995	6.1	317.1	196.7	142.7	54.0	0.0	1150.8	1150.8	0.0
2000	5.5	418.5	284.9	188.3	96.6	0.0	1793.3	1793.3	0.0
2005	5.8	561.6	405.9	252.7	153.2	0.0	2528.6	2528.6	0.0
2010	5.2	731.5	541.7	329.2	212.5	0.0	3408.8	3408.8	0.0
2015	4.7	929.9	705.5	418.4	287.0	0.0	4461.9	4461.9	0.0
2020	4.2	1154.8	891.8	519.7	372.2	0.0	5700.5	5700.5	0.0
2025	3.7	1400.7	1103.0	630.3	472.7	0.0	7121.4	7121.4	0.0
2030	4.0	1726.3	1367.1	776.8	590.3	0.0	8800.1	8800.1	0.0
2035	3.4	2060.5	1655.2	927.2	728.0	0.0	10740.4	10740.4	0.0
2040	2.9	2398.7	1962.2	1079.4	882.7	0.0	12866.4	12866.4	0.0
2045	2.6	2739.3	2284.7	1232.7	1052.0	0.0	15108.0	15108.0	0.0
2050	2.3	3082.7	2618.5	1387.2	1231.3	0.0	17411.1	17411.1	0.0
2055	3.1	3622.4	3055.2	1630.1	1425.1	0.0	20050.3	20050.3	0.0
2060	2.7	4170.7	3522.5	1876.8	1645.7	0.0	23137.3	23137.3	0.0
2065	2.4	4729.7	4020.5	2128.4	1892.1	0.0	26569.3	26569.3	0.0
2070	2.2	5300.9	4550.7	2385.4	2165.3	0.0	30246.5	30246.5	0.0
2075	2.0	5885.6	5108.4	2648.5	2459.9	0.0	34080.4	34080.4	0.0
ANNUAL AVERAGE GROWTH RATES:									
	4.106	4.094	4.856	4.094	0.0	0.0	6.852	6.852	0.0

WORLD TOTAL: CFC-113

COMPONENTS INCLUDED :
UNITED STATES TOTAL USE OF CFC-113: LINEAR MODEL 2
NON-US OECD USE OF CFC-113: LINEAR MODEL 2 DERIVED FROM U.S. USE
NON-OECD NON-AEROSOL USE OF CFC-113: LOGIT/POPULATION MODEL

(ALL ESTIMATES IN MILLIONS OF KILOGRAMS)

	% ANNUAL GROWTH	U S E	EMISSIONS TOTAL	EMISSIONS FROM USE	EMISSIONS FROM UBANK	EMISSIONS FROM OBANK	TBANK	UBANK	OBANK
1985	0.0	124.5	124.5	124.5	0.0	0.0	0.0	0.0	0.0
1990	7.6	187.1	187.1	187.1	0.0	0.0	0.0	0.0	0.0
1995	6.3	259.8	259.8	259.8	0.0	0.0	0.0	0.0	0.0
2000	5.5	344.8	344.8	344.8	0.0	0.0	0.0	0.0	0.0
2005	5.8	464.3	464.3	464.3	0.0	0.0	0.0	0.0	0.0
2010	5.2	604.5	604.5	604.5	0.0	0.0	0.0	0.0	0.0
2015	4.7	766.3	766.3	766.3	0.0	0.0	0.0	0.0	0.0
2020	4.2	948.5	948.5	948.5	0.0	0.0	0.0	0.0	0.0
2025	3.7	1147.2	1147.2	1147.2	0.0	0.0	0.0	0.0	0.0
2030	4.0	1418.7	1418.7	1418.7	0.0	0.0	0.0	0.0	0.0
2035	3.4	1699.0	1699.0	1699.0	0.0	0.0	0.0	0.0	0.0
2040	3.0	1984.8	1984.8	1984.8	0.0	0.0	0.0	0.0	0.0
2045	2.6	2275.0	2275.0	2275.0	0.0	0.0	0.0	0.0	0.0
2050	2.4	2569.8	2569.8	2569.8	0.0	0.0	0.0	0.0	0.0
2055	3.3	3049.5	3049.5	3049.5	0.0	0.0	0.0	0.0	0.0
2060	2.9	3538.6	3538.6	3538.6	0.0	0.0	0.0	0.0	0.0
2065	2.6	4038.5	4038.5	4038.5	0.0	0.0	0.0	0.0	0.0
2070	2.3	4550.4	4550.4	4550.4	0.0	0.0	0.0	0.0	0.0
2075	2.1	5074.9	5074.9	5074.9	0.0	0.0	0.0	0.0	0.0
ANNUAL AVERAGE GROWTH RATES:									
	4.219	4.206	4.206	4.206	0.0	0.0	0.0	0.0	0.0

ANNEX E

POPULATION AND GNP PER CAPITA PROJECTIONS

Projections of population and GNP per capita in the U.S., non-U.S. OECD, and the non-OECD countries were developed to provide a basis for projecting scenarios of potential future CFC use. Five projections were developed:

(1) "Limits to Growth," a likely lower bound on future GNP per capita and population growth;

(2) Low;

(3) Medium;

(4) High; and

(5) "No Limits to Growth," a likely upper bound on future GNP per capita and population growth.

Exhibit E-1 displays the population projections. First, global population projections were adopted from a review of published estimates; these are shown at the top of Exhibit E-1. Edmunds' (1984) low scenario was the lowest published projection, only 7.1 billion people in 2075.[1] For this population to be achieved, all portions of the world must achieve zero population growth by the middle of the next century.

The highest published estimate is from the United Nations (1981), over 13.6 billion people in 2075.[2] The middle three projections were developed from Lovins (1981),[3] the World Bank (1985),[4] and Edmunds' (1984)[5] middle scenario. To divide these global estimates into three regions, the expected share of world population in each region over time was estimated from Edmunds' three scenarios.[6] These shares (shown in Exhibit E-1) are

---

[1] J.A. Edmunds and J. Reilly, et al. An Analysis of Possible Future Atmospheric Retention of Fossil Fuel CO_2. Prepared for United States Department of Energy, Washington, D.C. September, 1984.

[2] Long-Range Global Population Projections 1984. World Bank, Washington, D.C., 1985.

[3] Amory Lovins et al. Least Cost Energy: Solving the CO_2 Problem, Brick House Publishing Company, Andover, MA. 1981.

[4] My T. Vu. World Population Projections 1984. World Bank, Washington, D.C., 1985.

[5] Edmunds, op. cit.

[6] Ibid.

EXHIBIT E-1

GLOBAL POPULATION PROJECTIONS
(MILLIONS)

YEAR	LIMITS TO GROWTH	LOW	MEDIUM	HIGH	NO LIMITS TO GROWTH
1985	4536	4745	4745	4835	5000
2000	5377	5901	5901	6147	6500
2025	6505	7384	7384	8160	9500
2050	7324	7664	8223	9496	12100
2075	7131	7944	8491	9960	13600

REGIONAL POPULATION SHARES

YEAR	US SHARE	OECD-US SHARE	NON-OECD SHARE
1985	0.048	0.120	0.832
2000	0.043	0.107	0.850
2025	0.038	0.094	0.868
2050	0.036	0.088	0.876
2075	0.035	0.087	0.879

REGIONAL POPULATION PROJECTIONS
(MILLIONS)

YEAR	REGION	LIMITS TO GROWTH	LOW	MEDIUM	HIGH	NO LIMITS TO GROWTH
1985	US POP	219	229	229	234	242
	OECD-US POP	545	570	570	581	601
	NON-OECD POP	3772	3946	3946	4020	4158
	TOTAL	4536	4745	4745	4835	5000
2000	US POP	232	255	255	266	281
	OECD-US POP	576	632	632	658	696
	NON-OECD POP	4569	5014	5014	5223	5523
	TOTAL	5377	5901	5901	6147	6500
2025	US POP	249	283	283	313	364
	OECD-US POP	612	695	695	768	894
	NON-OECD POP	5644	6407	6407	7080	8243
	TOTAL	6505	7384	7384	8160	9500
2050	US POP	262	274	294	339	432
	OECD-US POP	644	674	723	835	1064
	NON-OECD POP	6418	6716	7206	8322	10604
	TOTAL	7324	7664	8223	9496	12100
2075	US POP	247	275	294	345	471
	OECD-US POP	617	688	735	862	1177
	NON-OECD POP	6267	6981	7462	8753	11951
	TOTAL	7131	7944	8491	9960	13600

multiplied by the global values to produce population projections by region over time. As indicated by the increasing share of world population in non-OECD countries, this region's population is projected to grow faster than the other regions'.

To project GNP per capita we reviewed projections and historical data on the rates of growth of GNP and GNP per capita. Historically, the rates of growth of these quantities have varied significantly across regions and throughout time. The largest reported sustained growth of GNP per capita is for Japan, 1874 to 1967, 2.8 percent per year.[7] It is unlikely that global GNP per capita will grow this rapidly over the next 90 years. The lowest projected rates of growth are in Lovins (1981),[8] with growth declining from one percent per year through 2000, to under 0.3 percent per year by 2075. For purposes of developing projections, we assumed that all our scenarios would fall within these wide boundaries. To compute the five scenarios, we assumed the following growth rates in GNP per capita:

	1985-2000	2000-2025	2025-2050	2050-2075
Limits to Growth	1.0%	0.5%	0.5%	0.3%
Low	1.5%	1.2%	1.0%	1.0%
Medium	1.7%	1.7%	1.7%	1.7%
High	2.0%	2.0%	2.0%	2.0%
No Limits to Growth	2.5%	2.5%	2.5%	2.5%

These values reflect the full range of likely global GNP per capita over the next 90 years.

To develop estimates for each of the three regions of interest, we performed the following 5 steps:

(1) compute global GNP per capita through 2075 for each of the five projections (see top of Exhibit E-2);

(2) compute global GNP by multiplying the global GNP per capita by the number of people estimated in Exhibit E-1 (see middle of Exhibit E-2);

---

[7] Simon Kuznets. Economic Growth of Nations, The Beltnap Press of Harvard University Press, Cambridge, MA., 1972.

[8] Lovins, op. cit.

EXHIBIT E-2

PROJECTIONS OF GLOBAL GNP PER CAPITA (1975 US $)

YEAR	LIMITS TO GROWTH	LOW	MEDIUM	HIGH	NO LIMITS TO GROWTH
1985	1900	1900	1900	1900	1900
2000	2206	2375	2447	2557	2752
2025	2499	3201	3729	4195	5102
2050	2831	4105	5683	6863	9458
2075	3051	5264	8662	11292	17535

GLOBAL GNP COMPUTED USING GNP PER CAPITA AND POPULATION (BILLIONS OF 1975 US $)

YEAR	LIMITS TO GROWTH	LOW	MEDIUM	HIGH	NO LIMITS TO GROWTH
1985	8618	9016	9016	9187	9500
2000	11861	14017	14438	15719	17886
2025	16254	23635	27535	34233	48465
2050	20731	31459	46735	65359	114443
2075	21755	41818	73553	112468	238474

REGIONAL GNP SHARES

YEAR	US SHARE	OECD-US SHARE	NON-OECD SHARE
1985	0.227	0.391	0.381
2000	0.215	0.387	0.399
2025	0.179	0.374	0.447
2050	0.159	0.365	0.475
2075	0.162	0.369	0.469

EXHIBIT E-2 (continued)

REGIONAL GNP PROJECTIONS
(BILLIONS OF 1975 U.S. $)

YEAR	REGION	LIMITS TO GROWTH	LOW	MEDIUM	HIGH	NO LIMITS TO GROWTH
1985	US GNP	1959	2049	2049	2088	2159
	OECD-US GNP	3372	3528	3528	3595	3717
	NON-OECD GNP	3287	3439	3439	3504	3624
	TOTAL	8618	9016	9016	9187	9500
2000	US GNP	2547	3010	3100	3375	3841
	OECD-US GNP	4584	5418	5580	6075	6913
	NON-OECD GNP	4730	5590	5757	6268	7133
	TOTAL	11861	14017	14438	15719	17886
2025	US GNP	2909	4229	4927	6126	8673
	OECD-US GNP	6074	8832	10289	12792	18111
	NON-OECD GNP	7272	10573	12318	15315	21682
	TOTAL	16254	23635	27535	34233	48465
2050	US GNP	3303	5012	7446	10413	18234
	OECD-US GNP	7573	11492	17072	23875	41804
	NON-OECD GNP	9855	14955	22217	31071	54405
	TOTAL	20731	31459	46735	65359	114443
2075	US GNP	3520	6766	11901	18198	38587
	OECD-US GNP	8023	15423	27127	41479	87950
	NON-OECD GNP	10211	19629	34525	52791	111937
	TOTAL	21755	41818	73553	112468	238474

(3) estimate regional shares of global GNP from Edmunds' (1984) estimates[9] (see middle of Exhibit E-2);

(4) multiply the regional GNP shares by the global GNP estimates to compute regional GNP estimates (see end of Exhibit E-2); and

(5) divide the regional GNP projections by the regional population projections (Exhibit E-1) to compute regional GNP per capita projections (see Exhibit E-3).

The values shown in Exhibit E-3 show GNP per capita in the U.S. growing at an average rate between 0.5 percent and 2.5 percent per year. The rates in the non-OECD countries are larger: 0.7 percent to 2.7 percent per year.

---

[9] Edmunds, op. cit.

EXHIBIT E-3

REGIONAL GNP PER CAPITA PROJECTIONS
(1975 U.S. $)

YEAR	REGION	LIMITS TO GROWTH	LOW	MEDIUM	HIGH	NO LIMITS TO GROWTH
1985	US GNP	8932	8932	8932	8932	8932
	OECD-US GNP	6189	6189	6189	6189	6189
	NON-OECD GNP	872	872	872	872	872
	TOTAL	1900	1900	1900	1900	1900
2000	US GNP	10965	11808	12162	12711	13678
	OECD-US GNP	7964	8577	8834	9233	9935
	NON-OECD GNP	1035	1115	1148	1200	1291
	TOTAL	2206	2375	2447	2557	2752
2025	US GNP	11674	14953	17421	19599	23834
	OECD-US GNP	9927	12716	14814	16667	20268
	NON-OECD GNP	1288	1650	1923	2163	2630
	TOTAL	2499	3201	3729	4195	5102
2050	US GNP	12625	18308	25350	30699	42186
	OECD-US GNP	11758	17051	23609	28591	39289
	NON-OECD GNP	1536	2227	3083	3734	5131
	TOTAL	2831	4105	5683	6883	9458
2075	US GNP	14243	24576	40441	52718	81863
	OECD-US GNP	12998	22429	36908	48112	74711
	NON-OECD GNP	1629	2812	4627	6031	9366
	TOTAL	3051	5264	8662	11292	17535

R-3386-EPA

Product Uses and Market Trends for Potential Ozone-Depleting Substances, 1985–2000

James K. Hammitt, Kathleen A. Wolf,
Frank Camm, William E. Mooz,
Timothy H. Quinn, Anil Bamezai

May 1986

Prepared for the
U.S. Environmental Protection Agency

PREFACE

This report is one of a series of papers written at The Rand Corporation on policy issues associated with chemicals that could potentially deplete ozone in the stratosphere ("potential ozone depleters"). Stratospheric ozone is important because the ozone layer helps shield the earth from harmful ultraviolet radiation. Increases in ultraviolet radiation may threaten human health, speed deterioration of certain materials, reduce crop yields, and have a wide range of potentially important ecological effects. Atmospheric models developed and tested over the last decade suggest that global human emissions of potential ozone depleters may lead to chemical reactions that reduce stratospheric ozone, thereby increasing ultraviolet radiation with its concomitant effects. Substantial scientific uncertainty persists about whether human emissions of these chemicals actually threaten the stratospheric ozone layer and, if they do, whether lower ozone levels actually threaten human health and other activities at the earth's surface that concern policymakers. Policymakers must act in the face of this uncertainty, however, and Rand's work is designed to help them act with the best information available.

To that end, The Rand Corporation is developing a series of reports addressed to analysts and policymakers responsible for policy decisions on emissions of potential ozone depleters in the United States and elsewhere. These documents report the results of research that includes extensive literature reviews, interviews with knowledgeable officials associated with the production and use of potential ozone depleters, and formal chemical, cost, economic, and statistical analyses. The series should also interest the much broader audience of analysts and decisionmakers whose organizations would feel the effects of government policies with respect to emissions of such chemicals.

Published papers in the series include the following:

- A. R. Palmer, W. E. Mooz, T. H. Quinn, and K. A. Wolf, *Economic Implications of Regulating Chlorofluorocarbon Emissions from Nonaerosol Applications,* R-2524-EPA, June 1980.
- A. R. Palmer, W. E. Mooz, T. H. Quinn, and K. A. Wolf, *Economic Implications of Regulating Nonaerosol Chlorofluorocarbon Emissions: An Executive Briefing,* R-2575-EPA, July 1980.
- K. A. Wolf, *Regulating Chlorofluorocarbon Emissions: Effects on Chemical Production,* N-1483-EPA, August 1980.

- A. R. Palmer and T. H. Quinn, *Economic Impact Assessment of a Chlorofluorocarbon Production Cap,* N-1656-EPA, February 1981.
- A. R. Palmer and T. H. Quinn, *Allocating Chlorofluorocarbon Permits: Who Gains, Who Loses, and What Is the Cost?* R-2806-EPA, July 1981.
- W. E. Mooz, S. H. Dole, D. L. Jaquette, W. H. Krase, P. F. Morrison, S. L. Salem, R. G. Salter, and K. A. Wolf, *Technical Options for Reducing Chlorofluorocarbon Emissions,* R-2879-EPA, March 1982.
- E. M. Sloss and T. P. Rose, *Possible Health Effects of Increased Exposure to Ultraviolet Radiation,* N-2330-EPA, July 1985.
- T. H. Quinn, K. A. Wolf, W. E. Mooz, J. K. Hammitt, T. W. Chesnutt, and S. Sarma, *Projected Use, Emissions, and Banks of Potential Ozone-Depleting Substances,* N-2282-EPA, January 1986.
- F. Camm and J. K. Hammitt, *An Analytic Method for Constructing Scenarios from a Subjective Joint Probability Distribution,* N-2442-EPA, May 1986.
- F. Camm, T. H. Quinn, A. Bamezai, J. K. Hammitt, M. Meltzer, W. E. Mooz, and K. A. Wolf, *Social Cost of Technical Control Options to Reduce the Use of Potential Ozone Depleters in the United States: An Update,* N-2440-EPA, May 1986.
- W. E. Mooz, K. A. Wolf, and F. Camm, *Potential Constraints on Cumulative Global Production of Chlorofluorocarbons,* R-3400-EPA, May 1986.

This report was produced under Cooperative Agreement No. CR811991-02-0 with the U.S. Environmental Protection Agency.

SUMMARY

Global human emissions of chlorofluorocarbons (CFCs) and several related chemicals may reduce the concentration of stratospheric ozone and, in so doing, may induce significant negative effects on human health and a variety of economically important activities. Emissions of these "potential ozone depleters" depend fundamentally on their patterns of production over time. For the United States and the world as a whole, this report describes current patterns of use and projects future production levels for the seven most important potential ozone depleters—CFC-11, CFC-12, CFC-113, carbon tetrachloride, methyl chloroform, Halon 1211, and Halon 1301—over the period 1985 to 2000. The projections are based on detailed analysis of the major applications of these chemicals. The analysis is particularly detailed for CFC-11 and CFC-12, which are believed to be the most important potential ozone depleters.

Table S.1 summarizes the findings on estimated current and projected use for the world as a whole. Each projection includes a midrange estimate and a range of uncertainty around this estimate for 2000 that reflects three sources of uncertainty:

Table S.1

ESTIMATED CURRENT AND PROJECTED WORLD USE OF POTENTIAL OZONE-DEPLETING SUBSTANCES

	Use (thousands of metric tons)			Average Annual Growth Rate (%)	
		Projected in 2000			
Chemical	1985	Midrange	Uncertainty (%)	Lower	Upper
CFC-11	341.5	560	−25 to +32	1.4	5.2
CFC-12	443.7	620	−26 to +34	0.3	4.3
CFC-113	163.2	420	−31 to +44	3.9	9.2
Methyl chloroform	544.6	840	−26 to +34	0.9	5.0
Carbon tetrachloride	1029.0	1550	−25 to +33	0.8	4.8
Halon 1301	10.8	20	−38 to +59	1.1	7.6
Halon 1211	10.8	20	−39 to +60	0.9	7.6

- The rate of general economic growth,
- The rate of growth in demand for products using each chemical relative to the rate of general economic growth, and
- Economic, technical, and regulatory effects on demand for each chemical relative to the demand for the products in which it is used.

The projections assume no change in the regulations of these substances relating to potential ozone depletion, although they do consider other regulations such as the U.S. ban on land disposal of waste chlorinated solvents.

CFC-11 and CFC-12 are used in a variety of applications. Both are widely used as aerosol propellants. CFC-11 is used extensively as a blowing agent in manufacturing plastic foams and CFC-12 is widely used as a refrigerant. Carbon tetrachloride's principal use is as a chemical intermediate in the production of CFC-11 and CFC-12, although it is also used as a solvent and grain fumigant. CFC-113 and methyl chloroform are both solvents. CFC-113 is widely used in the electronic industry, whereas methyl chloroform is a general purpose solvent used in everything from electronics to shipbuilding. Halon 1301 and 1211 are newly marketed fire extinguishants used to protect valuable equipment.

In general, production of these chemicals will likely grow in step with the global economy, but average annual growth rates for individual chemicals could range from near 0 to 8 and 9 percent over the next 15 years. CFC-113 and the Halons are likely to grow the fastest.

Atmospheric modelers could use subjective probability distributions for chemical production, such as those reflected in the limits on the production ranges shown in Table S.1, to construct emission scenarios. In doing this, they should keep in mind that the joint probability of observing all low or all high growth rates is far smaller than the probability of observing a low or high growth rate for any chemical individually. Moreover, the growth rates for each chemical are probably correlated because of their relationship to general economic growth. To construct emission scenarios that account for the correlation among individual chemical growth rates, we propose a method and a resulting set of production scenarios in Camm and Hammitt (1986). By taking account of the time pattern of emissions from various applications these production scenarios can be translated to emission scenarios similar to those reported in Quinn et al. (1986).

In assessing the importance of each chemical to the possibility of significant depletion of stratospheric ozone (or other concerns, like climatic change), it is not appropriate to simply compare production

levels. Both the fraction of production that is ultimately emitted and the time pattern of emissions vary among chemicals. Moreover, the estimated effect of an equal quantity of each chemical on the ozone differs dramatically, perhaps by a factor of one hundred or more for the seven potential ozone depleters we consider. Thus, even though carbon tetrachloride and methyl chloroform are produced in the largest quantities, CFC-11 and CFC-12 are probably the most important of the chemicals considered here. Consequently, the report examines their use in the greatest detail.

The development of the projections reported here involves the development of a transparent set of accounts that can be used to calculate the joint implications of a large number of necessarily subjective judgments about the future. Wherever possible, we have sought the best expert judgment available as a basis for these projections. In the end, of course, the reader may disagree with judgments reported here. To the full extent possible, we have attempted to make it as simple as possible to trace the implications of changes in the assumptions that underlie the current results.

The accounts developed differ from one chemical to another to suit differences in the quality of data available. The production of CFC-11 and CFC-12 and U.S. chemical production generally receive the most attention because data on other chemicals and regions are in general less complete. Other world production outside the communist countries receives the next most detailed treatment, although gaps in the available data often require that we rely on U.S. data to infer production levels elsewhere. Production in the communist countries is the most difficult to analyze. To estimate global totals we estimate communist country use based on the best available data, but these estimates are the least certain of all.

In general, the accounts work from the bottom up, building from information about chemical use in particular products and regions to global production. But this method does not always yield global totals that are consistent with "top-down" information from other sources, like the Chemical Manufacturers Association. We review our differences with top-down sources and suggest a way to reflect them in the projections developed here.

Rand's work on current and likely future production of these chemicals is continuing, particularly with regard to U.S. production. Although the information presented here represents the best information we have today, we expect our understanding of current and future trends to improve as the work proceeds.

ACKNOWLEDGMENTS

We are indebted to many individuals and organizations for assistance in writing this report. Much of the information contained in the report was obtained through intensive interaction with industry representatives beginning in the 1970s. Over this period a large number of companies and trade organizations cooperated with Rand by providing basic data, current estimates, and projections. Many of these organizations are cited within the report: Others wish to remain anonymous. We thank them all.

Rand colleagues Arthur Alexander and Richard Salter painstakingly reviewed earlier drafts, David Rubenson and Toshiya Hayashi collected information on refrigeration applications, and Jan Acton helped to hasten review and production of the report under stringent deadlines. John Hoffman and Stephen Seidel of the U.S. Environmental Protection Agency helped to frame the analysis and contributed numerous specific suggestions. In addition, we received valuable comments from the Alliance for Responsible CFC Policy, John Wells, and other participants at the EPA-sponsored workshop "Protecting the Ozone Layer: Workshop on Demand and Control Technologies." Mary Vaiana assisted in preparing the presentation of the material to that workshop, Patricia Bedrosian ably edited the final draft, and Janet D'Amore, Chai Fosterling, Nancy Lees, and Alyce Shigg assisted in preparation of the manuscript.

Especially in a research area as contentious as this, none of the individuals and organizations that assisted us can be presumed to agree with all our conclusions. As always, the authors alone are responsible for any judgments or remaining errors of fact.

CONTENTS

PREFACE iii

SUMMARY v

ACKNOWLEDGMENTS ix

FIGURES xiii

TABLES xv

Section

I. INTRODUCTION 1
- Current Applications 4
- Summary of Projected Use 7
- Organization of the Report 11

II. METHODOLOGY 12
- Characterization of the Uncertainty About Projected Chemical Use 12
- Projected Growth in GNP 14

III. AEROSOL PROPELLANTS 17

IV. RIGID FOAM 22
- Rigid Urethane Foam 23
- Nonurethane Foam 26

V. FLEXIBLE FOAM 31
- Slabstock Foam 31
- Molded Foam 34

VI. REFRIGERATION AND AIR CONDITIONING SYSTEMS 39
- Mobile Air Conditioning 39
- Retail Store Refrigeration 42
- Home Refrigerators and Freezers 44
- Chillers 47

VII. MISCELLANEOUS USES OF CFC-11 AND CFC-12 54
- Sterilants 54
- Liquid Food Freezing 54
- Other Miscellaneous Applications 55

VIII. SOLVENTS 57
CFC-113 58
Methyl Chloroform 61
Carbon Tetrachloride 63

IX. FIRE EXTINGUISHANTS 68
Historical U.S. Use 69
Current and Future Reporting Country Use 70

X. USE OF POTENTIAL OZONE DEPLETERS IN THE COMMUNIST COUNTRIES 74
CFC-11 and CFC-12 Use 74
Solvent Use 76

XI. CONCLUSIONS 79
United States and Global Projections 79
Directions for Future Work 84

Appendix
A. ESTIMATES OF CURRENT CONSUMPTION OF CFC-11, CFC-12, METHYL CHLOROFORM, AND CARBON TETRACHLORIDE 87
B. COMPARISON OF ESTIMATED TOTAL CFC-11 AND CFC-12 USE WITH OTHER SOURCES 93
C. DERIVATION OF SUBJECTIVE CREDIBILITY INTERVALS 101

REFERENCES 105

FIGURES

1.1. Estimated CMA Reporting Country and U.S. Use of CFC-11, by Product 5
1.2. Estimated CMA Reporting Country and U.S. Use of CFC-12, by Product 6
3.1. Estimated Historical and Projected U.S. Use of CFC-11 and CFC-12 in Aerosols 19
4.1. Estimated Historical and Projected U.S. Use of CFC-11 and CFC-12 in Rigid Foam 29
4.2. Estimated Historical and Projected Reporting Country Use of CFC-11 and CFC-12 in Rigid Foam 30
5.1. Estimated Historical and Projected U.S. Use of CFC-11 in Flexible Foam 37
5.2. Estimated Historical and Projected Reporting Country Use of CFC-11 in Flexible Foam 38
6.1. Estimated Historical and Projected U.S. Use of CFC-11 and CFC-12 in Refrigeration and Air Conditioning 52
6.2. Estimated Current and Projected Reporting Country Use of CFC-11 and CFC-12 in Refrigeration and Air Conditioning 53
8.1. Estimated Historical and Projected U.S. Use of CFC-113, Methyl Chloroform, and Carbon Tetrachloride 66
8.2. Estimated Current and Projected Reporting Country Use of CFC-113, Methyl Chloroform, and Carbon Tetrachloride 67
9.1. Estimated Historical and Projected U.S. and Reporting Country Use of Halon 1301 and Halon 1211 73
10.1. Estimated Historical and Projected Use of CFC-11 and CFC-12 in the Communist Countries 77
11.1. Estimated Historical and Projected Use of CFC-11 and CFC-12 in the United States 81
11.2. Estimated Historical and Projected Use of CFC-11 and CFC-12 in the Reporting Countries 82

TABLES

S.1. Estimated Current and Projected World Use of Potential Ozone-Depleting Substances v
1.1. Estimated 1985 World Use of Potential Ozone-Depleting Substances 2
1.2. Estimated Current and Projected World Use of Potential Ozone Depleters 8
1.3. Estimated Current and Projected World Use of CFC-11 . . 9
1.4. Estimated Current and Projected World Use of CFC-12 . . 10
2.1. Projected Base GNP Growth Rates 15
3.1. Estimated Historical Use of CFC-11 and CFC-12 in Aerosols 18
3.2. Estimated Current and Projected Use of CFC-11 and CFC-12 in Aerosols 20
4.1. Estimated Historical U.S. Production of Rigid Urethane Foam 23
4.2. Estimated Historical U.S. Use of CFC-11 in Rigid Urethane Foam 24
4.3. Estimated Historical Reporting Country Use of CFC-11 in Rigid Urethane Foam 24
4.4. Estimated Current and Projected U.S. Use of CFC-11 in Rigid Urethane Foam 25
4.5. Estimated Current and Projected Reporting Country Use of CFC-11 in Rigid Urethane Foam 26
4.6. Estimated Historical U.S. Production of Nonurethane Foam and Use of CFC-12 27
4.7. Estimated Current and Projected U.S. Use of CFC-12 in Nonurethane Foam 28
4.8. Estimated Current and Projected Reporting Country Use of CFC-12 in Nonurethane Foam 28
5.1. Estimated Historical U.S. Production of Slabstock Foam and Use of CFC-12 32
5.2. Estimated Current and Projected U.S. Use of CFC-11 in Slabstock Foam 33
5.3. Estimated Historical Reporting Country Use of CFC-11 in Slabstock Foam 34
5.4. Estimated Current and Projected Reporting Country Use of CFC-11 in Slabstock Foam 34
5.5. Estimated Historical U.S. Production of Automotive Vehicles, Molded Foam and Use of CFC-11 35

5.6. Estimated Current and Projected Reporting Country Automotive Vehicle Production and Use of CFC-11 in Molded Foam 36
6.1. Estimated Historical and Projected U.S. Vehicle Sales and Use of CFC-12 in Mobile Air Conditioning 41
6.2. Estimated Current and Projected Reporting Country Use of CFC-12 in Mobile Air Conditioning 41
6.3. Estimated Historical and Projected U.S. Use of CFC-12 in Retail Food Refrigeration 43
6.4. Estimated Current and Projected Reporting Country Use of CFC-12 in Retail Food Refrigeration 44
6.5. Estimated Historical and Projected U.S. Home Refrigerator and Freezer Sales and Use of CFC-12 45
6.6. Estimated Historical World Production of Home Refrigerators 46
6.7. Estimated Current and Projected Reporting Country Use of CFC-12 in Home Refrigerators and Freezers 47
6.8. Estimated Historical and Projected U.S. Centrifugal Chiller Installations and Use of CFC-11 and CFC-12 48
6.9. Estimated Current and Projected Reporting Country Use of CFC-11 and CFC-12 in Centrifugal Chillers 49
6.10. Estimated Historical and Projected U.S. Reciprocating Chiller Installations and Use of CFC-12 . . . 50
6.11. Estimated Current and Projected World Use of CFC-12 in Reciprocating Chillers 51
7.1. Estimated Current and Projected Use of CFC-12 in Liquid Food Freezing 55
7.2. Estimated Current and Projected Use of CFC-11 and CFC-12 in Other Miscellaneous Applications 56
8.1. Estimated Historical and Projected U.S. Use of CFC-113 59
8.2. Estimated Current and Projected Reporting Country Use of CFC-113 60
8.3. Estimated Historical and Projected U.S. Use of Methyl Chloroform 62
8.4. Estimated Current and Projected Reporting Country Use of Methyl Chloroform 62
8.5. Estimated Historical U.S. Use of Carbon Tetrachloride 64
8.6. Estimated Current and Projected Reporting Country Use of Carbon Tetrachloride 64
9.1. Estimated Historical U.S. Use of Halon 1301 69

9.2. Estimated Current and Projected Reporting Country Use of Halon 1301 71
9.3. Estimated Current and Projected Reporting Country Use of Halon 1211 71
10.1. Estimated Historical Soviet Union and Projected Communist Country Use of CFC-11 and CFC-12 75
10.2. Estimated Current and Projected Communist Country Use of CFC-113, Methyl Chloroform, and Carbon Tetrachloride 78
11.1. Estimated Current and Projected U.S. Use of Potential Ozone-Depleting Substances 80
11.2. Estimated Current and Projected World Use of Potential Ozone-Depleting Substances 80
A.1. Regression Estimates of Reporting Country CFC-11 and CFC-12 Production 89
A.2. Reported and Predicted Reporting Country CFC-11 and CFC-12 Production 89
A.3. Regression Estimates of U.S. CFC-11 and CFC-12 Production 91
A.4. Reported and Predicted U.S. CFC-11 and CFC-12 Production 91
A.5. Regression Estimates of U.S. Methyl Chloroform and Carbon Tetrachloride Production 92
A.6. Reported and Predicted U.S. Methyl Chloroform and Carbon Tetrachloride Production 92
B.1. Comparison of Estimated 1985 CFC-11 Use 94
B.2. Comparison of Estimated 1985 CFC-12 Use 95
B.3. Comparison of Rand Estimates of 1976 and 1985 U.S. Nonaerosol CFC-11 and CFC-12 Use 96
B.4. Comparison of Rand and DuPont Estimates of 1976 U.S. Nonaerosol CFC-11 and CFC-12 Use 98
B.5. Estimated Shortfall in Rand 1976 Estimates of U.S. CFC-11 and CFC-12 Use Compared with DuPont Estimates 99

I. INTRODUCTION

Release of several chlorofluorocarbons (CFCs) and related chemicals to the atmosphere may reduce the concentration of ozone in the stratosphere. Almost all emissions of these chemicals result from human activities. Depletion of stratospheric ozone would increase the amount of ultraviolet radiation that penetrates to the earth's surface, potentially causing increases in human skin cancers and adverse effects on plants, animals, and marine life. In addition, when these substances are released to the atmosphere they may reduce the radiant cooling of the earth, thereby creating a "greenhouse effect," possibly warming the earth's surface and changing its climate.[1]

Potential ozone-depleting chemicals are used in a wide range of products. They are used to manufacture foam cushioning and insulation products, as the refrigerant in refrigeration and air conditioning systems, as solvents to clean electronic and other components in manufacturing processes, and as aerosol propellants and fire extinguishants. This report describes the major world uses of these chemicals, estimates the current quantities used in each product area, and projects future use to 2000.

Estimates of current use and projected future use are reported separately for the United States, the other non-communist countries, and the communist countries. This distinction is relevant because we have much better information on U.S. than on foreign use of most of these chemicals, and better information on non-communist than on communist use. Nearly all of the production of CFC-11 and CFC-12 outside the communist countries is by companies that report their production to the Chemical Manufacturers Association (CMA); production in the communist countries is not reported. Consequently, we divide the world into three regions for analysis: the United States, the "other reporting countries," and the "communist countries" (including the Soviet Union, Eastern Europe, China, and the other communist Asian nations). The non-communist countries are jointly called the "reporting countries."[2]

---

[1]For more information on the atmospheric processes and possible adverse consequences see Ramanthan et al. (1985) or National Academy of Sciences (1976, 1979, 1982, 1984).

[2]We treat annual production and use of the chemicals within regions as equivalent, since inventories and net regional imports and exports are generally small. As described in Appendix A, however, the difference between production and use in a single nation, the United States for example, may be significant. Systematic data on imports and

The chemicals discussed in this report are limited to those believed to pose the greatest threat to stratospheric ozone, if such a threat exists, as indicated by computer models that simulate atmospheric chemistry. They include CFC-11, CFC-12, CFC-113, methyl chloroform, Halon 1211, Halon 1301, and carbon tetrachloride. Current consumption estimates for the three world regions are summarized in Table 1.1.

Carbon tetrachloride and methyl chloroform are produced in the greatest quantities but are not considered the most important potential ozone depleters. Carbon tetrachloride is used primarily as a chemical intermediate in the production of CFC-11 and CFC-12, so the quantities that may be emitted are only a fraction of total production estimated here.[3] Although most methyl chloroform is used as a solvent and eventually released to the atmosphere, it is relatively unstable in the atmosphere and consequently more likely to decompose without reaching the stratosphere.

CFC-11 and CFC-12 are considered the most important potential ozone depleters because of their high production levels and relative depletion potency. CFC-113 use is significantly smaller, but CFC-113 is thought to be almost as effective a potential depleter as the two other CFCs.

Table 1.1

ESTIMATED 1985 WORLD USE OF POTENTIAL OZONE-DEPLETING SUBSTANCES

(In thousands of mt[a])

Chemical	World	United States	Other Reporting Countries	Communist Countries
CFC-11	341.5	75.0	225.0	41.5
CFC-12	443.7	135.0	230.0	78.7
CFC-113	163.2	73.2	85.0	5.0
Methyl chloroform	544.6	270.0	187.6	87.0
Carbon tetrachloride	1,029.0	280.0	590.0	159.0
Halon 1301	10.8	5.4	5.4	0.0
Halon 1211	10.8	2.7	8.1	0.0

[a]Metric tons.

exports of each chemical needed to estimate the size of the difference are apparently not publicly available, however.

[3]See Quinn et al. (1986) for a more explicit analysis of possible chemical emissions.

The Halons are produced in only small quantities, about 11,000 mt each worldwide. However, they contain bromine, which may be a much more effective ozone depleter per atom than the chlorine contained in the other substances. Although the Halons may not be important potential ozone depleters at present, their use is expected to grow rapidly and they may become more important in the future.

As shown by Table 1.1, the United States currently accounts for about one-quarter to one-half of world use of these potential ozone depleters. The U.S. share of specific applications of CFC-11 and CFC-12 is generally similar, except for use in aerosols where, because of a U.S. ban on CFCs in "nonessential" aerosol applications, the United States accounts for only about 5 percent of world use. Use in the communist countries is estimated to be less than 20 percent of the global totals. Because of the limited data available on communist use, the text focuses on use in the CMA reporting countries. Estimates of communist use are derived in Sec. X.

An important feature of these chemicals is their chemical stability: They do not readily react with others. This stability contributes to their safety and usefulness in a variety of applications but also to their potential threat to stratospheric ozone. Because of this stability most of these chemicals are believed to survive in the atmosphere 50 to 100 years or longer, so their concentrations in the lower atmosphere may remain high for many years after release. Only a small fraction of the molecules of these chemicals in the lower atmosphere is transported to the stratosphere; there it is decomposed by ultraviolet radiation and the freed halogen atoms may catalytically react with the ozone molecules. Consequently, if depletion occurs it may persist for decades, even if emissions are terminated. The radiative effect of these chemicals as greenhouse gases would also be persistent.

Differences in the time pattern of chemical emissions between products may be important. In some applications, such as aerosol propellants, the chemicals are released directly to the atmosphere as the aerosol product is used. In other uses, such as home refrigerators, the chemical is contained in a hermetically sealed system and not emitted, except for minor leakage, until the product is disposed of. If disposed of before the seals are broken it is theoretically possible to recover the chemical and so prevent emission, although it may not be practical. In cases like this the chemical constitutes a bank that may be released sometime in the future, or possibly never released.

Other chemicals may also affect the concentration of stratospheric ozone. Most of those that are suspected ozone depleters are simple organic molecules containing either chlorine or bromine. Other gases, including methane and oxides of nitrogen, may increase or decrease

stratospheric ozone concentrations, depending on the concentrations of other perturbants. Carbon dioxide emissions are believed to generally increase ozone concentrations. These gases are being examined in other research efforts funded by the Environmental Protection Agency (EPA) and other agencies. However, none of the other potential ozone depleters is thought to be as likely to pose a threat as the chemicals discussed here. The other chemicals may be less important either because they are produced in smaller quantities or because they are less likely to reach the stratosphere. Perhaps the most widely used of these less important chemicals is CFC-22, which is extensively used as the refrigerant in air conditioners and other refrigeration equipment.

CURRENT APPLICATIONS

The seven chemicals we discuss are used in the following applications: aerosol dispensers, rigid foam insulation and related products, flexible cushioning foams, refrigeration and air conditioning systems, solvents, fire extinguishants, and other products.

CFC-11 and CFC-12 are used in diverse applications. In the CMA reporting countries, CFC-11 is used almost entirely as an aerosol propellant and as a blowing agent in producing rigid and flexible foams. As shown by Fig. 1.1, these three uses account for an estimated 90 percent of reporting country use. Most of the remainder represents the difference between the sum of our estimates of CFC-11 use in each product area and total use, based on total production as reported by CMA (1985) for the last several years (see Appendix A for details).

In the United States, CFC use in "nonessential aerosols" was banned by the EPA effective in 1979 (the ban was announced in 1977). As a result, aerosols account for only about 5 percent of U.S. CFC-11 use, whereas rigid foams account for about half. The manufacture of flexible foam accounts for about one-fifth, similar to its share of world use. The unallocated uses, about 18 percent, represent the difference between the applications for which we estimate current use and 1985 domestic use estimated from U.S. International Trade Commission (ITC) production data (see Appendix A). We believe that part of the unallocated use of CFC-11 is in refrigeration and air conditioning (see Appendix B). In addition, it includes storage, packaging, and transport losses that may account for about 2 percent of use (see Wolf, 1980).

Reporting country and U.S. use of CFC-12 are shown in Fig. 1.2. An estimated 32 percent of CFC-12 use in the reporting countries is as an aerosol propellant, whereas 27 percent is used in the refrigeration applications we analyze, including mobile air conditioning, retail food

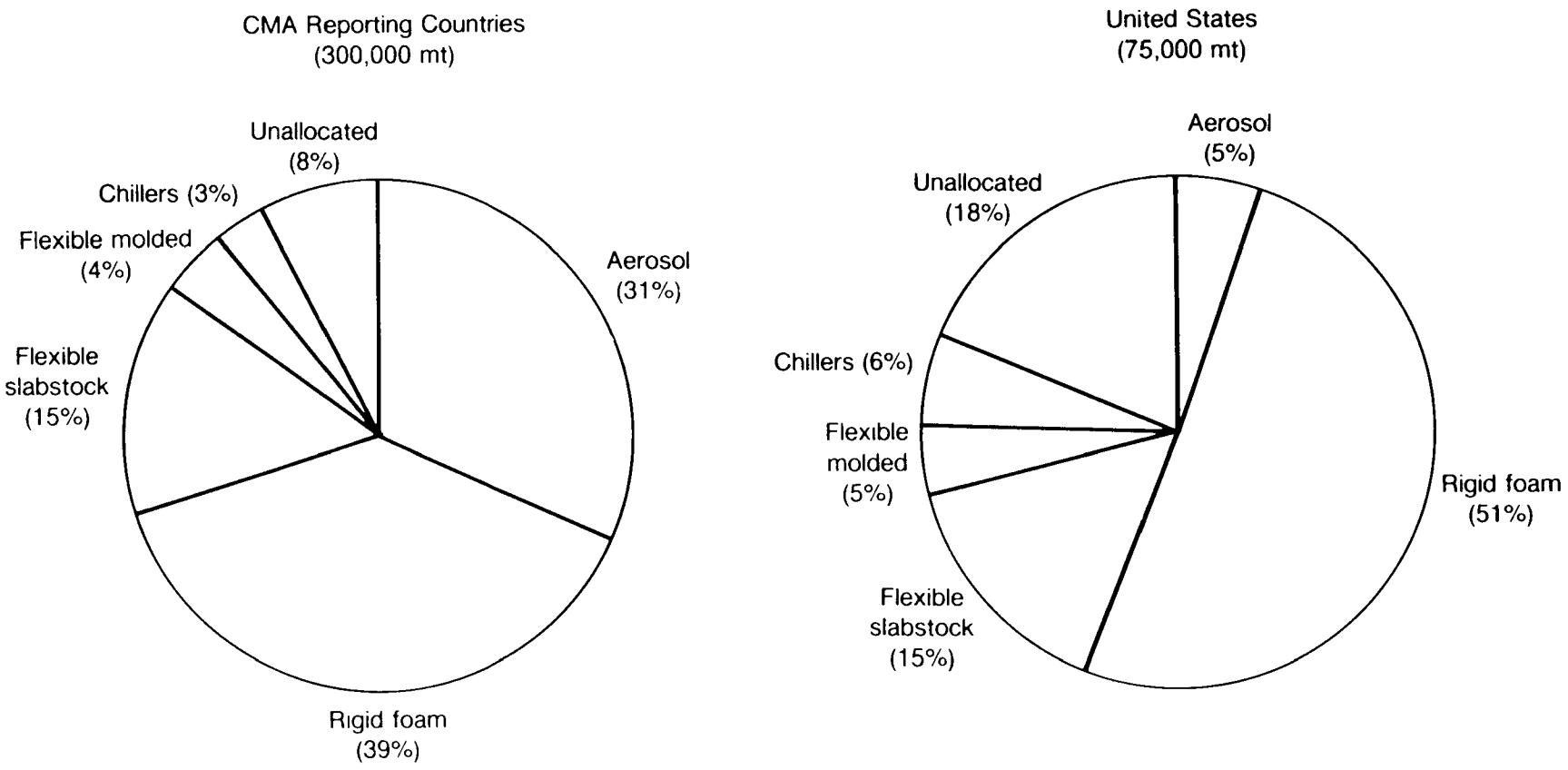


Fig. 1.1—Estimated CMA reporting country and U.S. use of CFC-11, by product

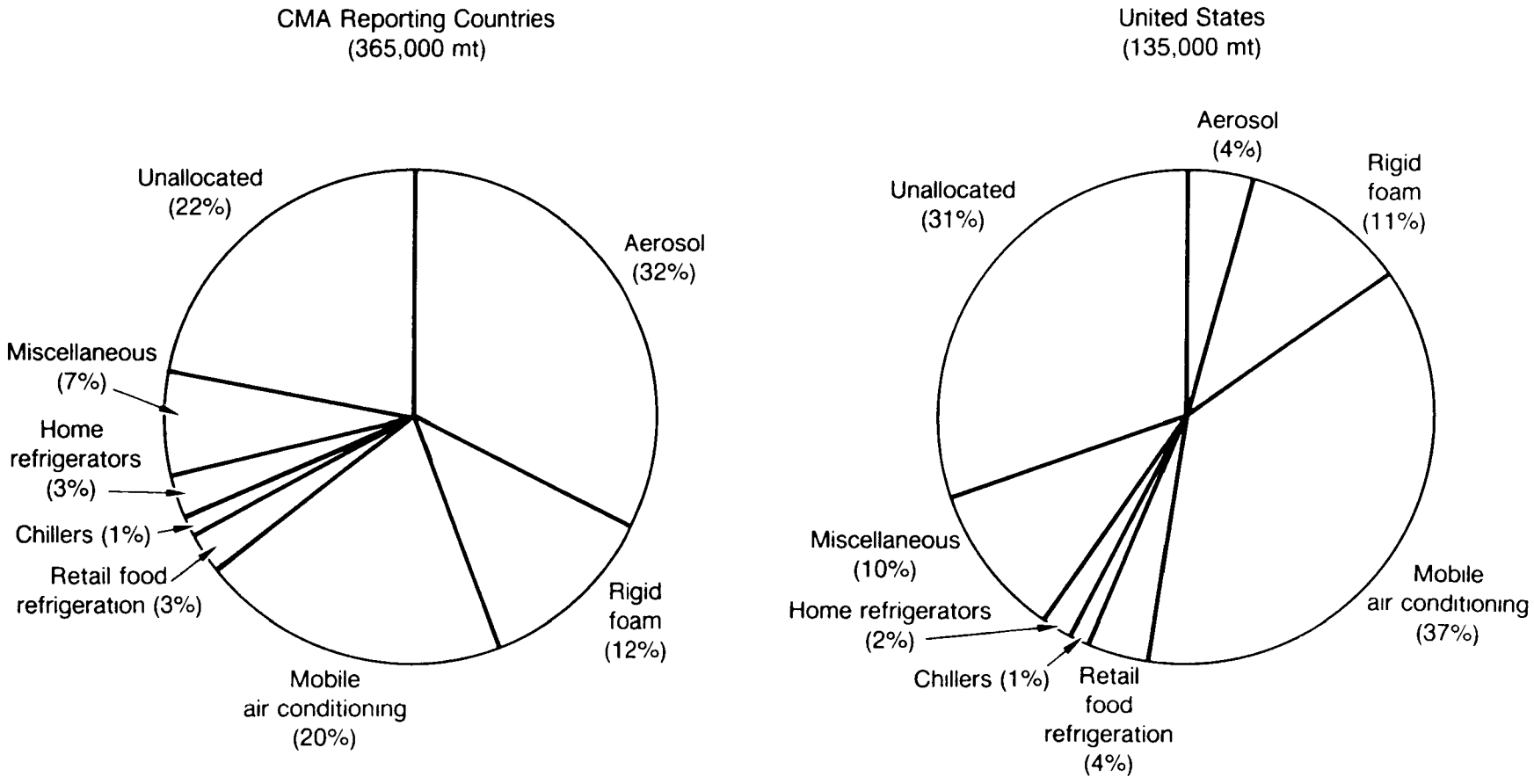


Fig. 1.2—Estimated CMA reporting country and U.S. use of CFC-12, by product

refrigeration, chillers (large commercial and industrial air conditioning systems), and home refrigerators and freezers. The unallocated uses total 22 percent.

In the United States, aerosols account for only about 4 percent of use, about the same share as of CFC-11. The refrigeration applications account for 44 percent, of which mobile air conditioning is by far the largest component. The unallocated uses are about 31 percent of estimated total domestic use. As discussed in Appendix B, we suspect that a large part of the unexplained use of CFC-12 is in food refrigeration applications, both in the United States and abroad. Again, storage, packaging, and transport losses may account for about 2 percent of total use.

The other chemicals are concentrated in fewer applications. Methyl chloroform and CFC-113 are used almost exclusively as solvents. CFC-113 is used largely in the electronics industry to "deflux" printed circuit boards and clean plastic parts including semiconductors; methyl chloroform is a general purpose solvent used in many types of metal and other cleaning applications. A small amount of CFC-113 is also used in specialty refrigeration applications.

Carbon tetrachloride is produced in larger quantities than any of the other chemicals but most is transformed into CFC-11 or CFC-12. Additional carbon tetrachloride is used as a solvent, as a grain fumigant, and in the pharmaceutical industry, but chemical producers in the United States have agreed to stop using it as an active ingredient in pesticides by 1986.

Halon 1211 and Halon 1301 are relatively new and are produced in small but growing quantities. They are used as fire extinguishants, Halon 1301 primarily in total flooding systems used to protect computer installations and other expensive equipment, Halon 1211 primarily in hand-held extinguishers.

SUMMARY OF PROJECTED USE

Table 1.2 summarizes current and projected annual global use of the seven potential ozone depleters we analyze. As described in Sec. II, our projections include a base production level assuming continuation of current and foreseeable trends and a range of uncertainty surrounding the base projection. They assume no change in the perceived likelihood of regulations on use or emissions of these chemicals because of the threat of potential ozone depletion. Thus, they are meant to characterize future use in the absence of additional regulations on potential ozone depleters as such. The projections do account for the

Table 1.2

ESTIMATED CURRENT AND PROJECTED WORLD USE OF POTENTIAL OZONE DEPLETERS

(In thousands of mt)

		2000 Use		
Chemical	1985 Use	Base Use	Annual Base Growth Rate (%)	Range of Uncertainty
CFC-11	341.5	560	3.3	−140 to +180
CFC-12	443.7	620	2.3	−160 to +210
CFC-113	163.2	420	6.5	−130 to +180
Methyl chloroform	544.6	840	3.0	−220 to +290
Carbon tetrachloride	1029.0	1550	2.8	−390 to +510
Halon 1301	10.8	20	4.4	−8 to +12
Halon 1211	10.8	20	4.2	−8 to +12

possibility of other regulations, such as the U.S. ban on land disposal of chlorinated solvents and regulations affecting substitute chemicals.

Table 1.2 characterizes the projections in terms of the projected base level of use, the average annual growth rate necessary to achieve that base level, and the range of uncertainty about the future level of use. Recall that the chemicals differ in the degree to which they may reduce the concentration of stratospheric ozone because of differences in emission patterns and chemical reactions in the atmosphere. Although carbon tetrachloride is produced in the largest quantities, because its dominant use is as a chemical intermediate only a small fraction of current production is released to the atmosphere (we estimate about 6 percent; see Quinn et al., 1986). Similarly, methyl chloroform, despite its large production volume, is not believed to be as important a potential ozone depleter as the three CFCs, because much of it decomposes in the lower atmosphere. In contrast, the Halons are thought to be very potent ozone depleters and thus merit attention despite their low production levels.

The seven chemicals may be divided into two groups on the basis of their expected future growth rates. As shown in Table 1.2, the baseline projections for CFC-11, CFC-12, methyl chloroform, and carbon tetrachloride involve growth at an average annual rate of about 3 percent. In contrast, CFC-113 and the two Halons are projected to grow much more rapidly: Their base projections entail about 4 to 6 percent

average growth until 2000. This contrast reflects a fundamental difference between the two groups of chemicals: The first, slowly growing group includes chemicals that have been produced for many years and have found applications in a variety of uses. In contrast, the second group is composed of "specialty" chemicals that are used in a narrower set of applications but are making rapid inroads in these markets.

Table 1.2 indicates that absolute uncertainty about future production is greatest for carbon tetrachloride and methyl chloroform, because of their high production levels. Future CFC-12 production is somewhat less certain than future CFC-11 production. The range for CFC-113 is almost as broad as for CFC-11, in part because the expected growth rate is higher. In contrast, the ranges for the Halons are significantly smaller because of their low production levels.

Tables 1.3 and 1.4 report the projected use of CFC-11 and CFC-12 in each application.[4] CFC-11 is used primarily as an aerosol propellant

Table 1.3

ESTIMATED CURRENT AND PROJECTED WORLD USE OF CFC-11

(In thousands of mt)

		2000 Use				
Applications in Reporting Countries	1985 Use	Base Use	Annual Base Growth Rate (%)	Range of Uncertainty		
Aerosol	93.7	95	0.1	−37	to	+59
Foam production						
Rigid	115.8	260	5.5	−67	to	+89
Slabstock	45.0	74	3.4	−26	to	+39
Molded	12.0	12	0.3	−4.2	to	+6.2
Refrigeration and air conditioning						
Centrifugal chillers	9.9	11	0.9	−3.2	to	+4.3
Miscellaneous and unallocated uses	23.6	39	3.4	−9.8	to	+13
Communist countries	41.5	100	6.0	−30	to	+42
Total world use	341.5	560	3.3	−140	to	+180

[4]The range of uncertainty for total use of the chemicals cannot be derived by adding the ranges for each application. As explained in Sec. II the ranges represent subjective 80 percent credibility regions. The region for total use derived by adding the regions for each application would correspond to a much higher credibility level. See Camm and

Table 1.4

ESTIMATED CURRENT AND PROJECTED WORLD USE OF CFC-12

(In thousands of mt)

Applications in Reporting Countries	1985 Use	2000 Use: Base Use	2000 Use: Annual Base Growth Rate (%)	2000 Use: Range of Uncertainty		
Aerosol	115.6	120	0.1	−46	to	+72
Foam production						
Rigid	42.8	76	3.9	−31	to	+51
Refrigeration and air conditioning						
Mobile air cond.	73.4	110	3.0	−34	to	+48
Retail food refrig.	9.7	6.4	-2.7	−3.5	to	+7.3
Home refrigeration	10.2	22	5.2	−7.6	to	+11
Centrifugal chillers	3.7	4.3	1.0	−1.2	to	+1.6
Reciprocating chill.	1.3	0.5	-5.7	−0.3	to	+0.5
Miscellaneous and unallocated uses	108.3	140	1.7	−38	to	+51
Communist countries	78.7	160	5.0	−53	to	+75
Total world use	443.7	620	2.3	−160	to	+210

and as a blowing agent in foam manufacturing. Growth trends in these applications are very dissimilar, however. Use in aerosols in the reporting countries is projected to remain approximately constant. In contrast, use in rigid foams is projected to grow rapidly, with a base projected growth rate above 5 percent. Largely because of this higher expected growth, the absolute uncertainty about CFC-11 use in rigid foam is substantially larger than the uncertainty about aerosol use.

Aerosol use of CFC-12 is also expected to remain about constant, as shown in Table 1.4. The next largest applications are mobile air conditioning and rigid foam production. Growth in these areas is expected to be strong, although the corresponding ranges of uncertainty include nearly constant use in each area.

Hammitt (1986) for more detail on our method for calculating the ranges. Because of approximations in that method the projected total base use does not equal the sum of the base uses in each application.

ORGANIZATION OF THE REPORT

Section II describes the methodology used to project future chemical use in each product area and to characterize the uncertainty associated with each projection. The following sections describe the diverse products in which the chemicals are used in more detail and report estimated current U.S. and other reporting country use and projected use to 2000.

The products are described in roughly decreasing order of their potential threat to stratospheric ozone, as measured by the quantities of potential ozone-depleting chemicals used, adjusted for their approximate estimated ozone-depletion potency. Within product areas, individual products are also discussed in decreasing order of importance. Sections III through VII describe reporting country use of CFC-11 and CFC-12 in aerosol products, in manufacturing rigid foams for insulation and other applications, flexible foams for cushioning, as a refrigerant in refrigeration and air conditioning systems, and in miscellaneous uses.

Section VIII describes solvent and other uses of CFC-113, methyl chloroform, and carbon tetrachloride (which is used primarily as a chemical intermediate in CFC-11 and CFC-12 production). Section IX describes fire extinguishant applications of Halon 1301 and Halon 1211. Section X estimates current and future use of all seven of the potential ozone-depleting substances we consider in the communist countries. Section XI summarizes the analyzed product applications and compares them with total use reported by the CMA and the U.S. ITC.

Supporting material is included in three appendices. Appendix A documents our method for estimating 1985 total use of the chemicals for which reported production data are available. Appendix B compares the sum of the estimates of current use in each major application of CFC-11 and CFC-12 to the total production reported by other sources. It then attempts to determine the source of the differences by comparing the estimates in this report with other sources. Appendix C elaborates on the method for characterizing the uncertainty about projected use described in Section II.

II. METHODOLOGY

The descriptions of product use and manufacturing processes are based on intensive interaction with industry that began in the 1970s. Over this period a large number of industrial companies and trade organizations cooperated with Rand by providing basic data, current estimates, and projections. More detailed descriptions of nonaerosol CFC use in the United States can be found in Palmer et al. (1980).

To date, most of our information has come from U.S. manufacturers and trade associations. Although we are actively pursuing information outside the United States, our current data are necessarily more limited.

Projections of future chemical use in each application are based on analysis of historical trends, industry projections, and comments. In many cases we project product use to remain a constant share of the U.S. or other national or regional economy—that is, to grow at a rate equal to the corresponding Gross National Product (GNP).

As we obtain additional information our estimates of current and likely future use will inevitably change. In a project of this nature there can never be a "final word," only a most recent estimate. This report summarizes our information as of early 1986.

CHARACTERIZATION OF THE UNCERTAINTY ABOUT PROJECTED CHEMICAL USE

Projecting the outcome of future events is always a hazardous undertaking. In this report we project a range of possible chemical uses in a number of applications. For expositional clarity we characterize each range by a base projection and a range of uncertainty for the year 2000. The base projection is intended to characterize the middle of the distribution of credible future outcomes. The range of uncertainty is described by two numbers that indicate the approximate upper and lower ends of what appears to us to be the range of reasonable outcomes, relative to the base projection. More precisely, we think that the probability that the future outcome will fall within the corresponding range is 0.8: Thus the ranges represent subjective 80 percent credibility intervals.

An alternative style for presenting our projections would be to report the limits of the range of uncertainty directly, without a central base projection. However, this style of exposition would assign too much

legitimacy to the bounds of the range, which are inherently fuzzy. It would also make the procedure for calculating the projections and the assumptions used less transparent.

Although we report a range of uncertainty for chemical use only for 2000, projected use in earlier years should also be characterized by a range. In most situations the range should be smaller for years closer to the present. If required, we suggest that the appropriate ranges for earlier years be calculated by assuming that the annual growth rates are normally distributed, calculating the corresponding means and standard deviations implied by the range for 2000, and from these calculating the desired credibility intervals.[1]

The base projections that characterize the center of the range of projected use are based on current and anticipated trends in chemical use in each application. They assume no unanticipated shocks, such as changes in the perceived likelihood that use will be regulated because of concern about possible ozone depletion, or unexpected changes in relative prices. Moreover, we do not attempt to project short-term oscillations in use associated with business cycles but instead try to characterize the basic trends.

The limits of the ranges of reasonable uncertainty are derived from explicit consideration of three levels of uncertainty:

- Uncertainty about the level of general economic activity, described by the GNP,
- Uncertainty about final product use conditional on GNP, and
- Uncertainty about the use of the chemical per unit of final product, conditional on final product use. Chemical use per unit of product may change because of changes in the relative costs of alternative manufacturing technologies resulting from technological innovation, regulation, or changes in real input prices.

We assess ranges of reasonable uncertainty for each of the three levels of uncertainty and combine them to produce an overall range using the procedure described in Appendix C.[2] The range of uncertainty about GNP growth is common to all of the product applications. It is described in the following subsection. The other ranges are based on

[1]See Camm and Hammitt (1986).

[2]We use log-normal distributions to approximate our subjective probability distributions corresponding to each level of uncertainty. Although the use of log-normal distributions imposes some restrictions on the character of the uncertainty that can be represented, they provide close approximations to our subjective distributions in most cases. The assumption that chemical use is distributed log-normally is equivalent to the assumption of normally distributed growth rates.

our knowledge of specific product areas and our beliefs about what changes might reasonably occur within the next 15 years.

Because part of the uncertainty about use in each application—that due to uncertainty about general economic growth—is common to all applications of a given chemical, derivation of the range of uncertainty for total use of a chemical requires accounting for this correlation among uses. The reported ranges of total CFC-11 and CFC-12 use account for this correlation using the procedure described in Camm and Hammitt (1986).

The chemical use projections do not explicitly account for uncertainty about current use. As noted in Sec. I, our "bottom up" estimates of use in each major application do not account for all of the CFC-11 and CFC-12 currently used. There may be other significant uses we have not analyzed, or our estimates for current use in some of the applications may be too low. It would be possible to develop a subjective range of uncertainty for current use, both in applications and in total, and to incorporate this uncertainty with the uncertainty about future growth. However, we have not yet taken this step. If future information reveals our estimates of current use in a specific application to be too low we would recommend revising the corresponding range of projected use upward.

Our ranges of uncertainty are reported in the discussion of each product area. Readers who find our intervals inappropriate are invited to supply their own and see how it affects the final range for total chemical use.

PROJECTED GROWTH IN GNP

In many of the baseline projections final products are assumed to remain a constant share of a nation's economy, that is, to grow at the same rate as the GNP. The base GNP growth rates we assume are reported in Table 2.1. With one exception, the rates are based on those prepared by Edmonds et al. (1984) for the U.S. Department of Energy. These projections are a revision of the rates used in our earlier work projecting long-term growth (reported in Quinn et al., 1986). They are based on analysis of likely population and labor productivity trends and, compared with other published projections, are low to moderate.[3]

The one difference between our rates and the Edmonds et al. (1984) projections is for the United States. Edmonds et al. (1984) project a

[3]See Quinn et al. (1986), Appendix B.

Table 2.1

PROJECTED BASE GNP GROWTH RATES

(In percent per year)

Region	1985-2000
United States	3.0
Western Europe and Canada	2.8
Japan, Australia, and New Zealand	4.0
USSR and Eastern Europe	2.4
Centrally Planned Asia	4.5
Mideast	6.6
Africa	3.7
Latin America	5.3
South and East Asia	5.1
Other reporting countries	3.5
Communist countries	3.0
World	3.3

base growth rate of 2.7 percent per year. For the period 1985 to 1990 we have increased the base rate to 3.5 percent, consistent with Congressional Budget Office (1985) projections. This estimate is slightly lower than the prominent alternative of 4.0 percent suggested by the Council of Economic Advisors (1985). After 1990 we adopt the Edmonds et al. (1984) projection of 2.7 percent per year. The resulting average rate over the 15 year period is 3.0 percent.

For most product areas we do not disaggregate use in the CMA reporting countries outside the United States. Rather we use an aggregate growth rate of 3.5 percent for other reporting country GNP growth, which is the appropriate aggregate of the regional rates in Table 2.1.

As described above, we assessed ranges of uncertainty around the base GNP growth rates. For the United States our intervals include growth rates 1.5 percent higher or lower than the base projections. Thus, our intervals extend from 1.5 to 4.5 percent per year over the period. These intervals are based on the observation that, since World War II, U.S. growth has averaged between about 1.5 and 4.5 percent per year over periods of about a decade. For the other CMA reporting countries we use the same range of uncertainty as for the United States, plus or minus 1.5 percent from the base, or 2.0 to 5.0 percent per year. Although uncertainty about growth in some parts of the world is greater than for the United States, variations in different

regions will tend to partially offset one another so the range of uncertainty about the growth of the total is less than the range for an individual country. For the communist countries we use a wider range, plus or minus 2.0 percent (a range of 1.0 to 5.0 percent averaged over the period). We feel that a wider range is appropriate for these countries because we have less information about their likely growth and because the communist countries constitute a smaller region than the other reporting countries, and hence variations within the region are less likely to offset each other. The ranges of uncertainty implied by these ranges of possible growth rates are between 0.80 and 1.25 times the base projected GNP level in 2000 for both the United States and the other reporting countries, and between 0.74 and 1.35 times the base projected level in the communist countries.

III. AEROSOL PROPELLANTS

CFC-11 and CFC-12 are used extensively as propellants in a wide variety of aerosol products. Many of these are personal care products, such as deodorant, perfume, and hairspray; others include household products such as insecticides and drain cleaners, and household and industrial products, such as spray paints and lubricants. Substitute propellants include hydrocarbons and carbon dioxide, and in some applications aerosol cans can be replaced by pump dispensers or other nonpressurized applicators. CFCs are more expensive than the alternative aerosol propellants but they are not flammable like hydrocarbon propellants, and some of their attributes make them technically more attractive in limited applications.

Because the propellant is emitted as the aerosol is discharged emissions are typically prompt. Before 1975 aerosol use was the largest single source of worldwide CFC emissions.

Historical CFC use in aerosols is reported in Table 3.1 and Fig. 3.1. In 1978 the EPA banned use of CFC propellants in all aerosols except a limited list of "essential uses" (including military applications). Under the ban United States use fell about 95 percent from its peak (1973) level.[1] Subsequently the European Economic Community negotiated a 30 percent reduction in use. Current EEC use is about 45 percent below use in the late 1970s, well below the target reduction, as the voluntary reductions have apparently stimulated increased substitution of less expensive hydrocarbon and carbon dioxide propellants.

United States use has remained constant at about 9500 mt since the ban and no significant change is expected. We project constant use with an uncertainty range of 78 to 128 percent of the projected value in 2000. This range is composed of uncertainty in the level of aerosol use, conditional on the GNP, of 90 to 111 percent of the projected base level, combined with the uncertainty range for the U.S. GNP.

Use in the European Economic Community has declined steadily since the mid 1970s as manufacturers have substituted other propellants. The substitution of pump dispensers for aerosol cans is apparently not occurring to the extent it did in the United States.

[1]United States CFC use in aerosols fell substantially between 1973 and the announcement of the ban in 1977. This decline is probably related to several factors including the Arab oil embargo, anticipation of the regulation, and the discovery that additional aerosol products could be successfully marketed with non-CFC propellants. (Some aerosols were traditionally propelled without CFCs; for example, spray paint has usually employed hydrocarbons.)

Fundamental uncertainty exists as to how much further CFC use will decline there. It is possible that all of the decline that will occur in the absence of regulation has all ready occurred. Alternatively, reductions in use could parallel those in the United States. However, the level of peak use is uncertain. By analogy to the United States, we assume that the peak occurred in 1973 and was 50 percent higher than the 1976 level, that is, about 265,000 mt. If this estimate is correct, 1983 use is about 37 percent of estimated peak (1973) use.

We project EEC use to fall to about 50,000 mt or almost 20 percent of the assumed peak by 2000. As an upper bound on the range of uncertainty we use the current level of about 100,000 mt, since we do not expect CFC use in aerosols to grow in the EEC. The lower bound is 25,000 mt or almost 10 percent of the assumed peak. This amount is about twice the level of U.S. use (5 percent of peak use), which seems reasonable assuming no further regulation in the EEC.

Table 3.1

ESTIMATED HISTORICAL USE OF CFC-11 AND CFC-12 IN AEROSOLS

(In mt)

Year	United States[a]	EEC[b]	Japan[c]	Other Reporting Countries[d]	Total Reporting Countries[e]
1970	156,400	na	na	na	na
1971	161,400	na	na	na	na
1972	185,000	na	na	na	na
1973	212,700	na	na	na	na
1974	198,600	na	14,400	na	na
1975	162,700	na	14,000	na	na
1976	138,600	176,900	15,500	101,200	432,300
1977	79,500	162,600	14,000	94,700	350,800
1978	40,000	150,400	13,300	103,500	307,200
1979	9,500	136,600	12,900	95,600	254,600
1980	9,500	126,400	13,000	94,200	243,300
1981	9,500	116,100	12,500	83,500	221,600
1982	9,500	111,700	12,000	75,300	208,500
1983	9,500	98,800	11,800	91,900	212,000
1984	9,500	na	11,800	na	218,800

NOTE: na = not available.

[a]Wolf (1980).

[b]European Fluorocarbon Technical Committee data as supplied by EEC.

[c]Ministry of International Trade and Industry data as supplied by Japan Flon Gas Association (private communication, 1985).

[d]Total reporting countries less United States, EEC, Japan.

[e]CMA (1985).

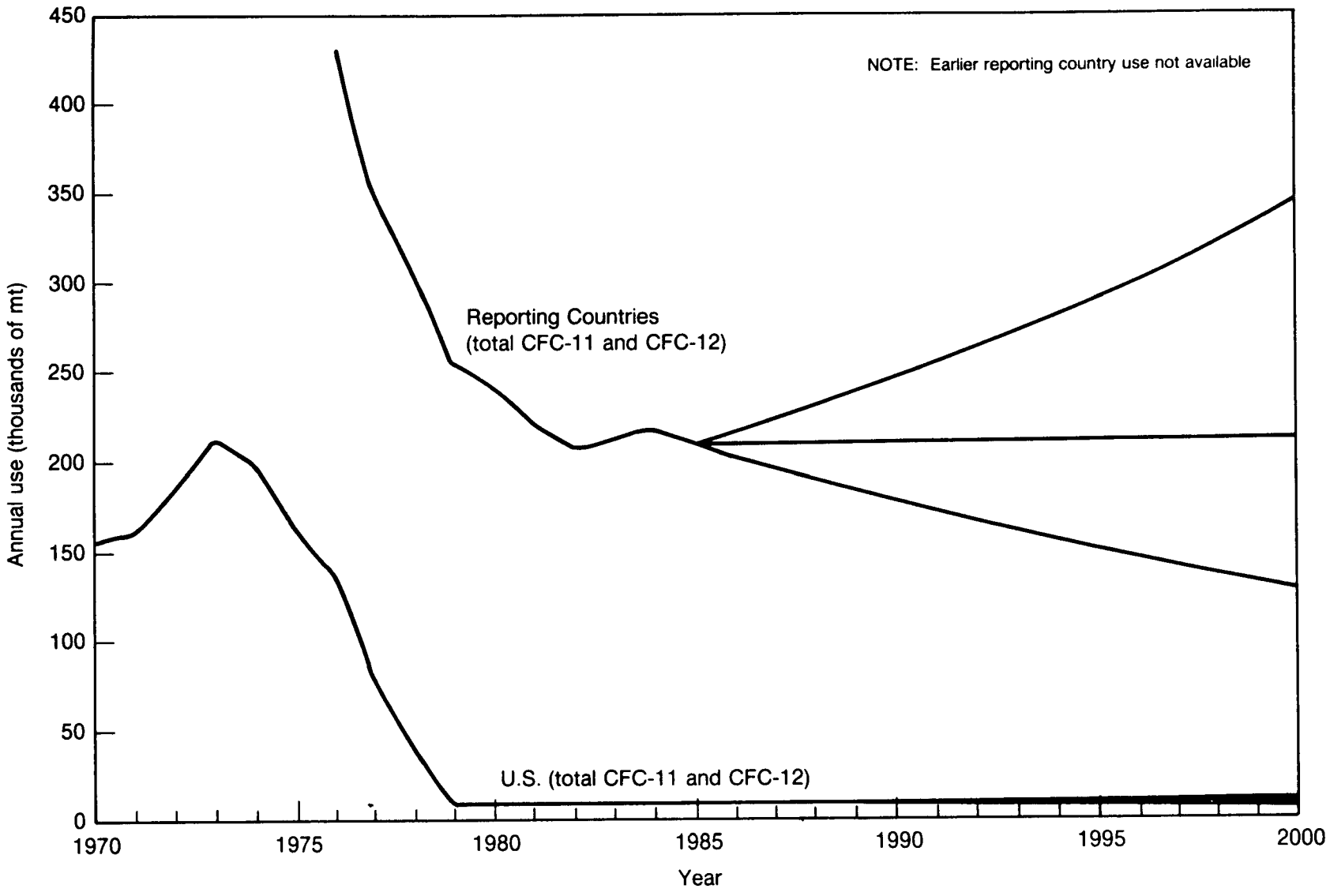


Fig. 3.1—Estimated historical and projected U.S. use of CFC-11 and CFC-12 in aerosols

Japanese use has declined slowly, in part because of substitution of a blend of CFCs and hydrocarbons. Since Japanese law prohibits using pure hydrocarbons as aerosol propellants (because of fire hazards) any substitution to other propellants is presumably to carbon dioxide; substitution from aerosols to pumps may also be occurring. As these alternatives are technically inferior in many uses, we use a base projection for Japanese CFC use equal to current production of about 12,000 mt with a range of uncertainty from three-quarters to one and one-third times that amount.

Further growth is likely in the industrializing nations, particularly in East Asia. These countries are undergoing rapid economic growth and are not party to the international agreements restricting CFC use in aerosols. Our base projection assumes modest growth of 2.5 percent, one-half the expected rate of GNP growth. We believe growth could reasonably range from one-half to twice as fast.

The base projections are summarized in Table 3.2 and Fig. 3.1. They assume that the proportions of aerosol production accounted for by each CFC remain constant at the current reporting country proportions: about 45 percent CFC-11 and 55 percent CFC-12. Note that the projected declines in the EEC almost exactly offset projected growth in the other reporting countries: Baseline projected use initially declines then rises as the developing countries account for a larger share of the total. Combined with the anticipated constant U.S. use, the offsetting trends in the EEC and other reporting countries produce a nearly constant base projection for reporting country aerosol use. As noted

Table 3.2

ESTIMATED CURRENT AND PROJECTED USE OF CFC-11 AND CFC-12 IN AEROSOLS

(In mt)

	United States		Other Reporting Countries		All Reporting Countries	
Year	CFC-11	CFC-12	CFC-11	CFC-12	CFC-11	CFC-12
1985	3,800	5,700	89,900	109,900	93,700	115,600
1990	3,800	5,700	88,100	107,700	91,900	113,400
1995	3,800	5,700	88,500	108,200	92,300	113,900
2000	3,800	5,700	90,800	111,000	94,600	116,700

above, the range of uncertainty for U.S. use is between 78 and 128 percent of projected base use in 2000. Outside the United States the range is from about 60 to 165 percent of projected base use in 2000.[2]

---

[2]This calculation assumes that use is correlated across regions, with a correlation coefficient of 0.75.

IV. RIGID FOAM

CFC-11 and CFC-12 have been used to produce rigid or "closed-cell" foams since the early 1960s. These products are widely used for insulation and packaging.

CFC-11 and CFC-12 are used as blowing agents to form the holes or cells when the foam is manufactured. In closed-cell foams the CFCs remain trapped inside, diffusing only slowly to the atmosphere. Because of the low thermal conductivity of the CFCs, these foams are about twice as effective insulators as equally thick nonfoam alternatives. Foam sheets or boards are sometimes clad with aluminum, paper, or asphalt sheathing to slow the diffusion of air into the foam and thus slow the degradation of its insulating capacity.[1]

There are two major types of closed-cell foams: rigid urethane or isocyanurate foam, usually produced using CFC-11, and nonurethane foam, usually produced with CFC-12. Rigid urethane foam accounts for the second largest share of world CFC-11 use, after aerosols, and by far the largest share of U.S. CFC-11 use. Rigid urethane foams are better insulators than the nonurethane foams, and over 90 percent of these foams are used as insulation in residential, commercial, and industrial construction, in home and commercial refrigerators, and in refrigerated trucks and railroad cars. Insulating foam is made into sheets or boards that are installed during construction, sprayed directly onto tanks, pipes, and other structures, or foamed in place, as inside the walls of a refrigerator. Noninsulation applications include flotation devices, marine buoys and use as a packaging material to protect valuable and delicate objects during shipment.

The most important CFC-consuming nonurethane foams—extruded polystyrene (PS) sheet and extruded PS board—use smaller quantities of CFC-12. PS sheet products include meat trays, egg cartons, plates, and other food containers. Extruded PS board was introduced by Dow Chemical Company during World War II under the trade name Styrofoam. It is used primarily as insulation and competes directly with rigid urethane foam in the residential and commercial wall and roof sheathing market.

---

[1]Insulating capacity may be degraded by changes in the amount and composition of gas retained in the foam, which apparently depend on complicated diffusion and dissolution processes. See Mooz et al. (1982).

RIGID URETHANE FOAM

Rigid urethane foam is used primarily for insulation in construction, refrigeration, and transportation applications. Table 4.1 presents historical U.S. foam use in these markets.

We estimate that each kilogram of foam requires an average of about 130 grams of CFC-11 to produce.[2] From the quantities of CFC-11 required per unit of foam we estimate CFC-11 use by application, reported in Table 4.2. As shown, the construction market currently accounts for about two-thirds of CFC-11 use, refrigeration for one-fifth, and transportation for one-ninth. Estimated reporting country use of CFC-11 in rigid urethane foams is presented in Table 4.3. United States use accounts for about one-third of the total.

The markets for rigid urethane insulating foam are closely related to the construction industry and tend to follow similar cycles. However, growth in most insulation markets has been strong and is expected to continue. Our base projections for U.S. use are reported in Table 4.4.

In the United States and Western Europe, growth in rigid foam use in construction averaged 12 percent annually between 1976 and 1981 (before the major recession in the early 1980s; see Table 4.3), whereas U.S. growth has historically averaged 5 to 8 percent (see Table 4.2).

Table 4.1

ESTIMATED HISTORICAL U.S. PRODUCTION OF RIGID URETHANE FOAM

(In mt)

	Insulation				
Year	Construction	Refrigeration	Transportation	Other	Total CFC-Blown
1978	131,000	45,000	21,000	18,000	215,000
1979	154,000	48,000	22,000	20,000	244,000
1980	142,000	48,000	18,000	18,000	226,000
1981	163,000	50,000	22,000	11,000	246,000
1982	152,000	48,000	16,000	10,000	226,000
1983	163,000	50,000	21,000	11,000	245,000
1984	177,000	53,000	32,000	12,000	274,000

SOURCE: *Modern Plastics* (various issues).

[2]Specifically, we estimate the following average quantities of CFC-11 to produce one kilogram of foam for each application: 126 (construction), 140 (refrigeration), 136 (transportation), and 137 (other applications). See Palmer et al. (1980) Tables III.C.2, F.2, and F.3.

Table 4.2

ESTIMATED HISTORICAL U.S. USE OF CFC-11 IN RIGID URETHANE FOAM

(In mt)

Year	Construction	Refrigeration	Transportation	Other	Total
1978	16,500	6,300	2,900	2,500	28,200
1979	19,400	6,700	3,000	2,700	31,900
1980	17,900	6,700	2,400	2,500	29,500
1981	20,500	7,000	3,000	1,500	32,000
1982	19,200	6,700	2,200	1,400	29,400
1983	20,500	7,000	2,900	1,500	31,900
1984	22,300	7,400	4,400	1,600	35,700

Table 4.3

ESTIMATED HISTORICAL REPORTING COUNTRY USE OF CFC-11 IN RIGID URETHANE FOAM

(In mt)

Year	United States[a]	EEC[b]	Other Reporting Countries[c]	Total Reporting Countries[d]
1976	18,500	20,100	13,500	52,100
1977	21,800	21,500	21,900	65,200
1978	28,200	27,300	10,600	66,100
1979	31,900	29,000	19,200	80,100
1980	29,500	33,400	21,200	84,100
1981	32,000	35,200	30,500	97,700
1982	29,400	na	na	94,900
1983	31,900	na	na	na
1984	35,700	na	na	na

NOTE: na = not available.

[a]From Table 4.2.

[b]Based on industry sources.

[c]Calculated as total reporting countries less United States and EEC.

[d]CMA reports.

Table 4.4

ESTIMATED CURRENT AND PROJECTED U.S. USE OF CFC-11 IN RIGID URETHANE FOAM

(In mt)

Year	Construction	Refrigeration	Transportation	Other	Total
1985	24,100	7,600	4,800	1,800	38,300
1990	35,400	8,700	7,800	2,000	53,900
1995	45,200	9,800	9,900	2,000	66,900
2000	57,600	11,100	12,700	2,000	83,400

The base projections for U.S. use in Table 4.4 assume that high growth averaging 8 percent will persist through 1990, followed by 5 percent average growth to the end of the century.

The refrigeration market is relatively mature and historic U.S. growth has been similar to the GNP. The base projections assume growth slightly slower than the GNP, 2.7 percent to 1990 and 2.5 percent thereafter.

The transportation market accounts for only a small share of use but is growing most rapidly, nearly doubling in the first half of the 1980s. The current 15 percent growth rate is unlikely to be sustained, however. Our base projections assume that the rate will average 10 percent for the remainder of the decade and 5 percent over the next decade.

The noninsulation rigid urethane markets declined significantly during the early 1980s and never recovered to mid 1970s levels. Here, we assume that they recover only slightly further, leveling off at 200 mt of CFC use by 1990.

Table 4.5 presents base projections for reporting country use of CFC-11 in rigid foams. Rigid urethane foam use in Western Europe has historically been similar to U.S. use and the projections assume similar growth. Other reporting countries have apparently experienced more rapid growth (according to CMA reports), which is reasonable, since they are undergoing more rapid economic development. The base projections assume that the entire rigid urethane markets in these countries will grow at the same rate as the rapidly growing construction markets in the United States and Europe, an average of 8 percent through 1990 and 5 percent thereafter.

To estimate the range of uncertainty about the base projections we start with the uncertainty about the size of final product markets conditional on GNP. Because these are well established, at least in the developed economies, we believe that uncertainty is similar to the

Table 4.5

ESTIMATED CURRENT AND PROJECTED REPORTING COUNTRY USE OF CFC-11 IN RIGID URETHANE FOAM

(In mt)

Year	United States	Other Reporting Countries	Total Reporting Countries
1985	38,300	77,500	115,800
1990	53,900	111,100	165,000
1995	66,900	139,600	206,500
2000	83,400	175,900	259,300

uncertainty about general economic growth, between 0.8 and 1.25 times the projected level. Additional uncertainty concerns the share of the final product markets that will be served by CFC-11, since there exist a number of other insulating products, such as fiberglass, extruded polystyrene board, and particle board, that are competitive in some applications. In contrast, the use of CFC-11-blown foam seems secure in applications where the foam is sprayed or poured in place. Consequently, we doubt that rigid urethane foams will lose more than 20 percent, or gain more than 25 percent, of their current share. Combining these ranges produces an overall range of uncertainty of 73 to 137 percent of projected base use.

NONURETHANE FOAM

The major nonurethane products are extruded polystyrene board, used for commercial and residential insulation, and extruded polystyrene sheet, used in egg cartons and food service trays. Jointly, they account for about two-thirds of the CFC-12 used in nonurethane foam products. Table 4.6 presents historical U.S. production of these foams and estimated CFC-12 use. CFC-12 use per unit of nonurethane foam is about 95 grams per kilogram of foam, smaller than CFC-11 use in rigid urethanes.

CFC-12 is the primary blowing agent for extruded polystyrene sheet, but use declined during the late 1970s and early 1980s. Palmer et al. (1980) estimate CFC-12 use in 1976 assuming that 64 percent of polystyrene sheet is CFC-blown (the remainder uses pentane) and that

Table 4.6

ESTIMATED HISTORICAL U.S. PRODUCTION OF NONURETHANE FOAM AND USE OF CFC-12

(In mt)

	Extruded PS Board		Extruded PS Sheet	
Year	Foam	CFC-12	Foam	CFC-12
1976	na	1,900	na	5,900
1977	na	2,300	na	7,300
1978	na	2,500	na	7,800
1979	31,000	2,900	151,000	7,600
1980	27,000	2,600	147,000	7,400
1981	32,000	3,000	140,000	7,000
1982	30,000	2,900	146,000	6,600
1983	34,000	3,200	153,000	6,500
1984	39,000	3,700	184,000	7,200

SOURCES: Foam production from *Modern Plastics* (various issues). CFC-12 use before 1979 from Palmer et al. (1980), after 1979 calculated from foam production (see text).

NOTE: na = not available.

CFC-blown foam contains 7.8 percent CFC-12 by weight. During recent years, however, a mixed blowing agent combining CFC-12 and carbon dioxide has reduced the CFC requirement by about 25 percent. By 1984, we calculate CFC-12 use in polystyrene sheet assuming that two-thirds of the foam uses 5.85 percent CFC-12 by weight.

Other nonurethane foams including expanded polystyrene foam (used for drinking cups) and the polyolefins are manufactured in large quantities but require only small amounts of CFC blowing agents. In the absence of direct data on CFC use in these products we assume that use grows at the same rate as in the extruded polystyrene foams.

Table 4.7 provides a base projection for U.S. use of CFC-12 in rigid foams. For extruded PS board, we assume growth comparable to that of rigid polyurethane insulation with which it competes. The base projections for use in polystyrene sheet and in the other nonurethane category grow with GNP.

Table 4.8 presents base projections for reporting country use of CFC-12 in nonurethane foam. Our base projections have the same growth rates outside the United States as within. Since about half of CFC-12 use in nonurethane foams is for extruded polystyrene sheet, which faces a variety of competing products such as cardboard egg

Table 4.7

ESTIMATED CURRENT AND PROJECTED U.S. USE OF CFC-12 IN NONURETHANE FOAM

(In mt)

Year	Extruded Polystyrene Board	Extruded Polystyrene Sheet	Extruded Polystyrene Total	Other Nonurethanes	Total Nonurethanes
1985	4,000	7,500	11,500	3,400	14,900
1990	5,900	8,900	14,800	4,000	18,800
1995	7,500	10,200	17,700	4,600	22,300
2000	9,600	11,600	21,200	5,300	26,500

cartons and food serving trays, and because some of these products can also be made with pentane, we believe that there is significant uncertainty about CFC-12 use conditional on the size of these packaging markets. We suggest a range of uncertainty for CFC-12 use in nonurethane foam from 60 percent of the projected level, if CFC-12-blown polystyrene sheet were to lose 80 percent of its market, to 167 percent of the projected level if it were to displace many of its competitors. Combining these with the range of uncertainty about GNP growth produces a range of uncertainty of 57 to 172 percent of the base projections.

Figures 4.1 and 4.2 summarize historical and base projected use of CFC-11 and CFC-12 in rigid foams, in the United States and all reporting countries, respectively. Note that the rigid urethanes account for the majority of CFC use in rigid foam.

Table 4.8

ESTIMATED CURRENT AND PROJECTED REPORTING COUNTRY USE OF CFC-12 IN NONURETHANE FOAM

(In mt)

Year	United States	Other Reporting Countries	Total Reporting Countries
1985	14,900	27,900	42,800
1990	18,800	35,200	54,000
1995	22,300	41,800	64,100
2000	26,500	49,600	76,100

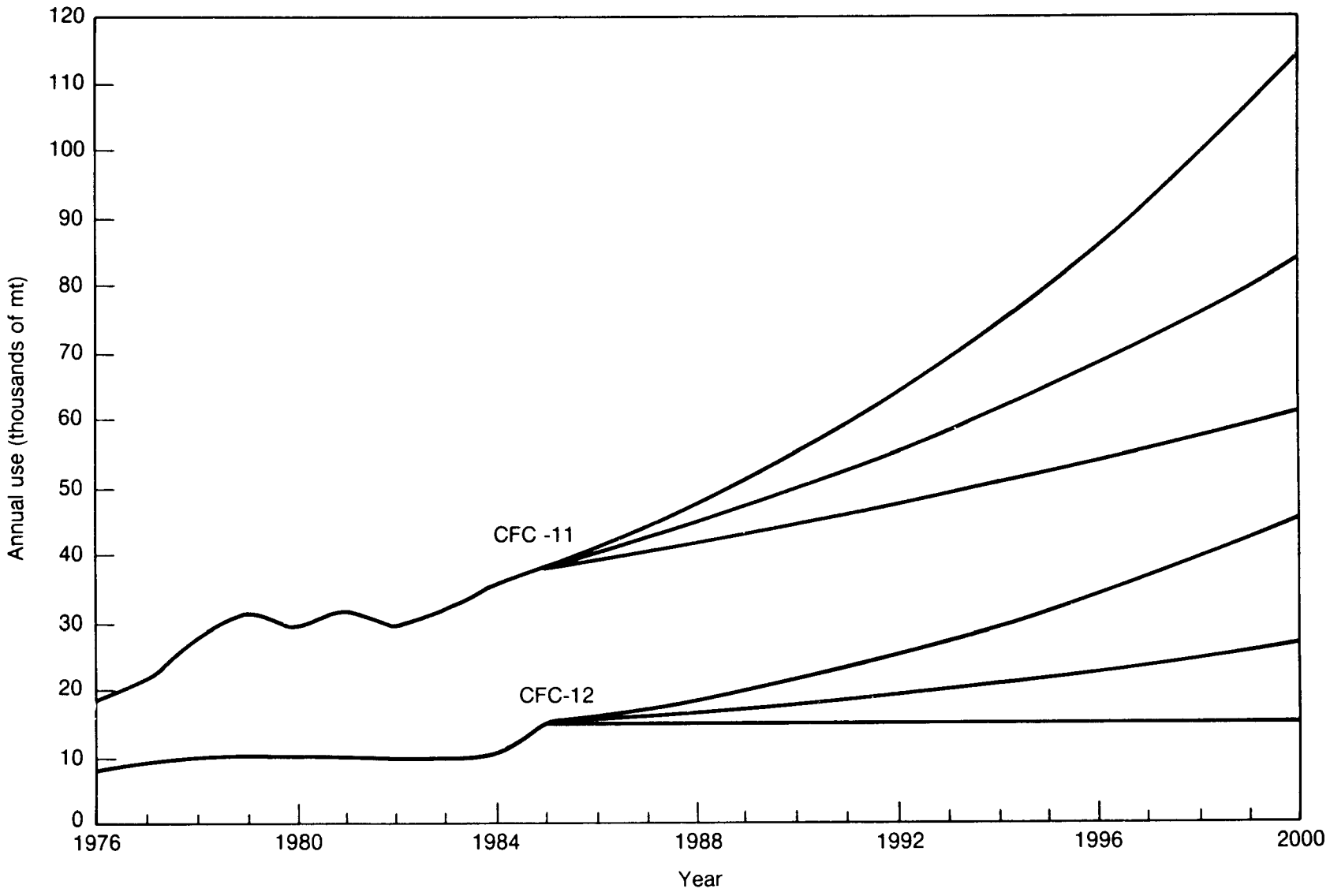


Fig. 4.1—Estimated historical and projected U.S. use of CFC-11 and CFC-12 in rigid foam

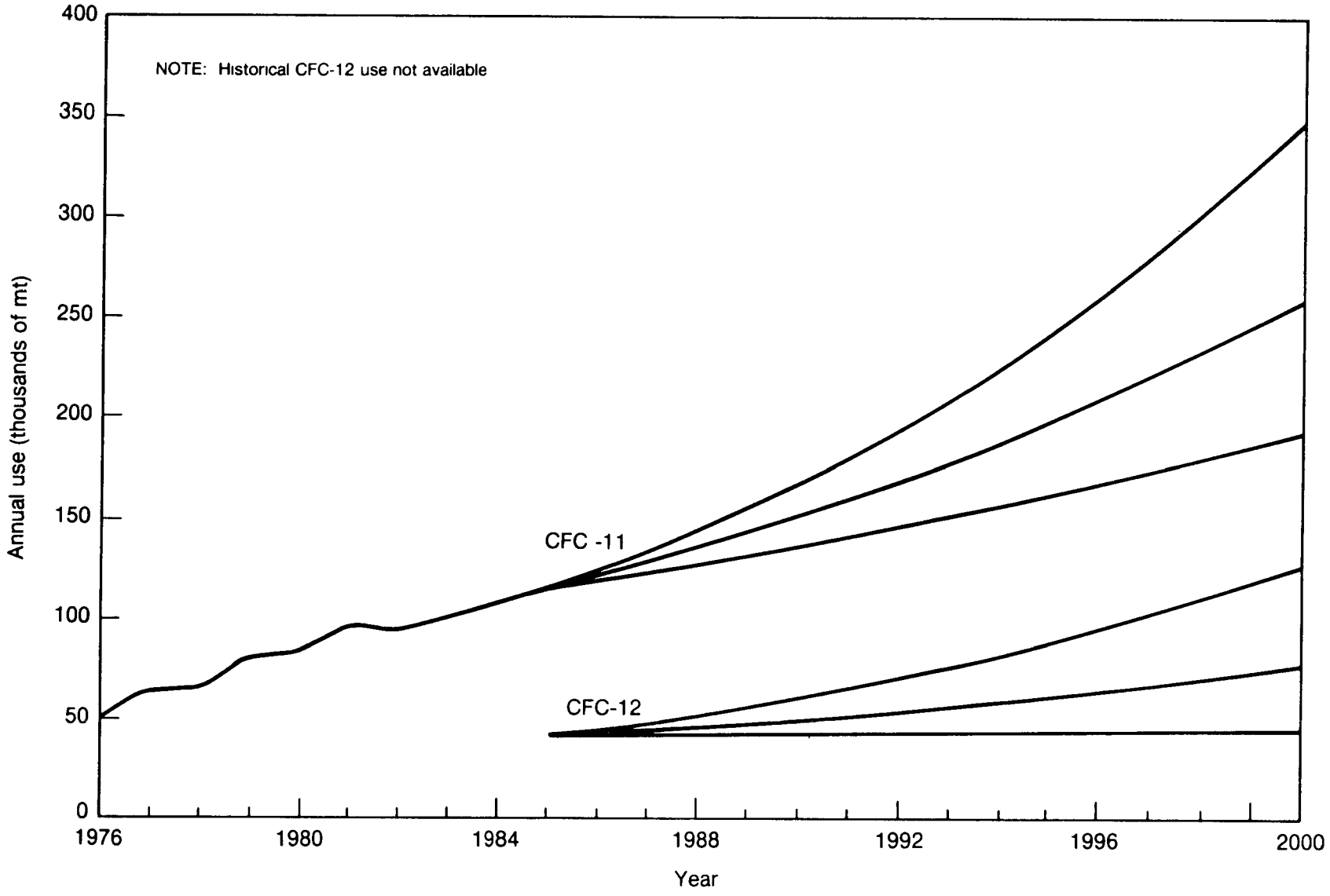


Fig. 4.2—Estimated historical and projected reporting country use of CFC-11 and CFC-12 in rigid foam

V. FLEXIBLE FOAM

CFC-11 is widely used to produce flexible foams, which first came into use in the 1950s. Because these foams are resilient, durable, and relatively inexpensive they are now widely used in furniture, bedding, carpet underlay, automobile seats and dashboards, and packaging applications.

There are two major processes for producing flexible foams. Most foam is manufactured in the form of slabstock, which is a piece of foam typically about six feet wide, four feet high, and from six to 200 feet long. Final shapes are cut from this large slab. The second process molds foam into its final shape, which is often rounded or has other features that would make it difficult or costly to carve from slabstock. Molded foam is used almost exclusively for automobile seats and seatbacks.

The important characteristics of flexible foam are imparted by blowing agents that form the holes or cells in the foam and give it flexibility. All flexible foams use carbon dioxide as the primary blowing agent. To produce softer (less dense) foams requires augmenting the carbon dioxide with an auxiliary blowing agent, either CFC-11 or methylene chloride. Since the carbon dioxide is produced by reacting water with TDI (toluene diisocyanate), foams produced without auxiliary blowing agents are called water-blown.

Flexible foams are often called "open-cell," since their cells are open to the atmosphere. As a result, CFC emissions are prompt: The blowing agent escapes from the foam within a matter of hours or days after its manufacture.

SLABSTOCK FOAM

Table 5.1 presents estimated U.S. production of slabstock foam and CFC-11 used. Foam production is reported in Mobay (1982–1985). CFC-11 use is based on estimated use of 50 grams per kilogram of CFC-blown slabstock foam. CFC-11 use peaked in the late 1970s, declined through 1982, and is currently increasing. The decline was primarily due to reduced foam production during the recession, but it also reflects reduced use of CFC-11 per unit of foam because of substitution to the less expensive methylene chloride. Currently, methylene chloride and CFC-11 each account for about half of the auxiliary blow-

Table 5.1

ESTIMATED HISTORICAL U.S. PRODUCTION OF SLABSTOCK FOAM AND USE OF CFC-12

(In mt)

Year	Foam	CFC-11
1976	380,000	11,400
1977	439,000	12,900
1978	472,000	13,600
1979	473,000	13,300
1980	425,000	11,700
1981	409,000	11,000
1982	369,000	9,700
1983	414,000	10,600
1984	448,000	11,200

ing agent used.[1] Further substitution to methylene chloride is not expected because the cost savings will not offset the necessary investment in learning to produce sufficiently high quality foam. Future use of methylene chloride may even decline because of concerns about its potential carcinogenicity and possible regulation. A new alternative blowing process has been recently patented. According to its Belgian developers, the new process is less expensive, can be used to produce all densities of foam, and uses no auxiliary blowing agent (CMR, February 28, 1983). If these claims prove correct, adoption of this new process could lead to substantial reductions in CFC-11 use.

Industry sources expect slabstock foam production to grow at the same rate as the GNP (Mobay, 1985). Table 5.2 reports our base projections for U.S. production of slabstock foam and CFC-11 use, assuming that CFC-11 use per unit of foam remains at its current level. We suggest that these projections are subject to the following range of uncertainty. First, the uncertainty concerning GNP growth implies that total use could be about 20 percent smaller or 25 percent greater than the base projection by 2000. We treat the uncertainty about the growth of the final product markets, conditional on a given level of GNP, as negligible. The level of CFC use, conditional on the size of the final product markets, is subject to substantial uncertainty, however. Considerable substitution away from CFC-11 to either methylene

[1]Thus CFC-11 use averages 25 grams per kilogram of slabstock foam.

Table 5.2

ESTIMATED CURRENT AND PROJECTED U.S. USE OF CFC-11 IN SLABSTOCK FOAM

(In mt)

Year	Slabstock Foam	CFC-11 Used
1985	459,400	11,500
1990	545,600	13,700
1995	623,400	15,700
2000	712,200	17,900

chloride or possibly to the alternative blowing method is possible. As a lower bound, we postulate that CFC-11 could lose one-half its share by 2000. Conversely, if the costs of using methylene chloride increase substantially because of regulation, its share could be taken by CFC-11, potentially doubling CFC-11 use. Combining these ranges of uncertainty produces a range of uncertainty in 2000 of from 0.48 to 2.07 times the projected base level.

Estimated reporting country use of CFC-11 in slabstock foam is reported in Table 5.3.[2] We estimate non-U.S. use by subtracting estimated U.S. use derived above. Assuming that non-U.S. use of CFC-11 in slabstock foam will also grow with the GNP of the respective countries, we project a future base level as shown in Table 5.4. The range of uncertainty is similar to that for the United States, albeit somewhat smaller. Uncertainty about GNP growth implies that total use could be 20 percent smaller, or 25 percent larger, than the projected baseline. We believe that total slabstock foam markets, conditional on GNP, could reasonably range between 80 and 125 percent of the projected level. Finally, since methylene chloride use is smaller overseas than in the United States and concerns about its possible carcinogenicity are perhaps greater, the share of foam blown by CFC-11 is likely to remain steadier than in the United States: We use an interval from 0.83 to 1.20. The resulting range for other reporting country CFC-11 use in slabstock foam falls between 0.69 and 1.44 times the base projection.

[2]CMA details reporting country use of CFC-11 in all flexible foams. We estimate use in molded foam by multiplying world vehicle production by the estimated quantity of CFC-11 used per vehicle and attribute the remainder to slabstock production.

Table 5.3

ESTIMATED HISTORICAL REPORTING COUNTRY USE OF CFC-11 IN SLABSTOCK FOAM

(In mt)

Year	United States	Other Reporting Countries	Total Reporting Countries
1976	11,400	20,500	31,900
1977	12,900	26,000	28,900
1978	13,600	25,500	39,100
1979	13,300	22,800	36,100
1980	11,700	26,900	38,600
1981	11,000	26,500	37,500
1982	9,700	22,900	32,600
1983	10,600	31,300	41,600

Table 5.4

ESTIMATED CURRENT AND PROJECTED REPORTING COUNTRY USE OF CFC-11 IN SLABSTOCK FOAM

(In mt)

Year	United States	Other Reporting Countries	Total Reporting Countries
1985	11,500	33,500	45,000
1990	13,700	39,800	53,500
1995	15,700	47,300	63,000
2000	17,900	56,100	74,000

MOLDED FOAM

Molded foam is used almost entirely for seats and seatbacks in automotive vehicles and its production is intimately related to total vehicle production. Table 5.5 reports estimated historical U.S. use of CFC-11 in molded foams, molded foam production, and total automobile production. Manufacturers report that average use of CFC-11 per unit of foam has been declining as they have changed product formulations, substituted methylene chloride, adopted the high resiliency process

Table 5.5

ESTIMATED HISTORICAL U.S. PRODUCTION OF AUTOMOTIVE VEHICLES, MOLDED FOAM AND USE OF CFC-11

Year	CFC-11 (mt)	Molded Foam (mt)	Automotive Vehicles (thousands)	CFC-11 per Vehicle (grams)
1976	3,900	156,000	11,500	340
1977	4,100	164,000	12,700	322
1978	4,300	178,000	12,800	333
1979	4,300	177,000	11,400	373
1980	3,000	131,000	8,000	376
1981	2,800	126,000	8,000	347
1982	2,500	118,000	6,900	360
1983	3,000	145,000	9,500	320
1984	3,200	162,000	10,900	297

SOURCE: Vehicles, *Automotive News*, April 24, 1985.

(which requires no auxiliary blowing agent), and switched to foam densities that can be produced using carbon dioxide alone.[3] CFC-11 use currently averages about 300 grams per vehicle. We combine this figure with projected growth in vehicle production to project CFC-11 use in molded foam.

Relying on industry sources, our base projections for vehicle sales in the United States (total import and domestic sales) grow at 1.9 percent per year, and sales in foreign markets grow at 2.9 percent. (CFC use is allocated to the region in which the car is produced though not necessarily sold.) To estimate CFC use outside the United States we assume that foreign automobiles also average 300 grams of CFC-11 per vehicle. Table 5.6 summarizes base projections for reporting country vehicle production and CFC-11 use.

Note that although the base projection for vehicle production grows at 2.9 and 1.9 percent, the base projection for CFC-11 use grows at only 0.5 percent outside the United States, and falls 0.4 percent per year within the United States. This occurs because of the fundamental uncertainty about future CFC-11 use in molded foam. We believe that there is little chance that CFC-11 use per vehicle will increase; however, substantial decreases are possible. Increases are unlikely because

[3]Molded foams have always used less auxiliary blowing agent than slabstock foam. Currently, we estimate that molded foams require an average of 20 grams per kilogram. The average level of CFC-11 use per vehicle is more erratic than CFC-11 use per unit of foam because of the changing average quantities of foam used per vehicle.

Table 5.6

ESTIMATED CURRENT AND PROJECTED REPORTING COUNTRY AUTOMOTIVE VEHICLE PRODUCTION AND USE OF CFC-11 IN MOLDED FOAM

	United States		Other Reporting Countries		Total Reporting Countries	
Year	Vehicles (thousands)	CFC-11 Used (mt)	Vehicles (thousands)	CFC-11 Used (mt)	Vehicles (thousands)	CFC-11 Used (mt)
1985	11,100	3,330	29,000	8,700	40,100	12,030
1990	12,200	3,260	33,400	8,910	45,600	12,170
1995	13,400	3,190	38,300	9,130	51,800	12,320
2000	14,700	3,120	44,100	9,360	58,800	12,480

methylene chloride is used much less frequently for molded than for slabstock foam, so that substitution to CFC-11 would not be as large if methylene chloride were to be regulated. However, according to industry sources it would be possible to reduce CFC-11 use drastically by switching to other, unspecified, processes for manufacturing automobile seats. Because of the possibility of substituting to methylene chloride, high resiliency or water-blown foam, CFC-11 use per vehicle could decline by half by 2000. Consequently we project a baseline average CFC-11 use per vehicle in 2000 to be only 212 grams, with a range of uncertainty falling between 150 and the current level of 300 grams.

Conditional on GNP, molded foam production could vary by a factor of about 10 percent, depending on future trends in automobile sizes in the United States and abroad. Combining these ranges with the range for GNP growth we obtain an uncertainty range for CFC-11 use in molded foams in the United States and in other reporting countries of 65 to 153 percent of the base projections.

Figures 5.1 and 5.2 summarize historical and projected use of CFC-11 in flexible foams in the United States and reporting countries. Slabstock foam accounts for the majority of reporting country use.

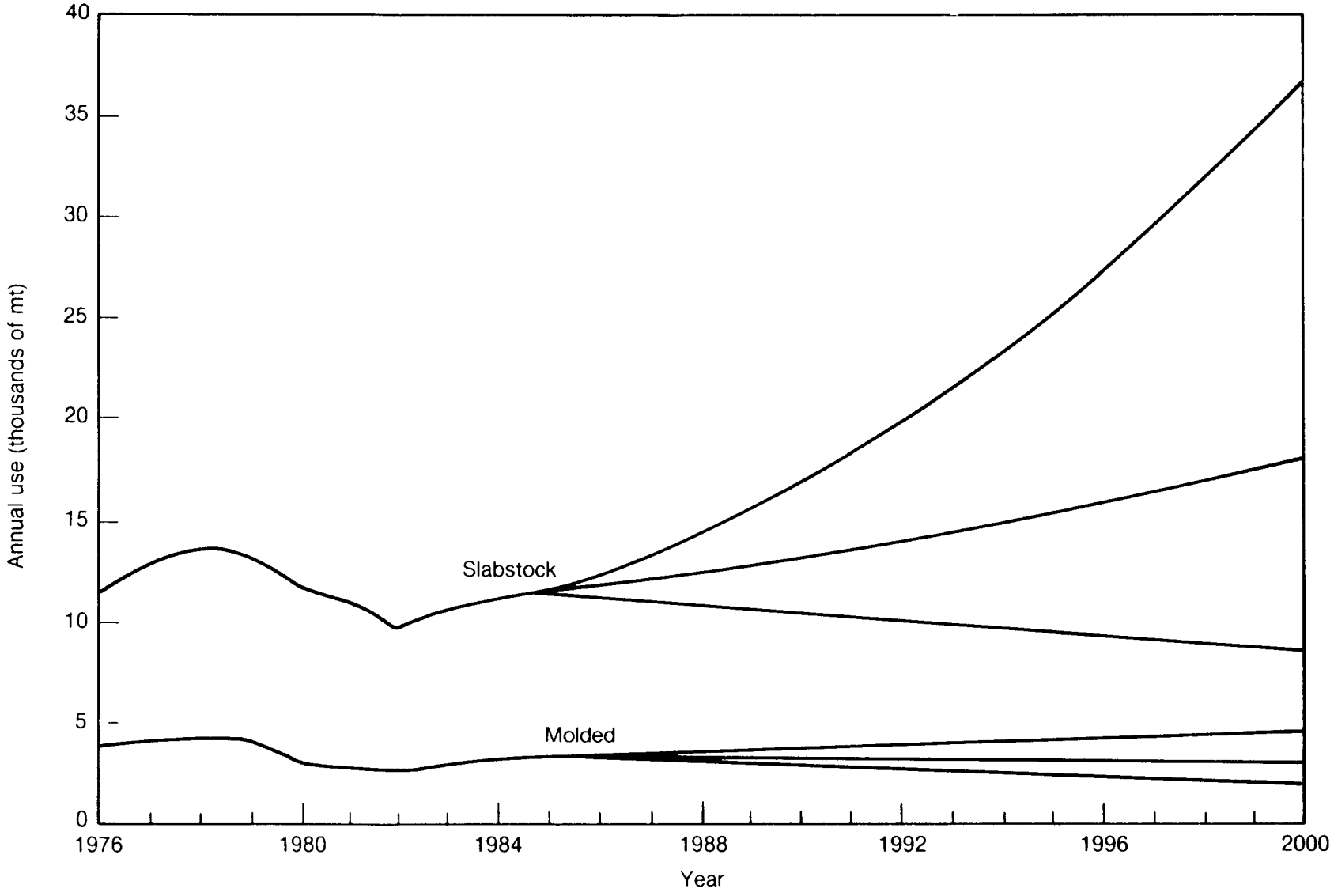


Fig. 5.1—Estimated historical and projected U.S. use of CFC-11 in flexible foam

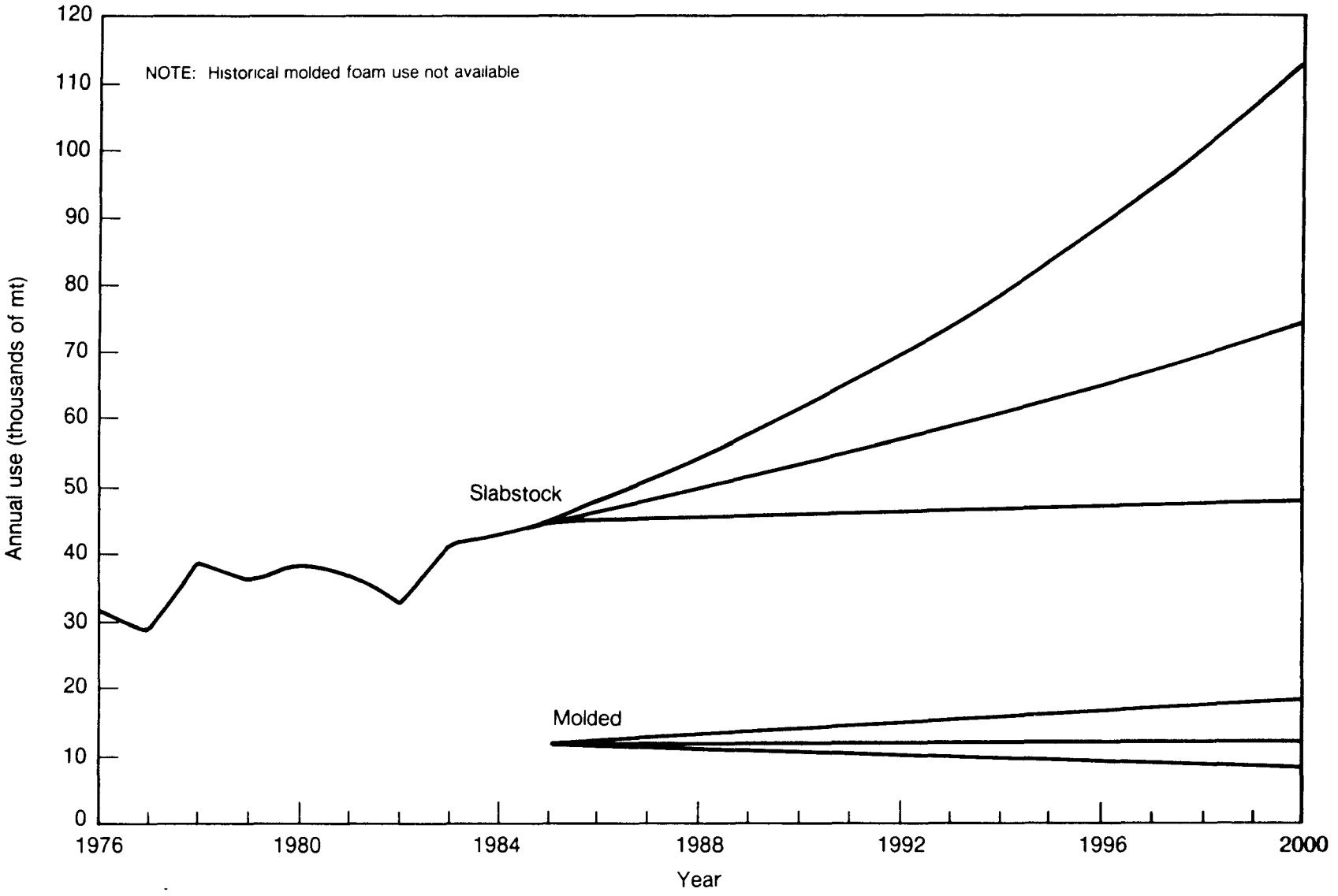


Fig. 5.2—Estimated historical and projected reporting country use of CFC-11 in flexible foam

VI. REFRIGERATION AND AIR CONDITIONING SYSTEMS

CFC-11 and CFC-12 are used as refrigerants in a variety of systems.[1] The largest quantities are used in home refrigerators and freezers, retail store refrigeration systems, chillers (used for cooling buildings) and mobile (automotive) air conditioners. Except for mobile air conditioners, all of these markets are well developed in the United States and Western Europe and little growth is expected there. Growth in the developing countries may be stronger.

The refrigeration cycle consists of compression of the refrigerant followed by cooling until it condenses to liquid form, and expansion to allow evaporation of the liquid. During evaporation the refrigerant absorbs heat from the refrigeration unit and then returns to the compressor to repeat the cycle. Since the refrigerant remains in a sealed system throughout the cycle, the CFC is not emitted until the unit is disposed of (except for quantities that leak from the system or are emitted during servicing).

MOBILE AIR CONDITIONING

Air conditioning in automobiles and other vehicles began as a luxury item in the 1940s and has become commonplace in the United States but remains a rarity in other countries. Mobile air conditioners use CFC-12 exclusively. A CFC-22 system was used in the past but has disappeared, presumably because of the higher cost and weight that result from the higher pressures required. As with other refrigeration systems, emissions are generally low until disposal, although significant emissions occur at servicing and when systems are damaged in automobile accidents.

Use of CFC-12 in mobile air conditioners depends on three factors: the number of new vehicles, the fraction that are air conditioned, and the average amount of refrigerant used per system. The fraction of new cars and trucks sold in the United States with air conditioning has increased rapidly, from about 6 percent in 1960 to about 60 percent in the 1970s. Since then that number has remained stable at the current

[1]When describing refrigerants the CFC prefix is often replaced by the letter R (for refrigerant) or F (for Freon, a DuPont trademark). Thus CFC-12 is frequently called R-12 or F-12.

level of 68 percent.[2] The average refrigerant charge in domestic automobiles declined from about 1.7 kilograms (3.8 pounds) to 1.3 kilograms (2.75 pounds) between 1974 and 1985 as systems were redesigned to reduce leakage and weight and smaller automobiles became more common. Further declines are not expected unless vehicles become smaller. Charges in imported automobiles are smaller, perhaps 0.9 kilograms (2.0 pounds).

Table 6.1 presents historical and projected baseline United States vehicle sales (total domestic and imported) and estimated CFC-12 used in mobile air conditioning. Note the decrease in CFC-12 use for 1978 through 1982 because of the decline in initial charge. Annual use includes the initial charge for new units, manufacturing and installation losses (about 10 percent of initial charge), replacement of routine leakage (30 percent of the initial charge is assumed to be lost every 5 years on average), other servicing losses (10 percent of stocks), and replacement of accident-caused losses (2.5 percent of stocks). The model for estimating use is described in Palmer et al. (1980). The base projections assume that United States vehicle sales will grow at 1.9 percent annually through 2000, as industry sources suggest, and that both the share of new vehicles that are air conditioned and the average charges will remain constant.

Mobile air conditioning is much less common outside the United States. We estimate that about 20 percent of non-U.S. vehicles are air conditioned (65 percent in Japan, 34 percent in Canada, one-half percent in the EEC, and negligible numbers elsewhere).[3] Assuming that average charges and losses are the same as for imports to the United States (0.9 kilograms average charge), annual use in the other reporting countries is estimated as 23,000 mt.

Relying on industry sources we project the number of new foreign vehicles sold to grow at 2.9 percent annually. We further assume that the share of new vehicles that are air conditioned will grow to 30 percent by 2000, a 50 percent increase from the estimated current level. Combining these factors leads to a baseline projection of 5.7 percent annual growth as reflected in Table 6.2.

Uncertainty about future domestic use of CFC-12 in mobile air conditioning is based on uncertainty about total vehicle sales, the share that are air conditioned, and average charge. We suggest that the

[2]This is the percentage of all new automotive vehicles, including both automobiles and trucks, that are air conditioned. The fraction of automobiles is higher, about 82 percent of those produced domestically.

[3]The Japanese share is reported in Nihon Reito Kucho Kogyo Kai (1985), the EEC share is from confidential industry sources, and the Canadian share is assumed to be one-half the United States share because of the colder climate there.

Table 6.1

ESTIMATED HISTORICAL AND PROJECTED U.S. VEHICLE SALES AND USE OF CFC-12 IN MOBILE AIR CONDITIONING

Year	Vehicles Sold (millions)	CFC-12 Use (mt)
1976	13.28	44,890
1977	14.84	50,780
1978	15.43	52,800
1979	14.13	50,910
1980	11.46	47,570
1981	10.80	47,860
1982	10.54	47,670
1983	12.31	48,650
1984	14.48	50,350
1985	14.76	50,400
1990	16.21	54,800
1995	17.81	59,900
2000	19.57	65,400

SOURCE: Historical vehicle sales, *Automotive News*, April 24, 1985.

Table 6.2

ESTIMATED CURRENT AND PROJECTED REPORTING COUNTRY USE OF CFC-12 IN MOBILE AIR CONDITIONING

(In mt)

Year	United States	Other Reporting Countries	Total Reporting Countries
1985	50,400	23,000	73,400
1990	54,800	30,300	85,100
1995	59,900	40,000	99,900
2000	65,400	52,800	118,200

uncertainty about vehicle sales is equivalent to that about general economic growth. The share of new vehicles with air conditioners has remained at about two-thirds over the last decade, despite substantial

changes in the size of automobiles. We suggest a range of uncertainty of plus or minus 10 percent of the current share. Finally, further design changes affecting the average charge are not expected, but if the average size of vehicles changes average charge could vary by perhaps 30 percent. Combining these uncertainties yields an overall range of uncertainty of 0.70 to 1.43 times the base projection.

Outside the United States, the uncertainty about the share of new vehicles with air conditioning is greater. Accordingly, we suggest a range of use conditional on GNP of 0.8 to 1.25 times the base projection, or an overall range of 0.67 to 1.50 times the base projection.

RETAIL STORE REFRIGERATION

Retail food store refrigeration systems are used to refrigerate the food and beverages in display cases and to store meat, produce, dairy products, frozen food, and ice cream in walk-in coolers. Systems are designed differently depending on whether they are for medium temperatures (storing dairy products) or low temperatures (storing frozen foods).

System design and choice of refrigerant are influenced by energy use, since refrigeration equipment accounts for as much as half of a typical store's energy use. CFC-12 is usually used for medium temperature systems, whereas most low temperature systems use CFC-502, a blend of nearly equal parts of CFC-22 and CFC-115. Some stores use CFC-502 for medium temperature systems as well, because of the convenience of handling only one refrigerant. However, CFC-502 is substantially more expensive than CFC-12.

CFC-22 was once employed in both low and medium temperature systems. Currently it is used only rarely, since it generates excessive heat in the compressor.

The average refrigerant charge increased during the mid 1970s as a number of energy saving features were adopted that required additional refrigerant. This trend will probably continue to some extent until about 1990. Eventually, the use of low pressure flooding systems in large supermarkets is expected to be implemented extensively. One industry source estimates that this will lead to a 10 percent reduction in average system charge. Another trend that may reduce refrigerant use is a decline in leakage and servicing emissions as older equipment is replaced by newer designs.

Table 6.3 presents historical United States data on the number of retail food stores and their use of CFC-12, and projections. CFC-12 use is estimated using the model described in Palmer et al. (1980),

which simulates refrigerant use in four sizes of stores. Annual use includes refrigerant used for charging new units (between about 60 and 1,100 kilograms, depending on size of store), in testing new units during manufacture (about 2 percent of initial charge), and in replacing losses that occur during installation (5 to 8 percent depending on store size), leakage, and servicing (about 10 percent of refrigerant in use).

The values in Table 6.3 show a decline in the total number of stores, but a slight increase in refrigerant use over the period. This reflects a trend toward larger supermarkets and away from small grocery stores that is expected to continue in the future. The effect of this trend is partially offset by expected further substitution to CFC-502 in medium temperature systems and lower leakage and servicing losses as newer units with better integrity replace old units.

The base projections for reporting country CFC-12 use are given in Table 6.4. Industry sources indicate that foreign systems are similar to those in the United States and that use in the other reporting countries is currently about equal to United States use. Future growth is expected to be at the same rate as GNP, 3.5 percent annually, somewhat more rapid than in the United States

Uncertainty about CFC-12 use in retail food stores can be divided into uncertainty about the number of such stores and about the average charges and types of refrigerants used. Uncertainty about the number of stores, conditional on the level of general economic activity, is small, plus or minus 10 percent. The average charge is highly sensitive to shifts between refrigerants. In recent years there has been some

Table 6.3

ESTIMATED HISTORICAL AND PROJECTED U.S. USE OF CFC-12 IN RETAIL FOOD REFRIGERATION

Year	Number of Stores	CFC-12 (mt)
1976	183,700	4,820
1980	174,570	4,830
1985	164,950	4,850
1990	155,330	4,620
1995	145,710	4,910
2000	136,090	5,200

Table 6.4

ESTIMATED CURRENT AND PROJECTED REPORTING COUNTRY USE OF CFC-12 IN RETAIL FOOD REFRIGERATION

(In mt)

Year	United States	Other Reporting Countries	Total Reporting Countries
1985	4,850	4,850	9,700
1990	4,620	4,620	9,240
1995	4,910	5,130	10,040
2000	5,200	5,670	10,870

movement toward use of CFC-502 in medium temperature systems because of the convenience of handling only the one refrigerant. CFC-502 could completely replace CFC-12 in new medium temperature installations by 2000. If it did CFC-12 use would be reduced by as much as 75 percent by 2000.[4] Alternatively, if the average refrigerant charge per store continues to increase after 1990, use of CFC-12 in 2000 could be higher by perhaps 20 percent. Combining these uncertainties we suggest a range for CFC-12 use of 0.25 to 1.33 times the base projections in 2000.

HOME REFRIGERATORS AND FREEZERS

In the early part of this century refrigerants such as methyl chloride, ammonia, and sulfur dioxide were employed in home refrigeration equipment. Since these chemicals are toxic, and some are also flammable or explosive, they are not considered safe enough for home use. CFC-12 has none of these drawbacks and has been used in all home refrigerating equipment in the United States since at least 1946.

Home refrigerators currently use either a rotary or reciprocating compressor. The reciprocating-compressor machines require only one-third to one-half as much refrigerant. Historically, the average charge in a domestic refrigerator was 280 grams (10 ounces) and the average

[4]Leakage and servicing use represent about half of refrigerant use. Older units using CFC-12 would still require CFC-12 for servicing. If half the medium temperature units in service used CFC-502 by then, CFC-12 use would still account for one-fourth the projected use.

charge in a freezer was 430 grams (15 ounces). Today, refrigerators use an average of about 210 grams (7.5 ounces) of refrigerant, whereas freezers require about 280 grams (10 ounces).[5] Although refrigerators outside the United States are typically smaller, we assume that initial charges are the same as in current U.S. practice, about three-quarters the historic U.S. level. We assume that home freezer use outside the United States is negligible.

CFC-12 is used in home appliances for charging new units, in testing and rework at manufacturing, and in replacing leakage and servicing losses. The models used to calculate historical and future use are described in Palmer et al. (1980).

Table 6.5 reports historical and projected baseline U.S. sales of home appliances and estimated use of CFC-12. CFC-12 use declined between 1976 and 1984 because of the increased use of reciprocating compressors in refrigerators, which require a smaller initial charge, and because the growth in freezers declined. Since the domestic home refrigerator market is well saturated, we project future growth slightly below the expected growth of GNP, 3 percent to 1990 and 2.5 percent to 2000. Freezer sales were strong in the early 1970s but have since declined. We assume only 1 percent growth to 2000.

Table 6.5

ESTIMATED HISTORICAL AND PROJECTED U.S. HOME REFRIGERATOR AND FREEZER SALES AND USE OF CFC-12

Year	Number of Refrigerators (thousands)	Number of Freezers (thousands)	CFC-12 (mt)
1976	5,090	1,740	2,920
1980	5,570	1,670	2,370
1984	6,200	1,340	2,400
1985	6,390	1,360	2,440
1990	7,410	1,430	2,660
1995	8,380	1,500	2,900
2000	9,480	1,570	3,190

SOURCES: Palmer et al. (1980), Mooz et al. (1982).

[5]Home refrigerators typically incorporate three to six times more CFC-11 blowing agent in the insulating foam in their walls than CFC-12 refrigerant in their cooling systems.

Both reciprocating and rotary compressors are competitive in the home appliance market. However, if their market shares were to shift significantly it could substantially affect CFC-12 use. At present, about 25 percent of domestic refrigerators and 30 percent of freezers contain rotary compressors. If the share of appliances using rotary compressors were to halve or double, average initial charges could fall 25 percent or increase by one-third by 2000. Combined with the uncertainty over the total number of home refrigerators and freezers produced (equivalent to the uncertainty about GNP) the range of uncertainty is from 0.7 to 1.43 times the projected base for CFC-12 use in 2000.

Table 6.6 reports estimated home refrigerator production by world region. As a baseline projection we assume that West European use will halt its historical decline and remain constant at 11,000 mt annually to 2000. For the other reporting countries we set baseline projected growth at the same rate as from 1972 to 1981, 6.2 percent per year. [6]

Table 6.7 reports our base projection for reporting country CFC-12 use in home appliances. Uncertainty about use outside the United States is greater, because of the greater uncertainty about the average charge and how it may change. We suggest a range of 0.67 to 1.50

Table 6.6

ESTIMATED HISTORICAL WORLD PRODUCTION OF HOME REFRIGERATORS

(In thousands)

Region	1972	1981	Average growth rate (%)
Western Europe	12,110	10,990	−1.1
North America (excl. U.S.)	830	1,350	5.6
South America	1,330	2,800	8.6
Asia (excl. USSR)	4,550	7,710	6.0
Africa	330	510	5.0
Oceana	450	460	0.0
Eastern Europe (excl. USSR)	2,510	3,340	3.2
USSR	5,030	5,930	1.8
Total	27,100	33,100	2.2

SOURCE: United Nations Statistical Office (1981).

[6]Recall that we do not project use in the communist countries in this section; the data on communist countries in Table 6.6 is included for reference.

times the base projection in 2000 to account for the uncertainty about average charge. Combined with uncertainty about GNP growth this produces a range of uncertainty of 0.63 to 1.59 times projected use.

CHILLERS

Chillers are air conditioning systems used in large commercial and industrial buildings. The cooling system consists of a central unit that chills a secondary refrigerant, typically water or brine, which is circulated to cooling coils throughout the building. Chillers may use either centrifugal or reciprocating compressors. The centrifugal units use primarily CFC-11 or CFC-12 and have capacities ranging from 75 to 10,000 tons.[7] The reciprocating units use CFC-22 and CFC-12 and are of smaller capacity, usually no more than 150 tons.

Estimates of historical and projected baseline CFC-11 and CFC-12 use are developed using a model described in Palmer et al. (1980). Use includes the CFC used for charging new units, for testing at manufacture (about 5 percent of initial charge, falling over time), for replacing losses during shipping and installation (4 percent of initial charge), and for replacing leakage and servicing losses (about 7.5 and 10 percent of banked refrigerant, respectively; estimated servicing losses decline over time).

Table 6.7

ESTIMATED CURRENT AND PROJECTED REPORTING COUNTRY USE OF CFC-12 IN HOME REFRIGERATORS AND FREEZERS

(In mt)

Year	United States	Other Reporting Countries	Total Reporting Countries
1985	2,440	7,790	10,230
1990	2,660	10,520	13,180
1995	2,900	14,220	17,120
2000	3,190	19,200	22,390

[7]Refrigerating system capacities are traditionally rated in tons, where one ton is the amount of heat required to melt one ton of ice in 24 hours or 200 Btu per minute. A commercial or industrial building generally requires about one ton of cooling capacity for every 300 square feet of floor area.

Centrifugal Chillers

The choice of refrigerant in a centrifugal chiller is also a matter of size. CFC-11 is used in about 80 percent of the units, but these are primarily small units (less than 500 tons), requiring an estimated 350 kilogram average charge. CFC-12 is used in about 10 percent of the units, with an average charge estimated as 950 kilograms. The largest units (over 1,000 tons) are usually charged with CFC-22, CFC-114, or CFC-500—a blend containing 74 percent CFC-12. Average charges are declining slowly as manufacturers make evolutionary advances in chiller design and reduce leakage.

Table 6.8 presents historical estimates of domestically installed centrifugal chillers and attendant CFC-11 and CFC-12 use and our base projection for future use. The number of chillers grew steadily between 1976 and 1981 and then declined slightly, perhaps because of the recession. CFC use over the period increased by only about 10 percent because of a decrease in servicing losses from an estimated 16 percent of stocks in 1976 to about 10 percent in 1985. Note the slower growth in CFC use after 1985 because of projected further decreases in servicing losses, to 5 percent of stocks by 2000.

Table 6.8

ESTIMATED HISTORICAL AND PROJECTED U.S. CENTRIFUGAL CHILLER INSTALLATIONS AND USE OF CFC-11 AND CFC-12

Year	Centrifugal Chillers	CFC-11 (mt)	CFC-12 (mt)
1976	1,930	3,910	1,460
1977	1,910	3,900	1,430
1978	2,280	4,010	1,480
1979	2,350	4,020	1,480
1980	3,090	4,260	1,590
1981	3,580	4,440	1,670
1982	3,210	4,330	1,620
1983	3,470	4,400	1,650
1984	3,420	4,360	1,640
1985	3,580	4,380	1,650
1990	4,490	4,840	1,800
1995	5,260	4,950	1,830
2000	5,750	5,400	2,000

SOURCES: Chillers, 1976-1980, Mooz et al. (1982); 1981-1984, industry sources.

One trend that may reduce future use of CFC-11 in centrifugal chillers is the increasing use of one or more reciprocating chillers, most of which use CFC-22, instead of a single centrifugal unit. This trend is expected to continue as larger reciprocating units are manufactured. The use of multiple reciprocating chillers in place of a single centrifugal unit provides greater system reliability and allows continued cooling while one unit is being serviced. If this trend were to continue, use of CFC-11 might be reduced by one-third by the year 2000.[8]

We estimate current reporting country use relying on industry sources who suggest that the United States currently accounts for about 45 percent of CFC-11 and CFC-12 use in centrifugal chillers. Table 6.9 reports projected reporting country use. We assume that chiller sales for new construction grow at the rate of GNP both in the United States and abroad.

Uncertainty concerning future use of CFCs in centrifugal chillers centers on possible substitution to reciprocating chillers. We suggest that uncertainty about the total demand for cooling systems is comparable to uncertainty over GNP growth, whereas the quantities of CFC-11 and CFC-12 used in centrifugal chillers could decline by one-third by 2000 if reciprocating chillers take a significant share of the centrifugal market. These uncertainties combine to a range of 63 to 125 percent of the base projections.

Table 6.9

ESTIMATED CURRENT AND PROJECTED REPORTING COUNTRY USE OF CFC-11 AND CFC-12 IN CENTRIFUGAL CHILLERS

(In mt)

	United States		Other Reporting Countries		Total Reporting Countries	
Year	CFC-11	CFC-12	CFC-11	CFC-12	CFC-11	CFC-12
1985	4,380	1,650	5,520	2,080	9,900	3,730
1990	4,840	1,800	6,090	2,270	10,930	4,070
1995	4,950	1,830	6,510	2,410	11,460	4,240
2000	5,400	2,000	7,420	2,750	12,820	4,750

[8]If reciprocating chillers take half the market we project for centrifugal units, the stock of centrifugal chillers would be 20 percent smaller than projected. Since replacement of leakage and servicing losses account for 68 percent of CFC-11 use in 2000, use would be only about two-thirds the projected level.

Reciprocating Chillers

Smaller cooling systems, of less than about 150 tons capacity, typically employ reciprocating chillers. Although the systems were originally designed to use CFC-12, CFC-22 designs have been replacing the older units since the 1960s; today only about 2 percent of new units use CFC-12. The CFC-22 systems have about a 60 percent greater capacity than CFC-12 systems for the same physical size.

Table 6.10 presents estimated historic U.S. sales of reciprocating chillers and associated CFC-12 use and the base projection for future use. Note that in spite of the growth in the number of chillers, CFC-12 use declined precipitously as an increasing share of chillers used CFC-22. This decline is projected to continue as older units that use CFC-12 are replaced by new CFC-22 using units.

Table 6.11 reports the base projection for reporting country CFC-12 use in reciprocating chillers. Estimated current use is based on industry sources indicating that reporting country use of CFC-12 in reciprocating chillers is currently 3.6 times as large as U.S. use. We believe that growth in new reciprocating chillers outside the United States will be somewhat more rapid, 5 percent annually, because most other countries have concentrated on reciprocating instead of centrifugal chillers because of the lower production capital costs.

Uncertainty over total demand for chillers is comparable to uncertainty over GNP growth. Moreover, the level of CFC-12 use in chillers

Table 6.10

ESTIMATED HISTORICAL AND PROJECTED U.S. RECIPROCATING CHILLER INSTALLATIONS AND USE OF CFC-12

Year	Reciprocating Chillers	CFC-12 (mt)
1976	5,020	890
1977	6,970	830
1978	6,300	750
1979	6,850	670
1980	8,020	600
1985	9,300	280
1990	10,350	130
1995	11,100	90
2000	12,700	90

SOURCE: 1976-1980, Mooz et al. (1982).

Table 6.11

ESTIMATED CURRENT AND PROJECTED WORLD USE OF CFC-12 IN RECIPROCATING CHILLERS

(In mt)

Year	United States	Other Reporting Countries	Total Reporting Countries
1985	280	1,000	1,280
1990	130	510	640
1995	90	400	490
2000	90	450	540

could vary widely. If all new chillers used CFC-22, use of CFC-12 could decline to about half the base projection by 2000. Alternatively, if centrifugal chillers continue to be replaced by reciprocating units and significant substitution of CFC-22 does not occur, CFC-12 use could conceivably double. Combining these uncertainties produces a range of possible use in 2000 of 48 to 207 percent of the base projections.

Figures. 6.1 and 6.2 summarize the projected baseline use of CFC-11 and CFC-12 in refrigeration applications. Almost all of the use we have analyzed is of CFC-12, and the United States accounts for the majority of analyzed use because of widespread mobile air conditioning.

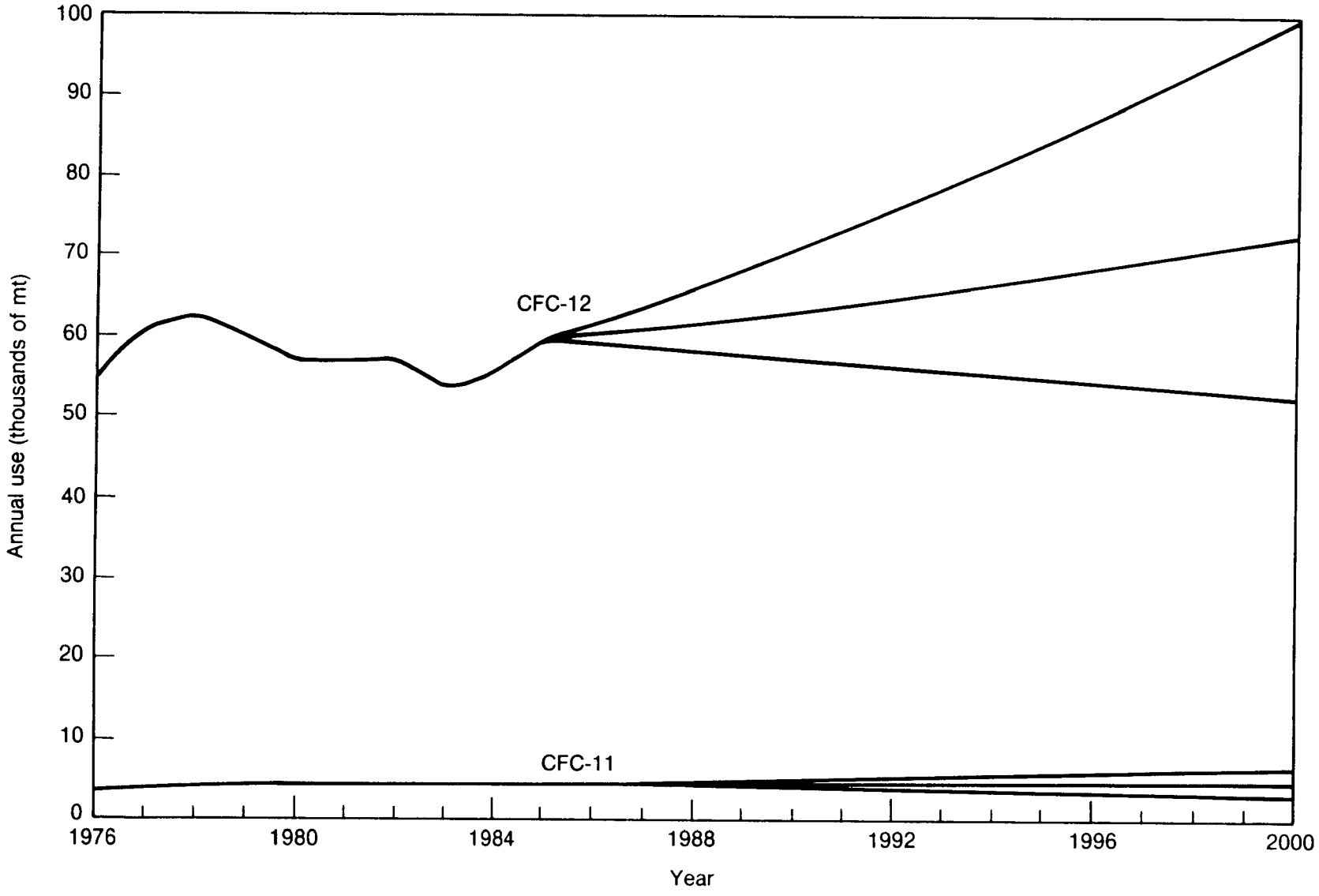


Fig. 6.1—Estimated historical and projected U.S. use of CFC-11 and CFC-12 in refrigeration and air conditioning

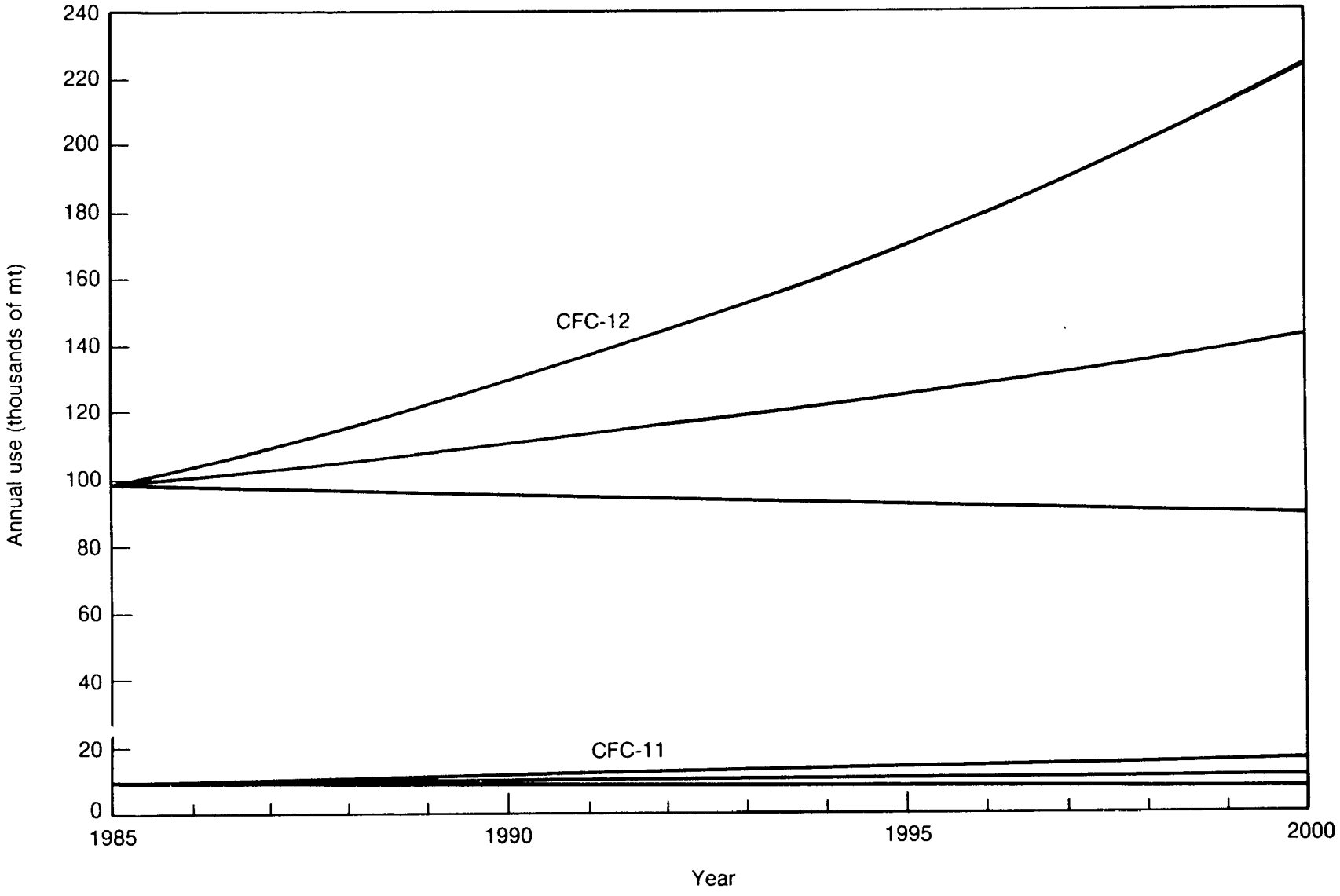


Fig. 6.2—Estimated current and projected reporting country use of CFC-11 and CFC-12 in refrigeration and air conditioning

VII. MISCELLANEOUS USES OF CFC-11 AND CFC-12

There are a variety of other applications that use small amounts of CFC-11 and CFC-12. Although the amount of CFC used in each specialty application alone is small, taken together such uses represent a significant fraction of CFC use. In what follows, we estimate the present and future use of CFC-11 and CFC-12 in miscellaneous applications. We do not attempt to construct ranges of uncertainty for these minor uses and present only point estimates for future years.

STERILANTS

CFC-12 is used as a diluent for ethylene oxide in hospital and industrial sterilants. In earlier work (Palmer et al., 1980; Mooz et al., 1982), Rand estimated U.S. use of CFC-12 in sterilants at 5,900 mt in 1976 and 6,800 mt in 1980. During that four year period the growth averaged 3.6 percent annually. Assuming the same rate of growth for the next five years would place 1985 use at about 8,000 mt.

Industry sources indicate that use of the ethylene oxide/CFC-12 blend will not increase in the future. Indeed, ethylene oxide, an animal carcinogen, may eventually be banned in sterilant applications. Accordingly, we assume no future growth. We arbitrarily assume that CFC-12 use in sterilants outside the United States accounts for an additional 8,000 mt and that this use will not grow.

LIQUID FOOD FREEZING

CFC-12 is used in a liquid food freezing process developed by DuPont. 1976 U.S. use was estimated at about 2,720 mt, with large future growth anticipated (Palmer et al., 1980). By 1980, the expected growth had not occurred and future growth was estimated at much lower levels (Mooz et al., 1982).

Using this information we estimate an average annual growth of 1 percent since 1976, placing 1985 use at 2,970 mt. Use in the other reporting countries is also small: We estimate that it is about equal to U.S. use.

Table 7.1 presents estimated CFC-12 use in liquid food freezing for the United States and other reporting countries. The projections were

Table 7.1

ESTIMATED CURRENT AND PROJECTED USE OF CFC-12 IN LIQUID FOOD FREEZING

(In mt)

Year	United States	Other Reporting Countries	Total Reporting Countries
1985	2,970	2,970	5,940
1990	3,530	3,530	7,060
1995	4,030	4,190	8,220
2000	4,600	4,980	9,580

derived assuming future growth at the projected regional GNP growth rates. Industry sources indicate that new LFF users are few and that CFC-12 use for this purpose may actually decline in the future.

OTHER MISCELLANEOUS APPLICATIONS

A variety of other applications use very small amounts of CFC-11 and CFC-12. They include CFC-12 use in fire and other warning devices, boat horns, dehumidifiers, pressurized blowers and drain cleaners, and trucking refrigeration, and CFC-11 use in coal cleaning. Total U.S. use in these applications was estimated at 450 mt of CFC-11 and 1,430 mt of CFC-12 in 1976 (Palmer et al., 1980). In Table 7.2 we provide estimates of current and future U.S. use based on growth at the GNP rate for all applications except coal cleaning. Industry sources indicate that this use has not grown and is unlikely to do so in the future. The table also presents estimated current and projected use of CFC-12 in the other reporting countries assuming that 1985 levels mirror those in the United States and that growth will occur at the same rate as the GNP. We do not include CFC-11 since we are not aware of its use for coal cleaning outside the United States.

Table 7.2

ESTIMATED CURRENT AND PROJECTED USE OF CFC-11 AND CFC-12 IN OTHER MISCELLANEOUS APPLICATIONS

(In mt)

	United States		Other Reporting Countries		Total Reporting Countries	
Year	CFC-11	CFC-12	CFC-11	CFC-12	CFC-11	CFC-12
1985	450	1,700	—	1,700	450	3,400
1990	450	2,020	—	2,020	450	4,040
1995	450	2,301	—	2,400	450	4,710
2000	450	2,640	—	2,850	450	5,490

VIII. SOLVENTS

CFC-113 and methyl chloroform are used primarily as solvents. Carbon tetrachloride was formerly used as a solvent but, at least in the industrialized countries, this use has been curtailed. It is also used as a grain fumigant, but that use has been discontinued in the United States. The chemical's major use is as an intermediate in the production of CFC-11 and CFC-12.

The use of solvents as "degreasers" is an important cleaning step in many manufacturing processes. Projections of future solvent use are especially uncertain because of the number of competing solvents and the possibilities for substitution among them as one or more are subjected to increasing regulation. Neither CFC-113 nor methyl chloroform has a dominant share of the overall solvent market, although each has a strong position in certain submarkets. CFC-113 is used primarily in the electronics industry, and methyl chloroform is used in a variety of applications from electronics to shipbuilding.

Most solvent uses can be described as either "cold cleaning," where the part to be cleaned is dipped into a tank of solvent, or "vapor degreasing," where the solvent is heated and the item to be cleaned is suspended in the vapor above the tank. In both types of cleaning the solvent displaces contaminants and then evaporates. Another use is drying, where the solvent is used to displace water. Solvent emissions are prompt, although equipment to recover and recycle the solvent can be used.

Use of methyl chloroform and CFC-113 may be strongly affected by government regulations. One factor that may discourage the use of these and other solvents is the U.S. ban on land disposal of waste chlorinated solvent, which becomes effective in November 1986. Some users may adopt more conservative practices or alternative cleaning processes, or substitute other solvents that have not been banned from land disposal to avoid much higher disposal costs. Alternatively, some of the competing solvents, such as trichloroethylene, perchloroethylene and methylene chloride, may be regulated more stringently because of concern over health risks to workers and the general population. (These solvents have been shown to cause chronic adverse health effects in animal studies.) Such restrictions could substantially increase demand for CFC-113 and methyl chloroform.

CFC-113

CFC-113 is used largely in the electronics industry, to deflux printed circuit boards and other metal components and for "critical cleaning" of plastic or specialty components, such as semiconductors, that are produced in a contamination-controlled environment. CFC-113 is more compatible with certain plastics than are other solvents: Without it many components could not be made of plastic. Small quantities are also used in chemical processing, as a blowing agent for foam production, as a specialty refrigerant, and for dry cleaning.

CFC-113 has several advantages over potential alternatives. First, it is a mild solvent, compatible with virtually all materials. Indeed, it is gentle enough to dry clean delicate suede and leather garments. Second, its TLV[1] in the workplace is 1,000 parts per million, the highest value assigned. This implies that costly methods of air circulation and dilution can be avoided. Third, CFC-113 is very stable, one of the characteristics that makes it a potential ozone depleter. Thus it can be used without stabilizing additives.

In Table 8.1 we present estimates of historical U.S. CFC-113 production and projected baseline future use. Because the chemical is produced by only two domestic producers, annual production data are not reported by the International Trade Commission. We estimated historical use as follows: The 1976 and 1977 values are from Palmer et al. (1980). The 1978 estimate was derived from a *Chemical Marketing Reporter* Chemical Profile on fluorocarbons indicating that solvent use amounted to 11 percent of total CFC use (*CMR*, 1978). Since virtually all solvent use is CFC-113, we estimate 1978 use as 11 percent of 1978 CFC production. Total CFC production is estimated from the ITC reports for CFC-11, CFC-12, and CFC-22, and a Rand estimate for CFC-114.[2]

For 1979, we based our estimate on a *Chemical Marketing Reporter* Chemical Profile on perchloroethylene, the precursor chemical used to produce CFC-113 and CFC-114 (*CMR*, 1979). The profile indicated that 13 percent of the chemical was used in CFC production. After subtracting the estimated amount used to produce CFC-114 the amount of CFC-113 produced can be estimated using the appropriate stochiometric equations (see Wolf, 1980).

---

[1]The Threshold Limit Value is the maximum allowable time-weighted average concentration to which a worker may be exposed over an eight-hour working day, 40-hour work week, as determined by the U.S. Occupational Safety and Health Administration (OSHA). Generally, the more toxic the chemical, the lower the TLV.

[2]Total CFC-113 use exceeds solvent use by the small amounts used as refrigerants and in plastic foams.

Table 8.1

ESTIMATED HISTORICAL AND PROJECTED U.S. USE OF CFC-113

(In mt)

Year	CFC-113
1976	31,300
1977	36,740
1978	39,010
1979	49,900
1980	57,150
1981	57,150
1982	57,150
1983	57,150
1984	68,040
1985	73,200
1990	105,600
1995	134,800
2000	172,000

The 1984 production estimate is from industry sources. The values for 1980 through 1983 are more uncertain. CFC-113 production during that time may have been as high as 59,870 mt (EPA, 1981) or as low as 57,150 mt (industry sources). We adopt the latter estimate and assume that the market was flat for the period because of the recession.

The estimates in Table 8.1 suggest that CFC-113 use more than doubled between 1976 and 1984. We expect future growth to be high as well. In the absence of the ban on land disposal of waste chlorinated solvents, CFC-113 use in defluxing and critical cleaning (about 50 percent of current use) would be expected to grow at the rate of other chemicals used in the electronics industry, 13 percent over the next several years.[3] As a base projection, we assume that defluxing and critical cleaning use grow at only 10 percent between 1984 and 1990 to account for the land disposal ban. We assume that the other CFC-113 applications grow at a lower rate, 5 percent through 1990. Combining these markets implies overall growth averaging 7.6 percent annually. Because industry sources expect the electronics industry to continue to grow more rapidly than GNP for an extended period, we project baseline CFC-113 use in all applications to grow at an average of 5 percent annually between 1990 and 2000.

[3]See Stinson (1983), *CMR* (1984), *Mining Journal* (1985), and *Manufacturing Chemist and Aerosol News* (1985).

Industry sources suggest that 1984 CFC-113 use in the EEC was less than 45,000 mt; we assume 40,000 mt. Japanese production of all CFCs is about 150,000 mt[4] of which CFC-11 and CFC-12 account for 110,000 mt.[5] Almost all of the remaining 40,000 mt should be CFC-113 and CFC-114; we assume that CFC-113 production is 35,000 mt. Finally, we assume that production in the other reporting countries outside the EEC and Japan is nominal, about 10,000 mt. This leads to an estimated 85,000 mt in the CMA reporting countries outside the United States.

Our base projections for reporting country CFC-113 production are reported in Table 8.2. Outside the United States, we project baseline growth of 9.3 percent for the period 1984 through 1990. This rate is based on one-half the market (defluxing and critical cleaning) growing at 13 percent, as U.S. use would in the absence of the land disposal ban, and the other half at 5 percent. After 1990, we assume an average annual rate of 6 percent growth in the baseline, about 70 percent higher than the expected GNP growth rate, to account for the fast growing electronics industry.

United States CFC-113 use may be lower than our projected base use if the impending ban on land disposal affects CFC-113 use more than we have estimated. Two of the most likely alternatives to land disposal are reclamation and incineration. Once the ban goes into effect there may be insufficient reclamation capacity to handle the greatly increased demand. Indeed, today only a handful of reclaimers in the country can properly reclaim CFC-113. The fluorine in CFC-113

Table 8.2

ESTIMATED CURRENT AND PROJECTED REPORTING COUNTRY USE OF CFC-113

(In mt)

Year	United States	Other Reporting Countries	Total Reporting Countries
1985	73,200	85,000	158,200
1990	105,600	132,600	238,200
1995	134,800	177,400	312,200
2000	172,000	237,500	409,500

[4]Ministry of International Trade and Industry data as supplied by Japan Flon Gas Association (private communication, 1985).

[5]Taya (1985).

apparently corrodes the refractory material lining incinerators, and industry sources report that incinerator owners charge dearly for fluorinated chemicals or refuse to accept them altogether. Consequently, it is possible that substitution and increased reclamation might reduce U.S. CFC-113 production by a third. Alternatively, regulation of trichloroethylene, perchloroethylene, and methylene chloride use could increase demand for CFC-113 by half. We believe that outside the United States any regulations are likely to have a smaller effect, since the existence and stringency of regulations will differ across nations. However, future growth in solvent use is more uncertain so we also assume a range of plus one-half or minus one-third.

METHYL CHLOROFORM

Although it is not a particularly strong potential ozone depleter, methyl chloroform is produced in large quantities. In the United States, it is used primarily for vapor degreasing and cold cleaning of electronic and other parts, although small amounts are used in adhesives, aerosols, and coatings. Methyl chloroform is a general purpose solvent that has certain advantages over its competitors. Its TLV, although lower than that of CFC-113, is higher than that of other chlorinated solvents. It is a stronger solvent than CFC-113 and is consequently not compatible with all materials. However, because it is stronger it can clean contaminants that CFC-113 cannot remove. A recently marketed blend of methyl chloroform and alcohol has made some inroads into the electronics market.

Table 8.3 reports U.S. methyl chloroform production between 1976 and 1984 and projected use. Note that production increased 16 percent over the period, an average of about 1.9 percent annually.

We estimate 1985 U.S. use of methyl chloroform as 270,000 mt. This estimate is based on the trend in reported production since 1979 and is derived in Appendix A. Since methyl chloroform is a widely used general purpose solvent we would expect use to grow at the same rate as the GNP in the absence of the land disposal ban. Because of the ban we assume a slightly lower growth, 3 percent between 1986 and 1990 and 2 percent through 2000 (compared with expected GNP growth of 3.5 and 2.7 percent, respectively). Before the ban's implementation in 1986 we assume growth at the GNP rate.

Industry sources indicate that 1980 U.S. production represented 59 percent of total world production outside the communist countries. If we assume this same relationship for 1985, we obtain the values shown in Table 8.4. We project baseline growth outside the United States at the same rate as GNP, 3.5 percent annually.

Table 8.3

ESTIMATED HISTORICAL AND PROJECTED U.S. USE OF METHYL CHLOROFORM

(In mt)

Year	Methyl Chloroform
1976	266,000
1977	288,000
1978	292,000
1979	325,000
1980	314,000
1981	279,000
1982	270,000
1983	266,000
1984	303,000
1985	270,000
1990	314,500
1995	347,300
2000	383,400

SOURCE: U.S. ITC (1976-1984).

Projected methyl chloroform use is subject to the same types of uncertainty as CFC-113 use. The land disposal ban may cause users to reduce their use of methyl chloroform (through reclamation, for

Table 8.4

ESTIMATED CURRENT AND PROJECTED REPORTING COUNTRY USE OF METHYL CHLOROFORM

(In mt)

Year	United States	Other Reporting Countries	Total Reporting Countries
1985	270,000	187,600	457,600
1990	314,500	222,800	537,300
1995	347,300	264,600	611,900
2000	383,400	314,300	697,700

example) or to switch to other solvents or processes. Alternatively, regulation of alternative chlorinated solvents, including methylene chloride, trichloroethylene, and perchloroethylene, could substantially increase domestic use of methyl chloroform. Since methyl chloroform is used in a wider range of applications than CFC-113, its use is less sensitive to trends in particular industries and the range of uncertainty should be smaller. We suggest a range of uncertainty of 80 to 125 percent of the base projection, conditional on GNP. Combined with the uncertainty about GNP growth, the overall range of uncertainty is 0.73 to 1.37 times the base projection for the United States and for the other reporting countries.

CARBON TETRACHLORIDE

Carbon tetrachloride is an excellent solvent in many applications. At one time, it was widely used as a solvent in the United States. Because of its acute and chronic toxicity, however, it is used only in small amounts for such purposes today. Although our information on carbon tetrachloride use in the rest of the world is limited, we suspect that carbon tetrachloride is commonly employed as a general purpose solvent in many developing nations.

Carbon tetrachloride's major use in the United States and most of the rest of the world is as an intermediate in the production of CFC-11 and CFC-12. A second large use in this country has been for grain fumigation. Domestic producers have voluntarily agreed to halt production for this application beginning in 1986, however. Additional small amounts are used in the pharmaceutical industry.

Table 8.5 shows historical U.S. production of carbon tetrachloride and the fraction used to produce CFCs. Note the sharp decline in 1982 and 1983 because of the recession. Demand for CFC-11 and CFC-12 was off strongly for that period, and because a high percentage of carbon tetrachloride is devoted to CFC manufacture, its total production declined as well (*CMR*, 1983).

Table 8.6 presents estimated future carbon tetrachloride production using the base projections for United States and other reporting country CFC-11 and CFC-12 production. The estimates are based on the stochiometric equations for CFC production. These imply that production of one kilogram of CFC-11 requires 1.12 kilograms of carbon tetrachloride and that one kilogram of CFC-12 requires 1.27 kilograms (see Wolf, 1980). We estimate that additional losses in the production process amount to 2.7 percent of total use in CFC production, whereas other uses, not including grain fumigation, account for an estimated

Table 8.5

ESTIMATED HISTORICAL U.S. USE OF CARBON TETRACHLORIDE

(In mt)

Year	Carbon Tetrachloride	% Used To Produce CFCs
1976	389,000	—
1977	366,000	—
1978	334,000	95
1979	324,000	—
1980	322,000	—
1981	329,000	95
1982	266,000	—
1983	260,000	83.6[a]
1984	323,000	—

SOURCES: U.S. ITC (1976-1984); *CMR* (1978, 1981, 1983).

[a]The share allocated to CFC production decreased in 1983 because a large fraction of carbon tetrachloride was exported.

Table 8.6

ESTIMATED CURRENT AND PROJECTED REPORTING COUNTRY USE OF CARBON TETRACHLORIDE

(In mt)

Year	United States	Other Reporting Countries	Total Reporting Countries
1985	280,000	590,000	870,000
1990	323,200	668,500	991,700
1995	373,100	757,300	1,130,400
2000	430,700	857,700	1,288,400

additional 5.4 percent of total use. The resulting U.S. estimate, 277,000 mt, almost exactly matches the 280,000 mt estimate derived from reported production in recent years (see Appendix A). Since almost all carbon tetrachloride is used for CFC production the uncertainty about future production is based on uncertainty about future production of CFC-11 and CFC-12. Specifically, the range is based on the average of

the ranges of total CFC-11 and CFC-12 production and spans the interval from 0.76 to 1.32 times the projected base level in the United States and from 0.73 to 1.37 times the base projection for the other reporting countries.

Historical and projected consumption of CFC-113, methyl chloroform, and carbon tetrachloride are summarized in Fig. 8.1 for the United States and in Fig. 8.2 for the CMA reporting countries. Note that U.S. use of methyl chloroform about equals that of carbon tetrachloride, but carbon tetrachloride use far exceeds estimated methyl chloroform use in the reporting countries. This difference is due in part to the relatively low U.S. use of CFC-11, compared with the other reporting countries, and consequently lower carbon tetrachloride use.

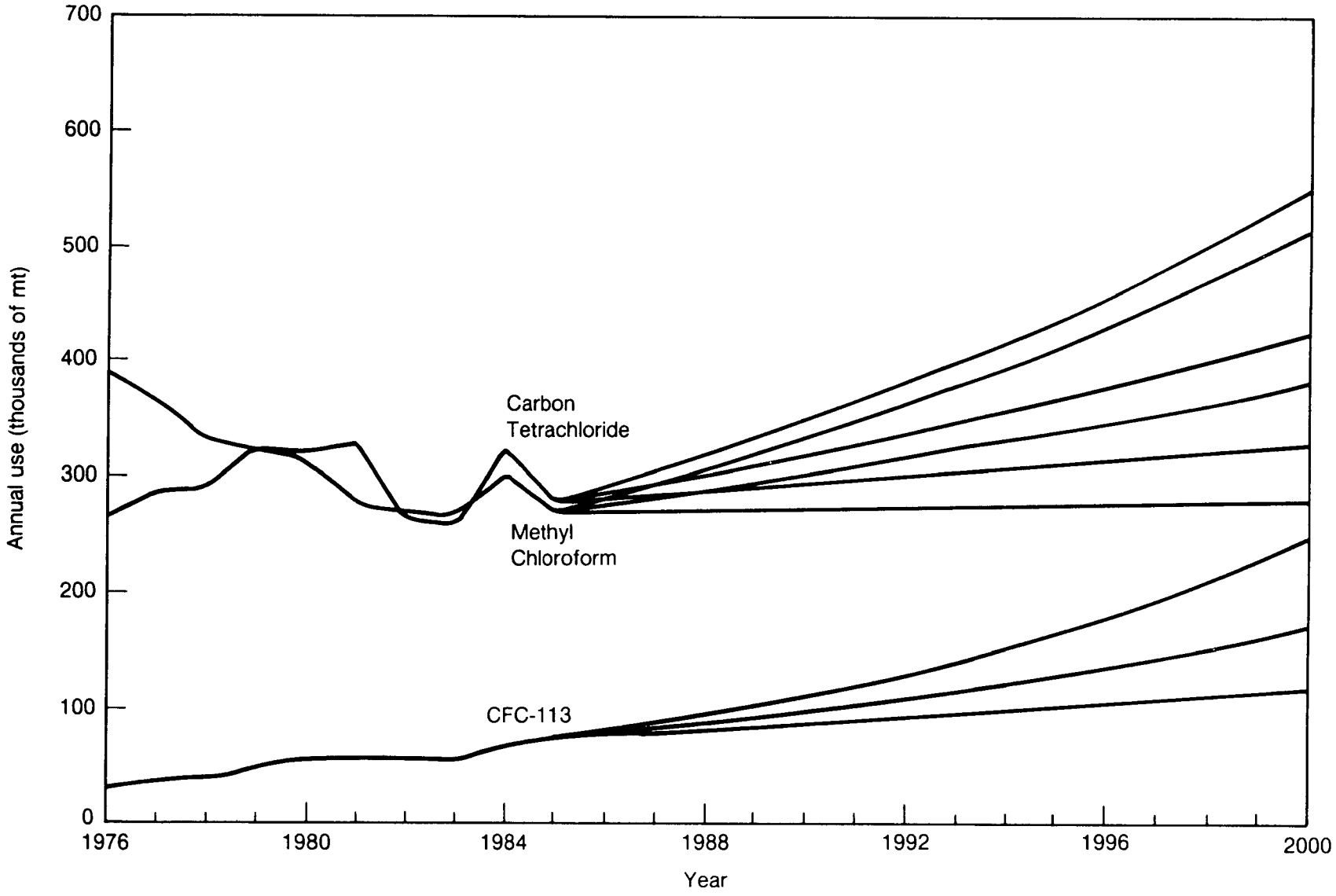


Fig. 8.1—Estimated historical and projected U.S. use of CFC-113, methyl chloroform, and carbon tetrachloride

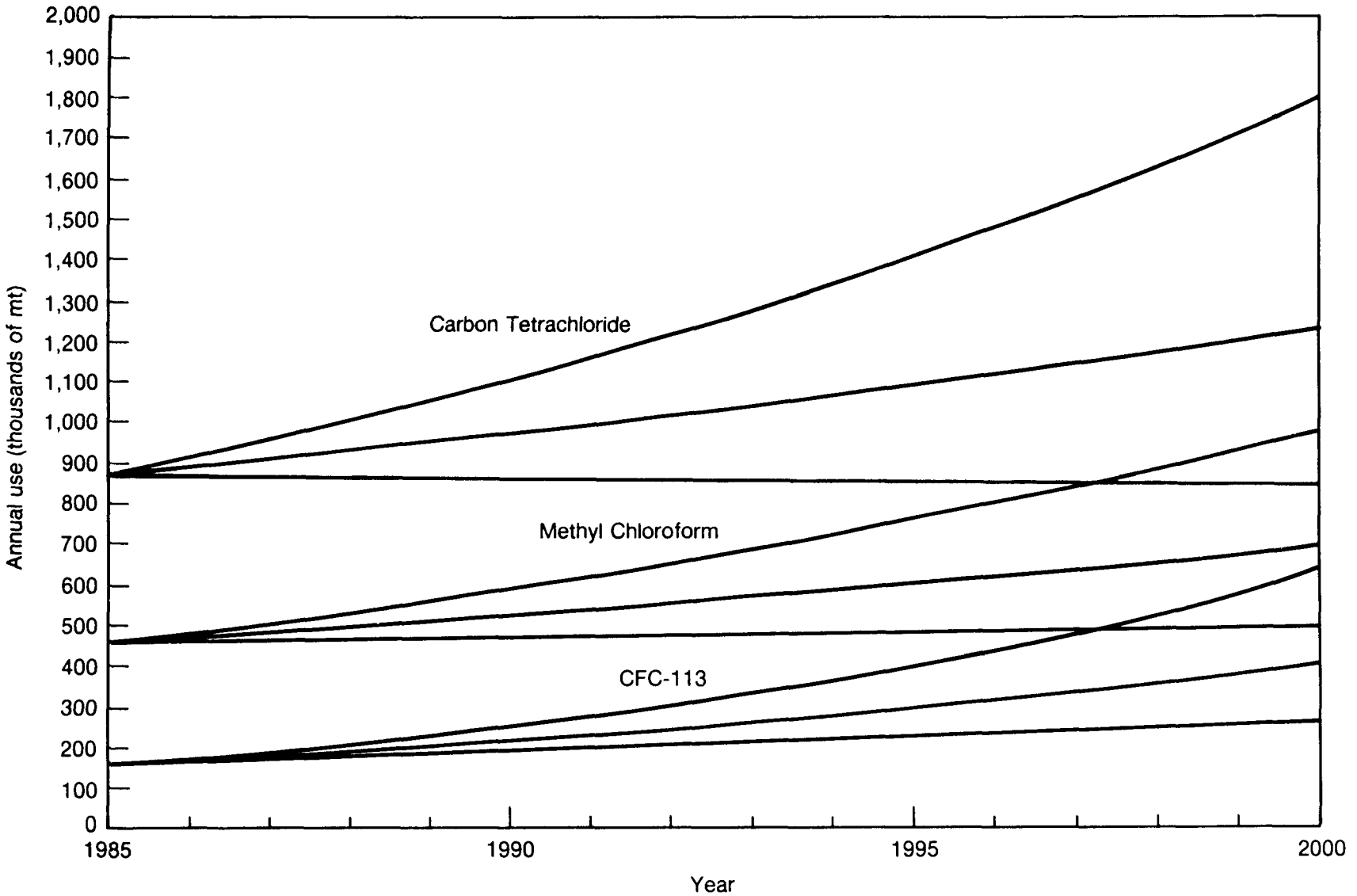


Fig. 8.2—Estimated current and projected reporting country use of CFC-113, methyl chloroform, and carbon tetrachloride

IX. FIRE EXTINGUISHANTS

Halons 1211 and 1301 were introduced for use as fire extinguishants in the United States in the early 1970s. Although total production is presently small relative to the other chemicals we consider, use is expected to grow rapidly. Moreover, since the Halons contain bromine they may present a much greater threat to the stratospheric ozone than do similar chlorinated chemicals.

Halon 1301 is used primarily in total flooding systems that protect valuable equipment and materials in enclosed spaces. These systems release a preset quantity of the gas from a pressurized cylinder in the event of a fire. Although Halon 1301 is relatively expensive it leaves no residue and does not damage valuable equipment. Moreover, unlike other extinguishants, it can be released before workers are evacuated from the room, thereby reducing fire damage. It is used primarily in computer rooms, telephone exchanges, pipeline compressor and pumping stations, airliners, some libraries and museums, battle tanks, and ship engine and boiler rooms. In the late 1970s more than 80 percent was used in computer rooms, telephone exchanges, and other rooms containing electronic equipment (DuPont, 1978). Halon 1301 is also being introduced into the hand-held extinguisher market for home and commercial use, and small quantities are used as a specialty refrigerant.

Halon 1211 is used primarily in hand-held fire extinguishers. It is also used in U.S. Air Force rapid intervention crash trucks.

Nearly the entire quantity of Halons produced in a year is banked in total flooding systems or other fire extinguishers. Emissions occur when the system is activated during a fire and from system testing, filling and servicing, leakage, and accidental discharges. Losses through accidental discharge are likely to be more significant for hand-held extinguishers than for the total flooding systems. Since the Halons are so expensive it is likely that the amounts stored in total flooding systems will often be recovered and re-used when the system is dismantled, so much of the bank may never be released to the atmosphere.

HISTORICAL U.S. USE

Table 9.1 presents estimated historical U.S. use of Halon 1301. We have little information on past use of Halon 1211, but suspect it is similar. Approximately 95 percent of annual Halon 1301 use is attributed to total flooding systems with the remaining 5 percent going to hand-held extinguishers, specialty refrigeration, and other uses.

The historical use estimates assume the introduction of 2,600 new systems each year beginning in 1972 and reaching a total of 13,000 systems in 1978. Subsequent growth was rapid: an estimated 30 percent annually during 1978 and 1979, falling to 25 percent in 1980 and 1981, to 15 percent in 1982 and 1983, and recovering to 20 percent in 1984 with the end of the recession. The estimates are consistent with estimates by industry sources that U.S. use in 1977 was between 1,100 and 1,400 mt and that use in recent years was 3,400 to 4,500 mt.

Although there is considerable uncertainty about the average system charge, industry sources indicate that it was quite high in the early years and has since fallen. Accordingly, we adopt an average system charge of 340 kilograms (750 pounds) for all new systems through 1983, falling to 318 kilograms in 1984.

Table 9.1

ESTIMATED HISTORICAL
U.S. USE OF
HALON 1301

(In mt)

Year	Use
1973	1,200
1974	1,200
1975	1,200
1976	1,200
1977	1,200
1978	1,600
1979	2,100
1980	2,600
1981	3,200
1982	3,700
1983	4,300
1984	4,800

The estimated use figures in Table 9.1 include: the Halon 1301 used to charge new units; use for testing, estimated at 19 percent of the initial charge; replacement of filling and servicing losses, estimated at 1 percent of the initial charge; replacement of leakage, estimated at 0.1 percent of the bank; replacement of Halon 1301 at system failure, estimated at 1 percent of the bank; and discharge during fire, estimated at 1 percent of the bank.

Halon 1301 use for system testing may increase substantially from its current estimated use of 19 percent of initial charge. Currently, three-quarters of new systems are tested, three-quarters of these using CFC-12, but installers are beginning to test with the Halon more frequently for two reasons. First, although it had been believed that an 82 percent charge of CFC-12 mimics a 100 percent charge of Halon 1301, recently it has become apparent that the hydraulics of the two chemicals differ as they move through the pipes of the flooding system. Second, and more important, CFC-12 at high concentrations has an anesthetic effect. To properly test a flooding system a gas concentration of 5 percent must be held in the room for 10 minutes. Because service workers have complained of headaches from CFC-12-filled rooms, some are moving toward Halon 1301 in spite of its much higher price.

CURRENT AND FUTURE REPORTING COUNTRY USE

In the United States, growth in new systems has remained high, an estimated 20 percent between 1984 and 1985. For the base projection we assume that rapid growth will continue at rates averaging 15 percent through 1988. By then, many existing computers will be protected by total flooding systems and growth is projected to decline to an average of 7 percent annually until 2000. In the base projection, the average system charge is also projected to decrease, from 320 kilograms in 1984 to 180 kilograms by 2000, as the systems are placed in progressively smaller installations (partly as a result of increasing miniaturization of computers and other electronic equipment). Combining these effects and the implied testing, servicing, and loss projections implies annual U.S. production of 10,200 mt by 2000.

Table 9.2 shows the U.S. baseline projections together with our estimates of reporting country Halon 1301 use. Relying on industry sources, we use a base projection for total reporting country use twice that in the United States.

These estimates and projections are subject to considerable uncertainty. Halon total flooding systems are a substantial improvement

Table 9.2

ESTIMATED CURRENT AND PROJECTED
REPORTING COUNTRY USE OF HALON 1301

(In mt)

Year	United States	Other Reporting Countries	Total Reporting Countries
1985	5,400	5,400	10,800
1990	6,700	6,700	13,300
1995	8,300	8,300	16,500
2000	10,200	10,200	20,400

over earlier fire-protection systems and it is difficult to estimate how widely they will be used. The average charge is subject to significant uncertainty depending on the types of future installations. Increased use of the Halon for testing could lead to substantially greater chemical use. To account for these factors we suggest a range of uncertainty between 0.6 and 1.67 times the base levels, for both the United States and abroad.

Estimated current use of Halon 1211, and its base projection, are shown in Table 9.3. Halon 1211 is used primarily in hand-held extinguishers. According to industry sources worldwide use is about equal to that of Halon 1301, but the United States accounts for only one-quarter of the total. For our base projection we assume that future use

Table 9.3

ESTIMATED CURRENT AND PROJECTED
REPORTING COUNTRY USE OF HALON 1211

(In mt)

Year	United States	Other Reporting Countries	Total Reporting Countries
1985	2,700	8,100	10,800
1990	3,300	10,000	13,300
1995	4,100	12,400	16,500
2000	5,100	15,300	20,400

will grow at the same rate as Halon 1301 and suggest a range of uncertainty between 0.6 and 1.67 times the base projected use.

United States use and reporting country use of Halons 1211 and 1301 are summarized in Fig. 9.1. The projected baseline growth is strong but the range of uncertainty includes the possibility of almost no growth.

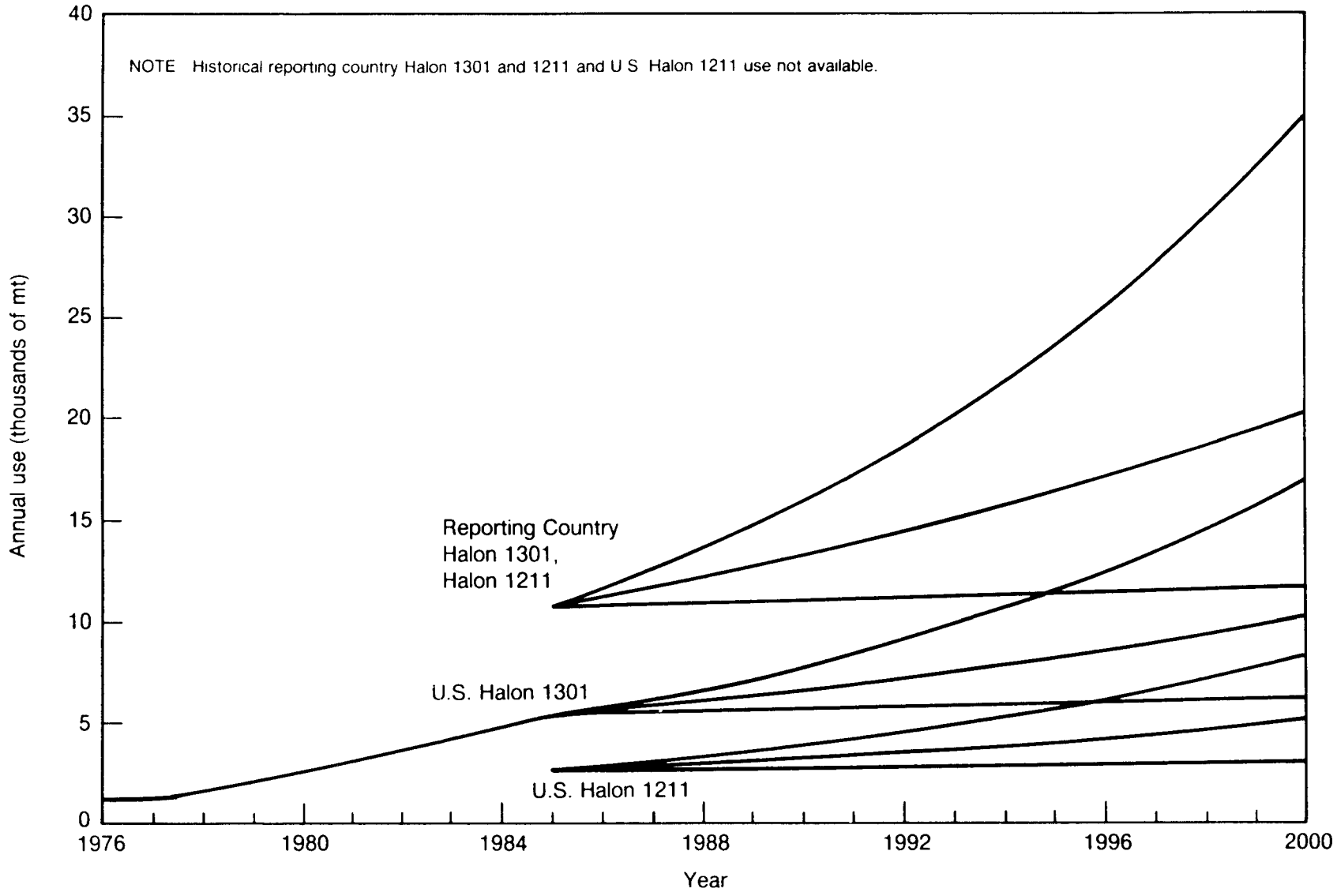


Fig. 9.1—Estimated historical and projected U.S. and reporting country use of Halon 1301 and Halon 1211

X. USE OF POTENTIAL OZONE DEPLETERS IN THE COMMUNIST COUNTRIES

Available data on use of potential ozone-depleting substances in the communist countries are extremely limited. The only published estimates are for Soviet Union use of CFC-11 and CFC-12 from 1968 through 1975. However, we believe that the Soviet Union accounts for the majority of use in these countries. Our approach to estimating base projections for CFC-11 and CFC-12 is to estimate total use by extrapolating from these historical data. Since we have little information on the pattern of CFC uses, we do not explicitly estimate communist country use by application.

The estimates of current solvent use are similarly uncertain. Carbon tetrachloride use is based on estimated CFC-11 and CFC-12 use. The methyl chloroform estimate assumes that communist country use relative to GNP is the same as the corresponding ratio in the reporting countries, whereas the CFC-113 estimate is based on industry sources who suggest that communist use of this solvent is quite small. Since we have no information that Halon 1301 and 1211 are even used in the communist countries, and because their use in the reporting countries is so small, we assume that use in the communist countries is negligible.

Our lack of information on potential ozone-depleter use in the communist countries is too great to treat the structure of uncertainty in detail. Our uncertainty ranges are based on our ranges for use of each chemical in the CMA reporting countries excluding the United States. To reflect our greater uncertainty about use in the communist countries, the uncertainty ranges are constructed so that the variance of use, conditional on the level of the GNP, is 1.25 times greater than the corresponding variance for the non-U.S. reporting countries. As described in Sec. II, our uncertainty range for communist country GNP is also wider than for the reporting countries.

CFC-11 AND CFC-12 USE

Table 10.1 presents estimated CFC-11 and CFC-12 production in the Soviet Union from 1968 through 1975 and base projections for the communist countries from 1985 to 2000. The production estimates were originally published in a Soviet journal (Borisenkov and Kazakov,

1980) and are reprinted in the CMA reports. Reported growth was very strong: 27 and 18 percent average annual growth rates for CFC-11 and CFC-12, respectively. Such high rates are unlikely to have been sustained in later years. For the period 1975 to 1985 we assume that use grew at rates 10 percent less than the historical rates, 17 and 8 percent per year, respectively. In addition, we assume that total communist country use is 15 percent greater than use in the Soviet Union (the same assumption as CMA used in their 1983 report). These assumptions lead to estimated 1985 communist country use of 41,500 and 78,700 mt of CFC-11 and CFC-12. These estimates are roughly consistent with estimates by other sources but are clearly more uncertain than our estimates for other regions.

Beyond 1985 we project CFC-11 to grow at an average rate of 6 percent through the end of the century and CFC-12 at an average rate of 5 percent. These rates are 2.0 and 1.67 times the base projected GNP growth rate (3.0 percent). Such high rates are justified by the level of development of the communist economies, a level at which uses of CFC-containing products are likely to grow rapidly, and by the historically strong growth. We suspect that CFC-11 will grow more rapidly

Table 10.1

ESTIMATED HISTORICAL SOVIET UNION AND PROJECTED COMMUNIST COUNTRY USE OF CFC-11 AND CFC-12

(In mt)

Year	CFC-11	CFC-12
	Soviet Union	
1968	1,400	9,800
1969	2,200	12,200
1970	2,500	13,500
1971	2,900	16,200
1972	3,700	18,500
1973	4,100	20,100
1974	6,200	25,900
1975	7,500	31,700
	Communist Countries	
1985	41,500	78,700
1990	55,500	100,400
1995	74,200	128,200
2000	99,400	163,600

than CFC-12 because the estimated 1985 use of CFC-12 is so much higher than that of CFC-11 (compared with the pattern in other regions) and because our analysis of specific applications suggests that CFC-11 use will grow more rapidly than CFC-12 use in other world regions. Estimated historical and projected use is depicted in Fig. 10.1.

SOLVENT USE

Table 10.2 reports our estimates of current and projected solvent use in the communist countries. Because we have no information to the contrary, and because CMA reporting country use of Halon 1301 and Halon 1211 is small, we assume that communist country use of these chemicals is negligible.

Current use of CFC-113 in the communist countries is believed to be modest at best, although some is likely to be used in manufacturing military and scientific electronic equipment. We estimate a nominal 5,000 mt. The baseline projection is based on projected growth in the non-U.S reporting countries: The difference between the baseline CFC-113 and GNP growth rates is the same as for these countries. Thus the baseline projection for the communist countries is 6.6 percent for the next 15 years, 3.6 percent higher than the projected GNP growth rate. The range of uncertainty is similarly based on the range for the non-U.S. reporting countries. Combined with uncertainty about the level of the GNP, the range is from 0.62 to 1.62 times the base projection.

Since methyl chloroform is a popular general purpose solvent in the reporting countries, we suspect it is also widely used in the communist countries. We estimate current use by assuming that the ratio of methyl chloroform use to GNP is the same as for the reporting countries. Thus communist use is estimated as 16 percent of world use, or 87,000 mt. In the reporting countries other than the United States, methyl chloroform is projected to grow at the same rate as the GNP. We adopt the same assumption for the communist countries, implying a baseline projected rate of 3 percent annually. The corresponding range of uncertainty is from 0.68 to 1.47 times the base projection in 2000.

The estimated current and projected use of carbon tetrachloride is based on the CFC-11 and CFC-12 estimates, using the same assumptions about other uses as for the reporting countries. Estimated current use is 162,700 mt, with a projected baseline growth rate of 5.2 percent. The range of uncertainty is between 0.68 and 1.47 times the projected base level.

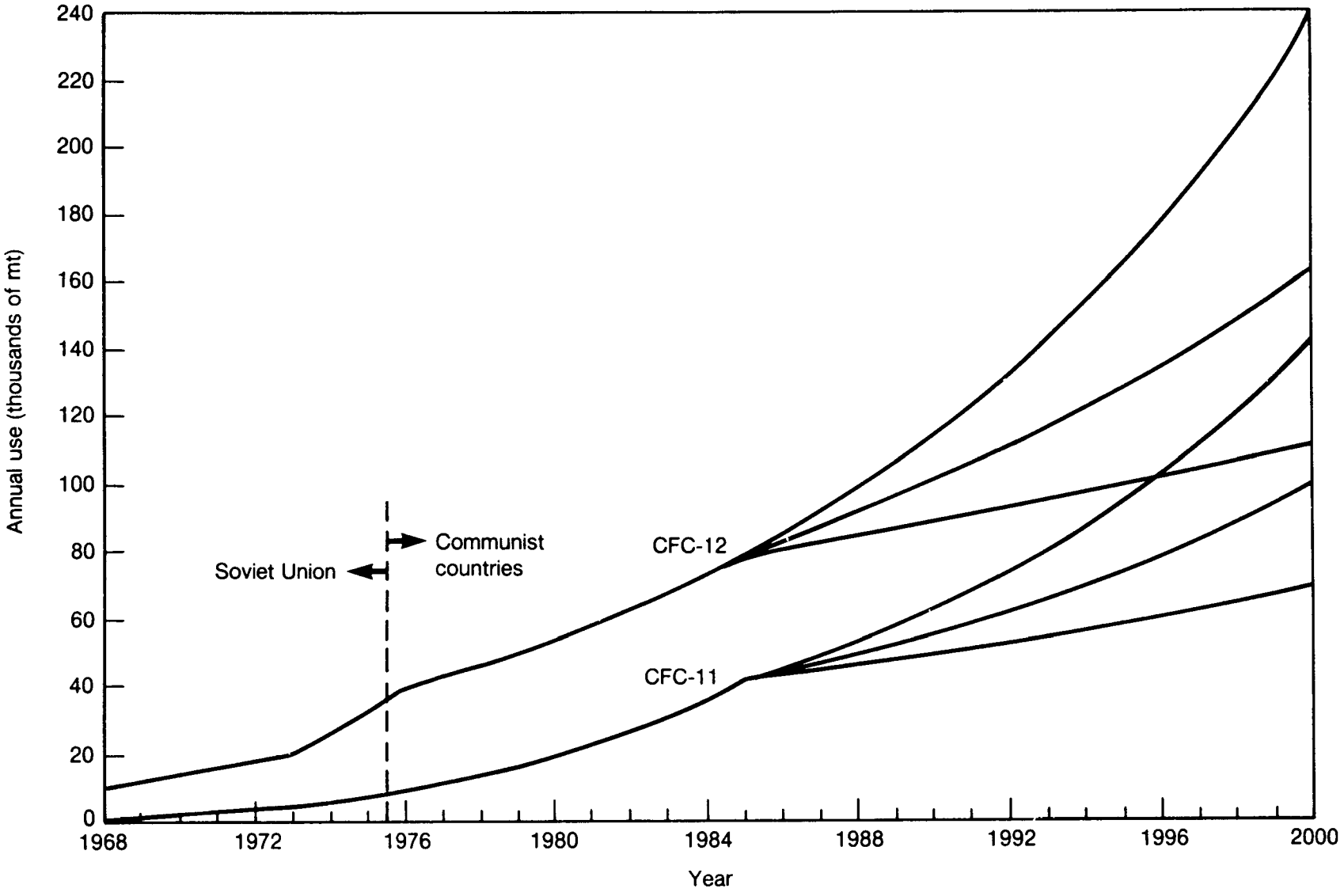


Fig. 10.1—Estimated historical and projected use of CFC-11 and CFC-12 in the communist countries

Table 10.2

ESTIMATED CURRENT AND PROJECTED COMMUNIST COUNTRY USE OF CFC-113, METHYL CHLOROFORM, AND CARBON TETRACHLORIDE

(In mt)

Year	CFC-113	Methyl Chloroform	Carbon Tetrachloride
1985	5,000	87,000	159,000
1990	6,900	100,900	205,900
1995	9,500	116,900	267,000
2000	13,000	135,500	346,400

XI. CONCLUSIONS

We are now in a position to aggregate all of the details of the preceding sections into global projections. This report examines the current and likely future global production levels of the seven most important potential ozone depleters—CFC-11, CFC-12, CFC-113, carbon tetrachloride, methyl chloroform, Halon 1211, and Halon 1301. It starts by looking at the products in which these chemicals are used in the United States and the other CMA reporting countries. It asks how demand for these products and hence derived demand for the chemicals themselves is likely to change over the next 15 years. It then posits similar, but much less detailed and confident, demand trends for the communist countries. This product-based or "bottom-up" approach cannot capture the full demand for CFC-11 and CFC-12; hence the report examines the magnitude of the uses not accounted for by the method and develops a way to project these unallocated uses into the future. By aggregating projections of demand for each chemical in the United States, other reporting countries, and communist countries, as well as projections of the likely shortfalls for CFC-11 and CFC-12, we can develop global projections for each chemical. This section reports those global projections and suggests some directions for future work.

UNITED STATES AND GLOBAL PROJECTIONS

Tables 11.1 and 11.2 summarize estimated current and projected U.S. and total world use of the seven potential ozone depleters we have analyzed. The tables present the range of projected use in 2000 and the average annual growth rates from 1985 to 2000 implied by these limits. In addition, Fig. 11.1 and Fig. 11.2 illustrate the estimated historical and projected use of CFC-11 and CFC-12 in the United States and CMA reporting countries. (Figures illustrating use of the other chemicals are in preceding sections.) Much of the evident decline in CFC-11 and CFC-12 use in the late 1970s was due to the discontinuation of CFC use in many aerosol products in the United States and elsewhere. As discussed in Sec. II, the bounds of the ranges of uncertainty reported in the tables and figures are meant to capture a "reasonable range" of outcomes for each chemical. The reader should keep in mind that this is not an exact concept.

The projections for total CFC-11 and CFC-12 use are aggregated from the projections for the specific applications we analyze. In

Table 11.1

ESTIMATED CURRENT AND PROJECTED U.S. USE OF POTENTIAL OZONE-DEPLETING SUBSTANCES

	Use (thousands of mt)			Average Annual Growth Rate (%)	
		Projected in 2000			
Chemical	1985	Lower	Upper	Lower	Upper
CFC-11	75.0	110	190	2.6	6.3
CFC-12	135.0	140	240	0.4	4.0
CFC-113	73.2	120	270	3.6	9.1
Methyl chloroform	270.0	300	560	0.7	5.0
Carbon tetrachloride	280.0	350	600	1.5	5.2
Halon 1301	5.4	7	18	1.4	8.3
Halon 1211	2.7	3	9	1.4	8.3

Table 11.2

ESTIMATED CURRENT AND PROJECTED WORLD USE OF POTENTIAL OZONE-DEPLETING SUBSTANCES

	Use (thousands of mt)			Average Annual Growth Rate (%)	
		Projected in 2000			
Chemical	1985	Lower	Upper	Lower	Upper
CFC-11	341.5	420	730	1.4	5.2
CFC-12	443.7	460	830	0.3	4.3
CFC-113	163.2	290	610	3.9	9.2
Methyl chloroform	544.6	630	1100	0.9	5.0
Carbon tetrachloride	1029.0	1200	2100	0.8	4.8
Halon 1301	10.8	13	33	1.1	7.6
Halon 1211	10.8	12	32	0.9	7.6

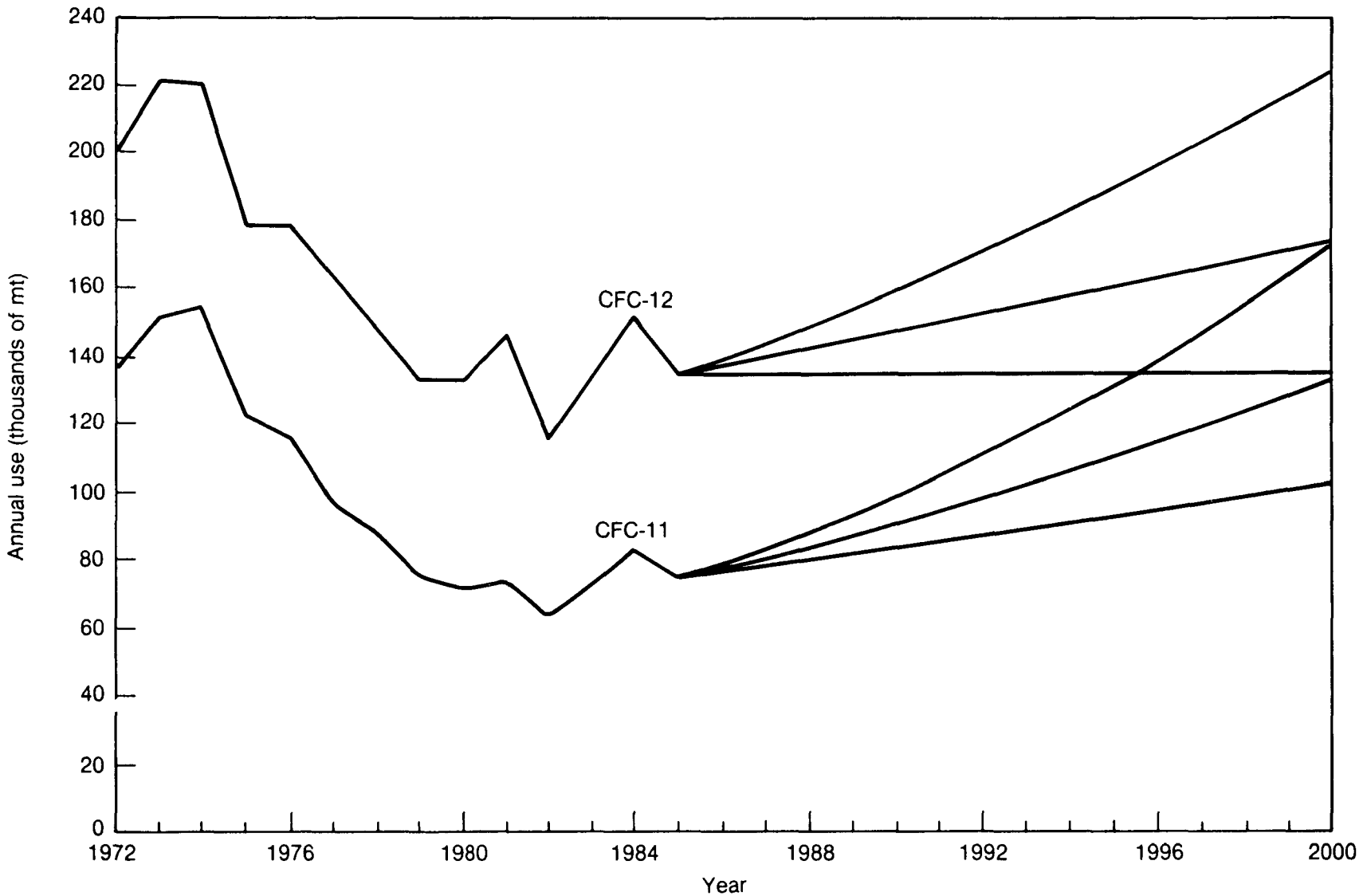


Fig. 11.1—Estimated historical and projected use of CFC-11 and CFC-12 in the United States

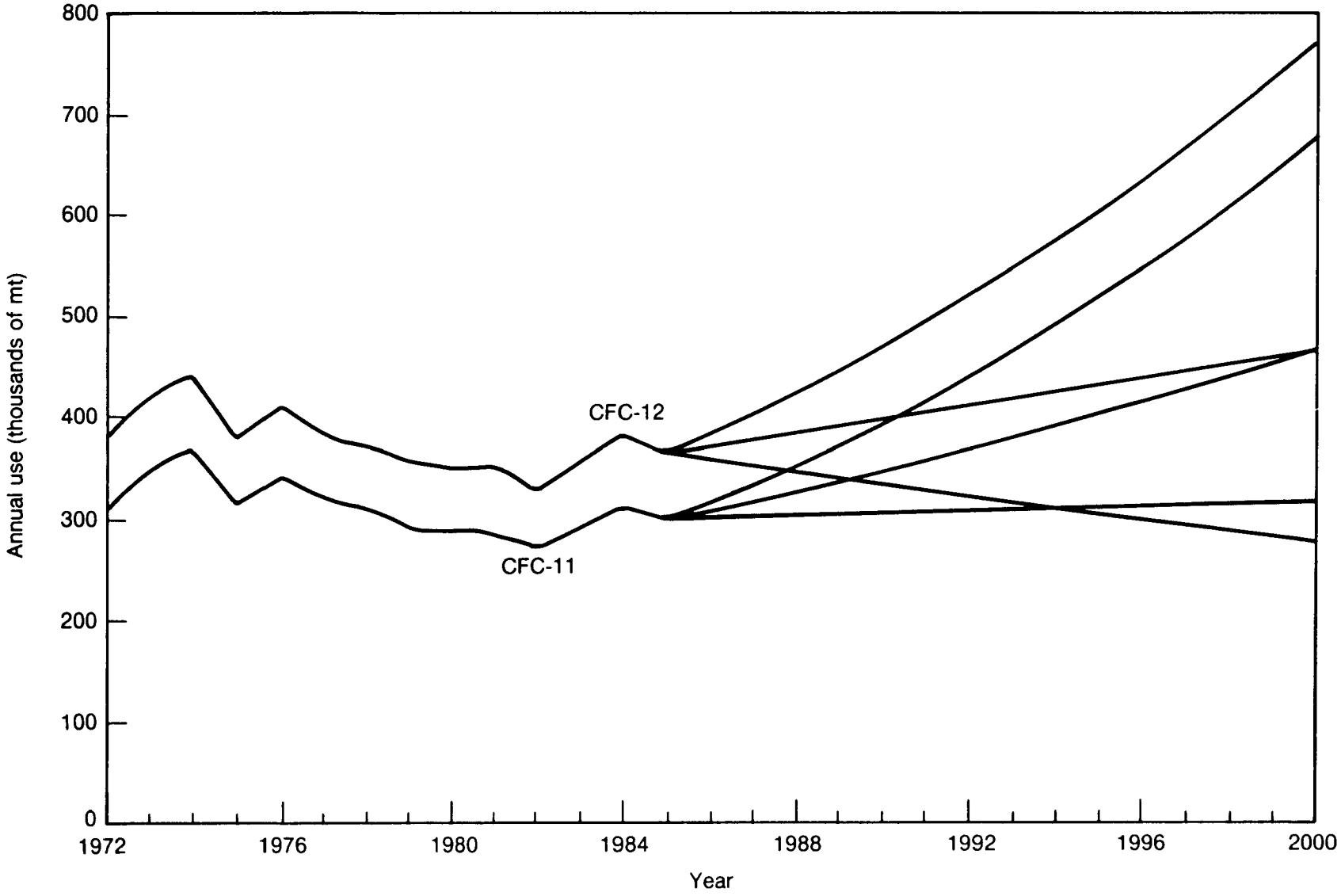


Fig. 11.2—Estimated historical and projected use of CFC-11 and CFC-12 in the reporting countries

addition, we project the unallocated uses to also grow at a rate equal to the average of the analyzed applications. As discussed in Appendix B, the unallocated uses are likely to include substantial amounts of CFC-12 used in refrigeration applications, and for CFC-11, unspecified refrigeration and miscellaneous uses. In addition, the unallocated uses include any new products that may be introduced over the next 15 years.

The U.S. and global projections are quite similar. In part this is because the United States accounts for such a large share of global demand and in part because our approach often infers demand outside the United States using information about U.S. demand. As is often true with chemicals, demand for those that are used in the largest quantities tends to grow more slowly than demand for smaller "specialty" chemicals. Of the seven chemicals, CFC-12 and methyl chloroform are projected to grow at the lowest rates, averaging between about 0 and 4 or 5 percent annually over the next 15 years. CFC-11 is expected to grow slightly more rapidly, but with a comparably wide range of uncertainty. The projected growth rates for carbon tetrachloride are similar to those of CFC-11 and CFC-12 because the major use of this chemical is in producing the two CFCs. The other chemicals are produced in smaller quantities and are expected to grow more rapidly, at rates of about 4 to 9 percent for CFC-113 and 1 to 8 percent for the Halons. Nonetheless, these growth rates are not large enough relative to those for the chemicals used in greater quantities to change the relative importance to potential ozone depletion of these seven chemicals much over the next 15 years.

Keep in mind that the quantities shown in Tables 11.1 and 11.2 are not the quantities relevant to potential ozone depletion. This is true for two reasons. First, these are levels of use, not of emissions: Depletion becomes a possibility only when these chemicals are emitted. Most carbon tetrachloride is never emitted because it is converted into other chemicals. Halons are rarely emitted and large amounts of CFC-11 and CFC-12 are not emitted until years after they are initially used. Second, emissions of equal quantities of different chemicals pose varying levels of potential threat to stratospheric ozone. Despite its high level of use, for example, methyl chloroform is estimated to present only a modest threat to stratospheric ozone. CFC-11 and CFC-12 are currently the most important potential ozone depleters and will probably continue to be for the next 15 years.

The ranges of uncertainty reported in Table 11.1 for CFC-11 and CFC-12 require aggregating the ranges for each application of these chemicals. Similarly, the ranges for all of the chemicals reported in

Table 11.2 require aggregation across world regions. These ranges were calculated using a method described in Camm and Hammitt (1986).[1]

DIRECTIONS FOR FUTURE WORK

The research reported here suggests several potential directions for future work. The first focuses on the areas where our understanding of demand for potential ozone depleters is least complete. Demand outside the United States, particularly in communist countries, is an obvious candidate. Work is under way in this area, but progress is slow. Formal data systems outside the United States are not nearly as good as those within. Producers of these chemicals do not face the same reporting requirements outside the United States as they do within. And the growing policy importance of information about potential ozone depleters can create incentives for governments outside the United States, which might be asked to restrict the use or production of these substances in the future, to make data collection more difficult than it might otherwise be. Hence, although additional information in this area would be beneficial, its collection is also proving to be costly.

It would also be useful to know more about the product areas or applications of CFC-11 and CFC-12 not explicitly captured by the "bottom-up" approach used here, in the United States and elsewhere. As Appendix B suggests, these are likely to fall primarily in the refrigeration area. If they do, this is important information for policymakers because refrigeration applications of CFCs are more difficult to displace than other uses. Whatever accounts for the shortfalls, better information about them would obviously improve our ability to project global and U.S. demand for CFC-11 and CFC-12.

Finally, it would be valuable to give greater formal attention to the sources of uncertainty underlying these projections. As explained in Appendix C, the current formulation uses the concept of a subjective probability distribution to combine information on different sources of uncertainty. The details of the method are explained in Camm and Hammitt (1986). At present, we assume that the levels of chemical use in each application, conditional on the level of general economic

[1]Briefly, we assume that the growth rates for each chemical are normally distributed and composed of one term corresponding to general economic growth and a second term describing growth conditional on the level of GNP. The term corresponding to GNP growth is common to all applications within a region, whereas the second term is independent of the first and independent across applications. We assume that the second term for the unallocated applications of CFC-11 and CFC-12 is distributed like the average of the terms for the analyzed applications. To aggregate across regions we assume that both GNP and chemical use relative to GNP are correlated across regions, both with correlation coefficients of 0.75.

activity, are independent of one another. However, there are clearly applications where use is positively or negatively correlated. For example, if some of the more toxic solvents that compete with CFC-113 and methyl chloroform were subjected to stricter regulation, both CFC-113 and methyl chloroform use could be expected to increase. Alternatively, if substitution of reciprocating chillers for centrifugal units were to occur at a more rapid pace than we project, CFC use in reciprocating chillers would increase and use in centrifugal units would decline. We have not been able to take these correlations into account as yet, in part because we have too little information to estimate the size of the effects.

In summary, we conclude that demand for potential ozone depleters as a class is likely to grow at a modest rate over the next 15 years. Some chemicals will grow faster than others but the relative mix of these chemicals in the world economy should not change markedly over this period. For specific chemicals, possibilities clearly exist for much more rapid growth or for almost no growth at all. Further work could allow us to refine our understanding of these basic trends.

Appendix A

ESTIMATES OF CURRENT CONSUMPTION OF CFC-11, CFC-12, METHYL CHLOROFORM, AND CARBON TETRACHLORIDE

The estimates of current chemical consumption reported in the text are intended to serve two purposes. First, we wish to present an accurate overview of current use of each of the seven potential ozone depleters we analyze. Second, since we base our projections of future use on these estimates, we want estimates that fairly characterize use in the mid 1980s. We wish to avoid basing our projections on the level of consumption in any single year because, if that year is atypical, the difference between consumption in that year and a more representative estimate would be propagated in the projections for all future years and even inflated because of the projection methodology.[1]

In addition, although our analysis focuses on consumption of the potential ozone depleters, available data measure production.[2] For total use of CFC-11 and CFC-12 in the reporting countries we believe the difference is not significant, because trade in these chemicals between the reporting and communist countries is probably negligible. In contrast, U.S. use may differ significantly from U.S. production, reported by the U.S. ITC, because of substantial imports and exports. Moreover, for both reporting country and U.S. estimates, inventory adjustments across years and other factors, although probably small, could affect the annual totals.

To accurately characterize the level of reporting country and U.S. use of the potential ozone depleters whose production is reported, we have developed estimates using not one year but the last several years of reported production. These estimates are based on simple linear regression models describing reported annual production as a function of time, for 1979 through 1984 or 1985 if available. Our estimate of

[1]If two otherwise identical projections use different base levels, projected levels in all future years will differ by the same factor as the base year levels. Because future use is expected to be greater than current use, the absolute difference will expand over time.

[2]Published total production estimates are available for CFC-11 and CFC-12 in the reporting countries and, in the United States, for CFC-11, CFC-12, methyl chloroform, and carbon tetrachloride. For the other chemicals and regions our estimates of total consumption are derived in the main text.

1985 consumption is simply the level of production predicted by the corresponding estimated regression equation. We do not use pre-1979 data because production of CFC-11, CFC-12, and carbon tetrachloride declined sharply in earlier years, largely as a result of the ban on most aerosol applications in the United States and other countries. The production trends show a definite shift beginning in 1979.

This method for estimating current consumption is implicitly based on two assumptions. First, it assumes that annual production, after adjusting for business cycle and other fluctuations, has increased or decreased by the same absolute amount over the period 1979 to 1985. As will be shown below, except for a few anomalous years, this is a good approximation. Second, the method assumes that consumption is on average equal to production. For the reporting countries as a whole this approximation is accurate, but for the United States the difference between production and consumption may be wider. However, because there is apparently no source of systematic, publicly available information on imports and exports of these chemicals, we are unable to adjust for either the average level of net imports or for changes in net imports over time.

REPORTING COUNTRY CONSUMPTION OF CFC-11 AND CFC-12

Table A.1 reports the estimated regression equations for reporting country production of CFC-11 and CFC-12. Because the 1985 CMA data are not yet available, we base our estimates on the 1979 through 1984 reports. The regression estimates imply that reporting country production has grown an average of about 3,000 mt annually since 1979. Table A.2 reports the actual reported production and the amount predicted by the estimated regression equation. As shown there, the regression predictions are quite accurate for both CFCs and all years except 1982 and 1984. Production in 1982 was significantly smaller than predicted by the regression equation, whereas 1984 production was significantly larger.[3] Whether 1984 marks the beginning of a period of substantial growth or simply an aberration will not be known for several years. For the present, we estimate 1985 production and consumption by extrapolating along the estimated regression line to obtain 300,000 mt of CFC-11 and 365,000 mt of CFC-12.[4]

---

[3]We judge the differences to be practically significant. They are not statistically significant by conventional criteria.

[4]We have rounded the estimates to the nearest 5,000 mt.

Table A.1

REGRESSION ESTIMATES OF REPORTING COUNTRY CFC-11 AND CFC-12 PRODUCTION

	CFC-11		CFC-12	
Independent Variable	Estimated Coefficient	t-statistic	Estimated Coefficient	t-statistic
Constant	−5690	−0.91	−6240	−0.73
Year	3.02	0.95	3.33	0.77
Dependent variable: reported annual production in thousands of mt				
R-squared:	0.185		0.129	
RMSE:	13.2		18.1	
Sample size:	6		6	

Table A.2

REPORTED AND PREDICTED REPORTING COUNTRY CFC-11 AND CFC-12 PRODUCTION

(In thousands of mt)

	CFC-11			CFC-12		
Year	Reported Production	Prediction	Difference	Reported Production	Prediction	Difference
1979	289.5	282.7	+6.8	357.2	345.7	+11.5
1980	289.6	285.7	+3.9	350.2	349.0	+1.2
1981	286.9	288.8	−1.9	351.3	352.4	−1.1
1982	271.4	291.8	−20.4	328.0	355.7	−27.7
1983	291.8	294.8	−3.0	355.3	359.0	−3.7
1984	312.4	297.8	+14.6	382.1	362.3	+19.8
1985	na	300.8	—	na	365.6	—

NOTE: na = not available.

UNITED STATES CONSUMPTION OF CFC-11, CFC-12, METHYL CHLOROFORM, AND CARBON TETRACHLORIDE

The ITC reports U.S. production of CFC-11, CFC-12, methyl chloroform, and carbon tetrachloride. However, because the United States imports and exports substantial quantities of these chemicals, domestic consumption need not correspond to production. Moreover, there have

been major shifts in international chemical trade over the last several years with the United States importing more and exporting less than before.[5] However, because systematic import and export data for these chemicals are apparently not publicly available, we are unable to adjust for this shift. As a result, our estimate of 1985 production may be a downward-biased estimate of current consumption. However, such a bias would not have a substantial effect on projected world consumption of CFC-11, CFC-12, or carbon tetrachloride, since its only effect is to incorrectly distribute total consumption between the United States and other reporting countries. Since the projected growth rates for these two regions do not differ widely, the effect on projected world consumption would not be large. Our estimates of methyl chloroform consumption in the non-U.S. reporting and communist countries are based on estimated U.S. use, however. If the U.S. estimate is biased, the estimate of the world total may also be biased.

Table A.3 reports the estimated regression equations for U.S. production of CFC-11 and CFC-12. As shown, average annual production has increased only about 500 mt per year over the post 1979 period. As described above, we believe that U.S. use has grown more rapidly than production because of increased imports and declining exports. The low R-squared values do not indicate that the regression models do not accurately summarize the production data. The values are low because the general trend is essentially flat, so a linear function of time cannot explain much of the variation in annual production.

As shown in Table A.4, the values predicted by the regression equation are quite close to the reported production levels. As for the reporting country totals, reported 1982 production is significantly below the model prediction and reported 1984 production is significantly above the prediction. After rounding, our estimates for 1985 consumption of CFC-11 and CFC-12 are 75,000 and 135,000 mt, respectively, about 1,000 and 7,000 mt larger than the reported 1985 production levels.

The regression estimates for methyl chloroform and carbon tetrachloride are reported in Table A.5. Annual U.S. production has declined on average over recent years, about 7,000 mt per year. As shown in Table A.6, reported 1982 production is lower than that predicted by the regression equation, whereas reported 1984 production

[5]Much of this shift is presumably attributable to the recent strength of the U.S. dollar. For at least some chemicals the shift has been dramatic. For example, using data from the *Chemical Marketing Reporter* profiles on trichloroethylene (January 27, 1986) and perchloroethylene (February 3, 1986), we calculate that the increase in net imports (imports minus exports) of these chemicals between 1980 and 1985 was about 40 and 27 percent of the 1985 U.S. consumption of these chemicals, respectively.

Table A.3

REGRESSION ESTIMATES OF U.S. CFC-11
AND CFC-12 PRODUCTION

	CFC-11		CFC-12	
Independent Variable	Estimated Coefficient	t-statistic	Estimated Coefficient	t-statistic
Constant	−1190	−0.49	−474	−0.10
Year	0.636	0.52	0.307	0.12
Dependent variable: reported annual production in thousands of mt				
R-squared:	0.052		0.003	
RMSE:	6.4		13.0	
Sample size:	7		7	

Table A.4

REPORTED AND PREDICTED U.S. CFC-11
AND CFC-12 PRODUCTION

(In thousands of mt)

	CFC-11			CFC-12		
Year	Reported Production	Predic-tion	Differ-ence	Reported Production	Predic-tion	Differ-ence
1979	75.8	71.8	+4.0	133.4	134.3	−0.9
1980	71.7	72.4	−0.7	133.8	134.6	−0.8
1981	73.9	73.0	+0.9	147.4	134.9	+12.5
1982	63.5	73.7	−10.2	117.0	135.2	−18.2
1983	73.0	74.3	−1.3	134.3	135.6	−1.3
1984	83.9	74.9	+9.0	152.9	135.9	+17.0
1985	73.9	75.6	−1.7	127.9	136.2	−8.3

Table A.5

REGRESSION ESTIMATES OF U.S. METHYL CHLOROFORM AND CARBON TETRACHLORIDE PRODUCTION

	Methyl Chloroform		Carbon Tetrachloride	
Independent Variable	Estimated Coefficient	t-statistic	Estimated Coefficient	t-statistic
Constant	14,400	1.82	13,800	1.26
Year	−7.13	−1.79	−6.80	−1.23
R-squared:	0.400		0.233	
RMSE:	21.1		29.2	
Sample size:	7		7	

Table A.6

REPORTED AND PREDICTED U.S. METHYL CHLOROFORM AND CARBON TETRACHLORIDE PRODUCTION

(In thousands of mt)

	Methyl Chloroform			Carbon Tetrachloride		
Year	Reported Production	Prediction	Difference	Reported Production	Prediction	Difference
1979	325.0	311.1	+13.9	324.0	321.6	+2.4
1980	314.0	304.0	+10.0	322.0	314.8	+7.2
1981	279.0	296.9	−17.9	330.0	308.0	+22.0
1982	270.0	289.7	−19.7	266.0	301.2	−35.2
1983	265.8	282.6	−16.8	259.9	294.4	−34.5
1984	306.2	275.5	+30.7	323.4	287.6	+35.8
1985	268.1	268.4	−0.3	283.0	280.8	+2.2

is higher, the same pattern as for the CFCs in both the United States and the reporting countries as a whole. However, reported U.S. production of methyl chloroform and carbon tetrachloride has fluctuated more (in absolute level) than reported CFC production, as shown by the larger differences between the reported and predicted production levels. After rounding, we estimate 1985 U.S. consumption of methyl chloroform and carbon tetrachloride as 270,000 and 280,000 mt, almost identical to the reported production levels.

Appendix B

COMPARISON OF ESTIMATED TOTAL CFC-11 AND CFC-12 USE WITH OTHER SOURCES

Our estimates of total CFC-11 and CFC-12 use are constructed "from the bottom up." That is, we estimate use in each application considered, usually by combining estimates of total final product produced and CFC use per unit of product. Our estimate of total use is simply the sum of the estimates for each application. In this section we compare our estimates to total reporting country production of CFC-11 and CFC-12 reported by the Chemical Manufacturers Association (CMA, 1984) and total U.S. production reported by the U.S. International Trade Commission (U.S. ITC, 1984). Our estimates are substantially lower than the CMA and ITC totals. Estimated CFC-11 use is about 18 percent lower for the United States and 8 percent lower for the reporting countries. For CFC-12, our U.S. estimate is 31 percent lower and the reporting country estimate is about 23 percent too small. To understand the source of these discrepancies we also compare our current estimates to those in earlier Rand work (Palmer et al., 1980) and to those published by DuPont (1978).

Our estimates for the other chemicals are based on published or industry-supplied estimates of total use that we allocated to various applications. These "top-down" estimates necessarily agree with the published totals.[1]

COMPARISON OF ESTIMATED CFC-11 USE

Table B.1 summarizes estimated current use of CFC-11 by application and compares it to ITC and CMA reported total use in the United States and reporting countries. The CMA estimates in each application are for 1984, when reported production totaled 312,400 mt. The ITC and CMA totals are based on annual production since 1979 and are derived in Appendix A. The Rand U.S. estimate is 18 percent lower than the adjusted ITC figure, whereas the reporting country estimate is 8 percent smaller than the adjusted CMA number.

[1]Note that estimated carbon tetrachloride use depends largely on reported CFC production levels and does not fall into either category.

Table B.1

COMPARISON OF ESTIMATED 1985 CFC-11 USE

(In mt)

	United States		Total Reporting Countries	
Application	Rand	ITC	Rand	CMA
Aerosol	3,800	na	93,700	97,500
Foam production				
Closed cell	38,300	na	115,800	110,600
Open cell	14,800	na	57,000	63,300
Refrigeration and air conditioning	4,400	na	9,900	23,900
Miscellaneous	450	na	450	17,000
Total	61,750	75,000[a]	276,850	300,000[a]

[a]Estimated 1985 use is derived in Appendix A. The CMA reported applications total 312,300 mt.

The ITC does not provide estimates of use by product area. Comparison of the Rand and CMA estimates reveals the Rand numbers to be comparable in aerosols and foam production but substantially lower in the refrigeration and miscellaneous categories, 14,000 and 17,000 mt lower, respectively. This suggests that there may be significant use in other applications we have not explicitly considered, including some refrigeration and air conditioning applications. The difference between the adjusted CMA total and the Rand reporting country estimate is 23,000 mt. Comparison of the Rand U.S. and ITC estimates suggests that 13,000 mt, about half of the unallocated uses, are in the United States.

COMPARISON OF ESTIMATED CFC-12 USE

Estimated CFC-12 use is presented in Table B.2 together with the ITC and CMA estimates. Again, the ITC and CMA totals are based on recent production trends and are derived in Appendix A. The reporting country estimate is 23 percent smaller than the adjusted CMA figure, whereas the U.S. estimate is about 31 percent lower than the adjusted ITC estimate. Comparison of specific product areas again

reveals the Rand estimate to be much smaller than the CMA estimate for refrigeration categories: We estimate only 98,000 mt in the reporting countries in comparison to 188,000 mt reported by CMA, a difference of 90,000 mt or 48 percent.

The Rand aerosol estimate of 115,600 mt is slightly lower than the CMA figure of 121,300. The Rand foam production estimate is also somewhat lower than the CMA estimate, 42,800 versus 49,200 mt,[2] but the miscellaneous use estimates are very close.

The difference between the adjusted CMA total and the Rand reporting country estimate is 83,000 mt. The difference in the U.S. estimates is 42,000 mt, again about half the difference in the reporting country estimates.

Table B.2

COMPARISON OF ESTIMATED 1985 CFC-12 USE

(In mt)

	United States		Total Reporting Countries	
Application	Rand	ITC	Rand	CMA
Aerosol	5,700	na	115,600	121,300
Blowing agent				
Closed cell	14,900	na	42,800	30,700
Open cell	—	—	—	18,500
Total	14,900		42,800	49,200
Refrigeration and air conditioning				
Mobile air conditioning	50,400	na	73,400	na
Retail food	4,800	na	9,700	na
Centrifugal chillers	1,600	na	3,700	na
Reciprocating chillers	300	na	1,300	na
Home appliances	2,400	na	10,200	na
Total	59,500	—	98,300	187,500
Miscellaneous	12,700	na	25,400	24,100
Total	92,800	135,000[a]	282,100	365,000[a]

[a]Estimated 1985 use is derived in Appendix A. The CMA reported applications total 382,100 mt.

[2]Note the difference in classification of foam production. Rand attributes all CFC-12 use to closed-cell foams and CMA attributes part to open-cell foams.

COMPARISON WITH EARLIER RAND WORK

In Table B.3 we compare the Rand 1985 U.S. CFC-11 and CFC-12 nonaerosol use estimates with the 1976 estimates of Palmer et al. (1980). Between 1976 and 1985 these applications grew at estimated average annual rates of 5.3 percent for CFC-11 and 2.3 percent for CFC-12.

Most of the CFC-11 growth is attributable to insulating (closed-cell) foams. In flexible (open-cell) foam applications CFC-11 use declined slightly reflecting an increase in the use of methylene chloride. Estimated use of CFC-11 in chillers increased slightly and the amount going to other applications remained approximately constant.

In the United States most CFC-12 is used in refrigeration and air conditioning applications. Between 1976 and 1985 estimated use in each of these decreased or remained constant, except for mobile air conditioning where the increased number of air conditioned vehicles more than offset the declining average charge. Estimated use in chillers declined slightly, reflecting lower leakage and servicing rates in reciprocating chillers. Estimated retail food use remained approximately constant, whereas CFC-12 use in home appliances declined

Table B.3

COMPARISON OF RAND ESTIMATES OF 1976 AND 1985 U.S. NONAEROSOL CFC-11 AND CFC-12 USE

(In mt)

	CFC-11		CFC-12	
Application	1976	1985	1976	1985
Blowing agent				
Closed cell	16,783	38,300	10,433	14,900
Open cell	15,422	14,800	—	—
Refrigeration and air conditioning				
Mobile air conditioning	—	—	40,733	50,400
Retail food	—	—	4,822	4,800
Chillers[a]	3,674	4,400	2,227	1,900
Home appliances	—	—	2,841	2,400
Miscellaneous	450	450	10,049	12,700
Total	36,329	57,950	71,105	87,100

SOURCE: 1976 estimates from Palmer et al. (1980).
[a]Centrifugal and reciprocating chillers combined.

somewhat because of a reduction in the average initial charge. In contrast, CFC-12 use in closed-cell foam (polystyrene sheet and board) and other uses increased substantially.

The estimates for CFC-11 and CFC-12 use in 1976 are 8,600 and 14,600 mt smaller than production reported by the U.S. ITC. In contrast, the current estimates are 13,250 and 42,200 mt short, indicating a growth in unidentified uses, especially of CFC-12.[3] In the next section we attempt to identify other product areas where the CFCs might be used.

COMPARISON WITH DUPONT ESTIMATES

Table B.4 compares 1976 CFC-11 and CFC-12 use as estimated by Rand (Palmer et al., 1980) and by DuPont (1978). The DuPont estimates for each product area include all CFCs used for that purpose, making comparison of use by chemical difficult. For example, the total for food processing and handling includes use of CFC-12, CFC-22, and CFC-502. However, by making some simple assumptions we can obtain some insight into the composition of our unallocated uses. Our estimates of the likely uses included in our unallocated sector are summarized in Table B.5.

The Rand and DuPont estimates of CFC use as a foam blowing agent are similar. In flexible foams, Rand's estimate of CFC-11 use exceeds DuPont's by about 3,000 mt. In rigid foams, the comparison is complicated by the use of both CFC-11 and CFC-12. The Rand total of CFC-11 and CFC-12, 27,200 mt, is about 1,000 mt smaller than the DuPont total for rigid polyurethane and polystyrene foams, 28,350 mt. However, DuPont reports an additional 2,000 mt of CFCs used in other foam, most of which is probably CFC-11 and CFC-12. Thus DuPont estimates greater use in rigid foam and smaller use in flexible foam than Rand, but the total foam blowing estimates are very close.

The major differences are in the refrigeration and air conditioning categories, especially in air conditioning and in food processing and handling. The estimates for air conditioning, including mobile air conditioning and chillers, differ by about 18,200 mt (after combining the Rand CFC-11 and CFC-12 estimates). As indicated in note b to Table B.4, we have all ready subtracted Rand estimates of the CFC-500 and some of the CFC-22 included in the DuPont figure. Most of the

[3]Part of the difference between the estimates of unallocated uses in 1976 and 1985 is attributable to differences in accounting procedures: Palmer et al. (1980) explicitly accounted for exports, intermediate use, and storage, packaging, and transport losses from the unallocated uses.

Table B.4

COMPARISON OF RAND AND DUPONT ESTIMATES OF U.S. 1976 NONAEROSOL CFC-11 AND CFC-12 USE

(In mt)

	Rand		DuPont	
Application	CFC-11	CFC-12	Quantity	CFCs
Blowing agent				
Flexible foams	15,422	—	12,202	11
Rigid foams				
Polyurethane			20,094	11, 12
Polystyrene			8,255	12
Other			2,041	11, 12, 113, 114, 115
Total	16,783	10,433	30,390	11, 12, 113, 114, 115
Refrigeration and air conditioning				
Air conditioning	3,674	42,960[a]	64,819[b]	11, 12, 22
Food processing and handling	—	4,822	33,112[c]	12, 22, 502
Refrigerators and freezers	—	2,841	3,130	12
Small appliances	—	—	1,270	12
Industrial process refrigeration	—	—	2,087	12, 22
Miscellaneous	—	—	907	12
Miscellaneous uses				
Liquid fast freezing	—	2,722	2,722	12
Sterilants	—	5,897	5,897	12
Other	450	1,430	—	—
Total	36,329	71,105	184,296	All CFCs

SOURCES: DuPont (1978), Palmer et al. (1980).

[a]Includes CFC-12 in centrifugal and reciprocating chillers and mobile air conditioning.

[b]DuPont estimate less estimated 635 mt of CFC-500 in chillers (Palmer et al., 1980, p. 147) and 1,361, 20,865, and 13,154 mt of CFC-22 used in in chillers, home, and supermarket air conditioning, respectively (Palmer et al., 1980, p. 35).

[c]DuPont estimate less estimated 4,763 mt of CFC 502 and 680 mt of CFC-22 used in retail food applications (Palmer et al., 1980, p. 178).

Table B.5

ESTIMATED SHORTFALL IN RAND 1976
ESTIMATES OF U.S. CFC-11 AND CFC-12
USE COMPARED WITH DUPONT ESTIMATES

(In mt)

	Shortfall	
Application	CFC-11	CFC-12
Air conditioning	9,100	—
Food processing and handling	—	14,150
Refrigerators and freezers	—	300
Small appliances	—	1,270
Miscellaneous	—	907
Industrial process refrigeration	—	1,044
Total	9,100	16,671

remaining difference is likely to be CFC-11 and CFC-22. If we arbitrarily assume that half is CFC-11 the estimated Rand shortfall in this category is 9,100 mt.

In food processing and handling, Rand analyzed only retail food store refrigeration systems. As indicated in note c of Table B.4, we have subtracted Rand estimates of CFC-22 and CFC-502 used in retail food store applications from the DuPont figure. We do not know whether this accounts for all the CFC-22 and CFC-502 included in this category. Even after this adjustment, the DuPont figure exceeds the Rand estimate by 28,300 mt. If we arbitrarily assume that CFC-12 represents half of this difference (the same share as its share of retail food store refrigeration applications), then Rand's estimate of CFC-12 use in food handling and processing is estimated as 14,150 mt too low.

DuPont's estimate of CFC-12 use in home refrigerators and freezers exceeds the Rand estimate by about 300 mt. Dupont reports additional CFC-12 use of 1,270 mt of CFC-12 in small applicances and 907 mt in miscellaneous refrigeration applications, categories that Rand did not analyze. DuPont also reports 2,087 mt of CFC-12 and CFC-22 used in industrial process refrigeration. If we arbitrarily assume that half this amount is CFC-12, the implied Rand shortfall is 1,044 mt in this category.

Table B.5 summarizes the differences as estimated above. To summarize, comparison with the DuPont estimates suggests that about 9,000 mt of CFC-11 not accounted for by Rand is probably used in air conditioning. This figure is very close to the 8,600 mt difference

between the Rand estimate and the ITC total. In addition, some 17,000 mt of CFC-12 not accounted for by Rand may be used primarily in food processing and handling. Again, this estimate is close to the 14,500 mt difference between the Rand and ITC totals estimates.

SUMMARY OF COMPARISONS

Rand estimates of CFC-11 and CFC-12 use in the United States and reporting countries are smaller than ITC and CMA reported production levels. The CFC-11 estimates are 13,000 mt lower for the United States, and 23,000 mt lower for the reporting countries. Estimated CFC-12 use is 42,000 mt lower for the United States and 83,000 mt lower in the reporting countries. Thus, about half the reporting country use of each CFC that we do not account for apparently occurs in the United States. In contrast, estimated total CFC-11 use in the United States is about 25 percent, and CFC-12 use about 37 percent, of the estimated reporting country totals.

Comparison of our estimates by application suggests that much of the shortfall, particularly of CFC-12, is in refrigeration and air conditioning applications. For the reporting countries, comparison with CMA estimates suggests that our estimates fail to account for 17,000 mt of CFC-11 in miscellaneous applications and for 14,000 mt of CFC-11 and 98,000 mt of CFC-12 used as refrigerants. Comparison with estimates for the EEC and some other reporting countries recently furnished by the European Fluorocarbon Technical Committee (EFCTC, 1985) supports this conclusion.

For the United States, Rand's current estimates are consistent with its estimates for 1976 but the current estimates account for a smaller share of total U.S. use (based on ITC production reports), suggesting that use in other applications has grown. Comparison of the Rand 1976 U.S. data with DuPont estimates for the same year suggests that the Rand estimates fail to account for about 9,000 mt of CFC-11 used in air conditioning and 17,000 mt of CFC-12 used primarily in food processing and handling refrigeration applications.

Appendix C

DERIVATION OF SUBJECTIVE CREDIBILITY INTERVALS

The ranges of uncertainty for projected chemical use and for each of the three levels of uncertainty described in Sec. II can be interpreted as subjective 80 percent credibility intervals. When one must act in the face of uncertainty about future outcomes that will affect the desirability of the chosen action, a long line of analytic work recommends the use of subjective probability distributions for the relevant outcome.[1] We choose to present 80 percent credibility intervals, rather than the more conventional 90 or 95 percent levels, because experimental evidence shows that people are often poor at thinking about small probabilities.[2] Using 80 percent credibility intervals should enable us to assess the ranges, and readers to interpret them, more accurately.

The subjective credibility intervals for chemical use are derived from the intervals corresponding to each level of uncertainty. The procedure is exact if the subjective probability distributions for each level of uncertainty are log-normal. If not, it at least provides a useful heuristic for calculating the credibility intervals.

To calculate the subjective credibility interval for chemical use we posit a random variable associated with each level of uncertainty that is multiplied by the base projected use. These random variables are assumed to be log-normally distributed with the median equal to one. This assumption implies that the probability that the outcome variable is more than Z times the projected level is equal to the probability that it is less than 1/Z times the projected level. For example, actual GNP is as likely to be more than 1.5 times the projected level as it is to be less than two-thirds of that level. For projecting future chemical pro-

[1]See Raiffa (1968) for a very clear description of the principles and a historical overview.

[2]For an extensive reporting of the experimental evidence on common difficulties in evaluating probabilities see Kahneman, Slovic, and Tversky (1982). The work reported there suggests that most people overestimate their ability to predict random variables, especially when attempting to use high credibility-level intervals. When assessing subjective 90 or 99 percent credibility regions, the random variable falls outside the region far more often than the theoretical 10 or 1 percent of cases.

duction the log-normal distribution provides a close approximation to most of our subjective probability distributions.[3]

The random variable describing the uncertainty about total chemical use is the product of the random variables corresponding to each level of uncertainty. Since the random variables are independent (by construction) and the median of each factor is one, the base projections reported in the text constitute the median of the subjective credibility intervals. If, as we assume, each of the components is distributed log-normally then so is final chemical use. Moreover, the parameters of the distribution of chemical use can be readily obtained from the parameters of the distribution functions of the component random variables, which can in turn be derived from the subjective credibility intervals. Hence, it is a simple procedure to calculate a credibility interval for chemical use from the subjective credibility intervals for each level of uncertainty.[4]

If one is unwilling to characterize his subjective uncertainty about one or more of the random variables describing each level of uncertainty as approximately log-normal, an alternative procedure can be used. However, it does not provide an exact probability for the resulting credibility interval, and the bounds on that probability may be unhelpfully wide. The procedure is to calculate the range of possible values for chemical use obtained by setting all components at the limits of their respective credibility intervals. For example, assume that we believe an 80 percent credibility interval for GNP in 2000 ranges from 0.80 to 1.25 times the projected base value. Similarly, we believe that the 80 percent credibility interval for final product use, conditional on GNP, ranges between 0.67 and 1.50 times the projected use, and that the 80 percent credibility interval for use of chemical Y per unit of final product ranges from 0.50 to 2.00 times the projected use. The alternative credibility interval for final use of chemical Y is from 0.27 ($= 0.80 \times 0.67 \times 0.50$) to 3.75 ($= 1.25 \times 1.50 \times 2.00$) times projected use. The probability that this interval includes the actual use is at

---

[3]The ranges reported in the text are consistent with log-normal distributions in almost all of the cases. For a few minor CFC-11 and CFC-12 applications the ranges are not geometrically symmetric about the base projections. To calculate the ranges for total CFC-11 and CFC-12 use we adjust the base projections for these applications to obtain the required symmetry.

[4]If the distribution of X is log-normal it can be characterized by two parameters: μ, the expected value of the logarithm of X, and σ^2, the variance of the logarithm of X. These parameters can be derived from the subjective credibility interval using a table of the normal distribution function. The parameters of the distribution of chemical use are simply the sum of the corresponding parameters of the distributions of each of its components, and a credibility region for any chosen significance level can be derived with reference to the tabulated normal distribution function.

least 0.51 (= 0.8^3) and no more than 0.99 (= $1 - (1 - 0.8)^3$).[5] In contrast, if these distributions are log-normal the calculated credibility interval would include actual chemical use with probability 0.96, and an 80 percent credibility interval would range from 0.43 to 2.30 times the base projected use.

---

[5]In general, if the n component credibility intervals have probability levels p_i, i = 1,2, . . . ,n, then the probability associated with the aggregate credibility limit will be at least $\Pi\ p_i$ and at most $1 - \Pi\ (1 - p_i)$ (assuming the component random variables are independent, as here).

REFERENCES

Automotive News, April 24, 1985.

Borisenkov, E. P., and Y. E. Kazakov, *Trudy. Glavnaia Geofizicheskaia Observatoriia,*, Vol. 438, pp. 62–74, 1980.

Camm, Frank, and James K. Hammitt, *An Analytic Method for Constructing Scenarios from a Subjective Joint Probability Distribution,* The Rand Corporation, N-2442-EPA, May 1986.

Chemical Manufacturers Association, Fluorocarbon Program Panel, *World Production and Sales of Chlorofluorocarbons CFC-11 and CFC-12,* various years.

Chemical Marketing Reporter, "Chemical Profile: 1,1,1-Trichloroethane," September 27, 1982; March 28, 1983; January 20, 1986.

Chemical Marketing Reporter, "Chemical Profile: Carbon Tetrachloride," April 10, 1978; May 4, 1981; February 21, 1983; February 24, 1986.

Chemical Marketing Reporter, "Chemical Profile: Fluorocarbons," August 7, 1978; March 10, 1986.

Chemical Marketing Reporter, "Chemical Profile: Methylene Chloride," February 10, 1986.

Chemical Marketing Reporter, "Chemical Profile: Perchloroethylene," June 18, 1979; February 3, 1986.

Chemical Marketing Reporter, "Chemical Profile: Trichloroethylene," January 27, 1986.

Chemical Marketing Reporter, "Fluorocarbon 11 Competitor," February 28, 1983.

Chemical Marketing Reporter, "Specialty Chemicals' Growth Pegged at 5 Pct.," May 14, 1984.

Congressional Budget Office, *Economic and Budget Update,* August 1985.

Council of Economic Advisors, *Economic Report of the President,* February 1985.

E. I. DuPont deNemours and Company, *Information Requested by EPA on Non-Aerosol Propellant Uses of Fully Halogenated Halocarbons,* Wilmington, Delaware, March 15, 1978.

Edmonds J. A., J. Reilly, J. R. Trabalka and D. E. Reichle, *An Analysis of Possible Future Atmospheric Retention of Fossil Fuel CO_2,* DOE/OR/21400–1, U.S. Department of Energy, Washington D.C., September 1984.

European Fluorocarbon Technical Committee (EFCTC), Conseil Européen des Fédérations de L'Industrie Chimique, *Halocarbon Trend Study 1983-1995*, Brussells, 1985.

International Bank for Reconstruction and Development, *World Development Report 1984*, Oxford University Press, New York, 1984.

Kahneman, Daniel, Paul Slovic, and Amos Tversky (eds.), *Judgment Under Uncertainty: Heuristics and Biases*, Cambridge University Press, Cambridge, 1982.

Manufacturing Chemist and Aerosol News, "Strong Growth Is Forecast for Electronics Chemicals," August 1985, p. 25.

Mining Journal, "Demand Surge Forecast for Electronic Metals," July 5, 1985, p. 5.

Mobay Chemical Corporation, *Urethane Market Summary*, Polyurethane Division, 1982–1985.

Modern Plastics (various issues).

Mooz, W. E., S. H. Dole, D. L. Jaquette, W. H. Krase, P. F. Morrison, S. L. Salem, R. G. Salter and K. A. Wolf, *Technical Options for Reducing Chlorofluorocarbon Emissions*, The Rand Corporation, R-2879-EPA, March 1982.

National Academy of Sciences, *Causes and Effects of Changes in Stratospheric Ozone: Update 1983*, Washington D.C., 1984.

National Academy of Sciences, *Causes and Effects of Stratospheric Ozone Depletion: An Update*, Washington D.C., 1982.

National Academy of Sciences, *Halocarbons: Effects on Stratospheric Ozone*, Washington D.C., 1976.

National Academy of Sciences, *Protection against Depletion of Stratospheric Ozone*, Washington D.C., 1979.

Nihon Reito Kucho Kogyo Kai (Japan Refrigeration and Air Conditioning Association), *Reito to Kucho* (Refrigeration and Air Conditioning), February 1985.

Palmer, Adele R., William E. Mooz, Timothy H. Quinn, and Kathleen A. Wolf, *Economic Implications of Regulating Chlorofluorocarbon Emissions from Nonaerosol Applications*, The Rand Corporation, R-2524-EPA, June 1980.

Quinn, Timothy, Kathleen A. Wolf, William E. Mooz, James K. Hammitt, Thomas W. Chesnutt, and Syam Sarma, *Projected Use, Emissions, and Banks of Potential Ozone Depleting Substances*, The Rand Corporation, N-2282-EPA, January 1986.

Raiffa, Howard, *Decision Analysis: Introductory Lectures on Choices under Uncertainty*, Addison-Wesley Publishing Co., Reading, Massachusetts, 1968.

Ramanthan, V., R. J. Cicerone, H. B. Singh, and T. J. Kiehl, "Trace Gases and Their Potential Role in Climatic Change," *Journal of Geophysical Research*, Vol. 90, No. D3, June 20, 1985.

Reilly, John, Rayola Dougher, and Jae Edmonds, *Determinant of Global Energy Supply to the Year 2050*, Institute for Energy Analysis, Washington, D.C., 1981.

Seidel, Stephen, and Dale Keyes, *Can We Delay a Greenhouse Warming?*, U.S. Environmental Protection Agency, EPA-230-10-84-001, Washington, D.C., 1983.

Stinson, Stephen C., "Chemicals for Electronics: New Growth in Competitive Field," *Chemical and Engineering News*, August 8, 1983.

Taya, Chikako, "Environmental Protection and the United Nations—The Convention for the Protection of the Ozone Layer and the CFC Regulation Issue," *The Jurist*, July 15, 1985.

Tversky, Amos, and Daniel Kahneman, "Judgement Under Uncertainty: Heuristics and Biases," *Science*, September 1974.

U.S. Environmental Protection Agency, *Environmental Risk Assessment of Dichloromethane, Carbon Tetrachloride, Trichloroethylene, Methyl Chloroform, Tetrachloroethylene and Freon-113*, Office of Toxic Substances, Washington, D.C., September 1981.

U.S. International Trade Commission, *Synthetic Organic Chemicals*, 1976–1984.

United Nations Statistical Office, *Industrial Statistics Yearbook*, 1981.

Wolf, Kathleen A., *Regulating Chlorofluorocarbon Emissions: Effects on Chemical Production*, The Rand Corporation, N-1483-EPA, August 1980.

AN ANALYTIC METHOD FOR CONSTRUCTING SCENARIOS FROM A SUBJECTIVE JOINT POSSIBILITY DISTRIBUTION

May 1986

ACKNOWLEDGEMENTS

This paper was written by Frank Camm and Jim Hammitt of the RAND corporation under contract with the U.S. Environmental Protection Agency.

PREFACE

This Note is one of a series of papers written at The Rand Corporation on policy issues associated with chemicals that could potentially deplete ozone in the stratosphere ("potential ozone depleters"). Stratospheric ozone is important because the ozone layer helps shield the earth from harmful ultraviolet radiation. Increases in ultraviolet radiation may threaten human health, speed deterioration of certain materials, reduce crop yields, and have a wide range of potentially important ecological effects. Atmospheric models developed and tested over the last decade suggest that global human emissions of potential ozone depleters may lead to chemical reactions that reduce stratospheric ozone, thereby increasing ultraviolet radiation with its concomitant effects. Substantial scientific uncertainty persists about whether human emissions of these chemicals actually threaten the stratospheric ozone layer and, if they do, whether lower ozone levels actually threaten human health and other activities at the earth's surface that concern policymakers. Policymakers must act in the face of this uncertainty, however, and Rand's work is designed to help them act with the best information available.

To that end, The Rand Corporation is developing a series of reports addressed to analysts and policymakers responsible for policy decisions on emissions of potential ozone depleters in the United States and elsewhere. These documents report the results of research that includes extensive literature reviews, interviews with knowledgeable officials associated with the production and use of potential ozone depleters, and formal chemical, cost, economic, and statistical analyses. The series should also interest the much broader audience of analysts and decisionmakers whose organizations would feel the effects of government policies with respect to emissions of such chemicals.

Published papers in the series include the following:

- A. R. Palmer, W. E. Mooz, T. H. Quinn, and K. A. Wolf, *Economic Implications of Regulating Chlorofluorocarbon Emissions from Nonaerosol Applications,* R-2524-EPA, June 1980.
- A. R. Palmer, W. E. Mooz, T. H. Quinn, and K. A. Wolf, *Economic Implications of Regulating Nonaerosol Chlorofluorocarbon Emissions: An Executive Briefing,* R-2575-EPA, July 1980.
- K. A. Wolf, *Regulating Chlorofluorocarbon Emissions: Effects on Chemical Production,* N-1483-EPA, August 1980.
- A. R. Palmer and T. H. Quinn, *Economic Impact Assessment of a Chlorofluorocarbon Production Cap,* N-1656-EPA, February 1981.
- A. R. Palmer and T. H. Quinn, *Allocating Chlorofluorocarbon Permits: Who Gains, Who Loses, and What Is the Cost?* R-2806-EPA, July 1981.
- W. E. Mooz, S. H. Dole, D. L. Jaquette, W. H. Krase, P. F. Morrison, S. L. Salem, R. G. Salter, and K. A. Wolf, *Technical Options for Reducing Chlorofluorocarbon Emissions,* R-2879-EPA, March 1982.
- E. M. Sloss and T. P. Rose, *Possible Health Effects of Increased Exposure to Ultraviolet Radiation,* N-2330-EPA, July 1985.
- T. H. Quinn, K. A. Wolf, W. E. Mooz, J. K. Hammitt, T. W. Chesnutt, and S. Sarma, *Projected Use, Emissions, and Banks of Potential Ozone-Depleting Substances,* N-2282-EPA, January 1986.
- F. Camm, T. H. Quinn, A. Bamezai, J. K. Hammitt, M. Meltzer, W. E. Mooz, and K. A. Wolf, *Social Cost of Technical Control Options to Reduce the Use of Potential Ozone Depleters in the United States: An Update,* N-2440-EPA, May 1986.
- J. K. Hammitt, K. A. Wolf, F. Camm, W. E. Mooz, T. H. Quinn, and A. Bamezai, *Product Uses and Market Trends for Potential Ozone-Depleting Substances: 1985-2000,* R-3386-EPA, May 1986.
- W. E. Mooz, K. A. Wolf, and F. Camm, *Potential Constraints on Cumulative Global Production of Chlorofluorocarbons,* R-3400-EPA, May 1986.

This Note was produced under Cooperative Agreement No. CR811991-02-0 with the U.S. Environmental Protection Agency.

SUMMARY

Over the last 12 years, photochemical models of the upper atmosphere have suggested that chlorofluorocarbons (CFCs) and several related chemicals may reduce the concentration of stratospheric ozone. Reducing the concentration of stratospheric ozone may increase the quantities of ultraviolet radiation penetrating to the earth's surface, which may harm human health, reduce crop yields, accelerate the degradation of certain materials, and have other important adverse effects. These chemicals, which we call "potential ozone depleters" or PODs, are emitted to the atmosphere primarily through human activities. As a result, changes in government policies could reduce emissions of PODs, thereby reducing their effects on ozone and reducing the potential negative effects mentioned above. This Note is one of a series of publications being produced by The Rand Corporation to support the development of better information on this policy issue.

Many uncertainties are important to the issue of potential ozone depletion and its possible effects. It is not even certain that PODs affect ozone or that changes in ozone concentrations have any of the negative effects mentioned above. The Environmental Protection Agency (EPA) has developed a large model that allows consideration of these uncertainties and their importance in policy decisions. It is developing scenarios to capsulize in simple illustrations important information about the range of outcomes possible with current uncertainty. For example, to represent uncertainty about future global emissions of methane, the EPA uses both a high growth and a low growth scenario. As part of its effort, The Rand Corporation is helping the EPA characterize the uncertainties about market and technological factors that may affect the future global production of seven PODs: CFC-11, -12, -113, carbon tetrachloride, methyl chloroform, and Halons 1201 and 1301. This Note explains how we use information about the uncertainties associated with each of these chemicals *separately* to develop scenarios that illustrate these uncertainties *jointly* in a useful way.

It is important to view the uncertainties associated with these chemicals jointly. For example, suppose we developed high growth scenarios for each chemical separately and then used them to construct a high growth scenario for the seven chemicals together. Unless the production levels of these chemicals always moved together, one would be highly unlikely to observe high growth levels for all of them simultaneously. Historically, they have not moved together. Hence, such an approach would yield a scenario so unlikely as to be irrelevant to policy considerations.

The high growth scenario chosen must be meaningful to policymakers in the sense that it must represent some likely range of events with, from their perspective, a "high" effect. The policymaker's perspective in this problem is focused primarily on ozone depletion (although chemicals discussed here probably also have an effect on climatic change, another concern to EPA). Hence, a "high" growth scenario should include production patterns for those chemicals that, if ozone depletion is a serious problem, are likely to lead to high ozone depletion. Similarly, a low growth scenario should be associated with a low level of potential ozone depletion. Simply put, this Note provides a way to define production scenarios for the seven chemicals examined here that policymakers could reasonably associate with a range of likely levels of potential ozone depletion.

The technique used here starts with subjective probability distributions for each chemical. These are based on detailed Rand analysis, reported elsewhere, of possible production of these chemicals during the period 1985-2040. Uncertainty about the growth rate for each chemical is characterized by the probability distribution of the sum of two normal variates. The first captures uncertainty about general economic growth, and the second captures uncertainty about the growth in intensity of use of each chemical relative to general economic growth.

The technique then uses these growth rates to calculate a rough proxy for the general rate of growth of these PODs. The proxy is defined by a "score function" that weights and sums the growth rates for the seven chemicals. The weights used reflect three important factors that help determine how likely a chemical is to affect ozone

concentration: its annual rate of production, the fraction of its production ultimately emitted into the atmosphere, and its ozone-depleting potential per gram in the atmosphere. That is, the score function simply weights growth rates to reflect their relative potential effects on ozone depletion. Because of the way it is constructed, uncertainty about the value of the score function is also captured by a normal distribution.

We define scenarios in terms of quantiles of the distribution of the score function. For example, a "high" growth scenario is associated with the 75th percentile of the distribution; a "low" growth scenario corresponds to the 25th percentile. Each of these corresponds to a set of events likely to have a "high" or "low" effect relevant to the policymaker. For each scenario, we then pick growth rates for the seven chemicals that, when weighted and summed, yield the value of the score function for that scenario. An infinite variety of individual growth rates is consistent with any value of the score function; this is a generic problem in scenario construction. We use a simple convention to pick growth rates that treats all sources of uncertainty equally.

Table S.1 illustrates the scenarios generated with this technique by showing the production levels for the seven chemicals in selected years under each of three scenarios.

The specific technique developed here allows us to convolute all uncertainties about POD growth rates analytically. To do this, we express all sources of uncertainty as normal distributions and use some simple approximations. The same general approach could be used with a broader range of distributional assumptions and without the approximations used here. It would require a simulation technique like Monte Carlo, which is substantially more costly and usually requires other kinds of approximations. The technique developed here illustrates the application of a general approach and provides a specific method to implement it. Although the general approach would easily allow more complex implementations, it is by no means clear that they would be superior to the technique used here.

The specific technique used here would allow greater subtlety in the specification of the subjective probability distribution that provides its inputs. For example, the scenarios developed here assume

Table S.1

SELECTED PRODUCTION LEVELS FOR SCENARIOS
BASED ON QUANTILES OF THE SCORE FUNCTION

(In thousands of metric tons)

		Scenarios/Quantiles of the Score Function		
Chemical	Year	"Low" 0.25	"Medium" 0.50	"High" 0.75
CFC-11	1985	342	342	342
	2000	498	556	619
	2040	1017	1435	2022
CFC-12	1985	444	444	444
	2000	555	622	696
	2040	1124	1606	2287
Carbon tetrachloride	1985	1029	1029	1029
	2000	1391	1554	1736
	2040	2827	4014	5686
CFC-113	1985	163	163	163
	2000	367	422	485
	2040	700	1091	1695
Methyl chloroform	1985	545	545	545
	2000	752	844	946
	2040	1517	2179	3123
Halon 1301	1985	11	11	11
	2000	17	20	24
	2040	26	44	76
Halon 1211	1985	11	11	11
	2000	17	20	24
	2040	31	53	91

that the intensities of use relative to general economic activity for any two chemicals are unrelated. As better empirical information becomes available on the substitutability of different PODs in consumption or their jointness in production, the technique presented

here could easily accommodate it. The intensities of use for substitutes in consumption would be negatively correlated; those for chemicals produced jointly would be positively correlated. Such relationships can have significant effects on the joint distributions of related chemicals and should ultimately be reflected in this kind of analysis.

The specific technique can also be used to develop scenarios that incorporate a much broader range of factors than those presented here. Scenarios that reflect additional factors may be important because of the correlations among economic variables. For example, if global economic growth is high, both the rate of production for PODs and the activities like agriculture that may potentially be affected by ozone depletion will grow faster. Assuring that "high economic growth" scenarios for PODs are matched with similar scenarios for the effects of ozone depletion on crop yields will yield a larger--and more accurate--measure of the benefit from limiting POD emissions than would be calculated if such scenarios were not matched. Developing scenarios that are conditional on general economic growth would allow such matching. The technique presented here would allow us to develop such conditional scenarios in the future.

Understanding how all of the uncertainties associated with stratospheric ozone depletion relate to one another is a complex task. The EPA is approaching this task by breaking it into manageable pieces, where complex information about uncertainties can be condensed into scenarios that effectively illustrate the breadth of the uncertainty. The technique developed here shows a way to assure that, even though scenarios relevant to different sources of uncertainty are developed separately, they can still be related to the primary issue relevant to policymakers--ozone depletion--and hence to the goals of the analysis as a whole.

ACKNOWLEDGMENTS

John Hoffman and Stephen Seidel organized an informal workshop that gave us an early opportunity to present the general approach used here and get suggestions. Suggestions from Michael Gibbs, Michael Kavanaugh, and Gary Yohe were especially helpful. James Hodges read an earlier draft and provided detailed comments that have significantly improved the Note. Jan Acton helped facilitate its production and review under tight deadlines. Mary Vaiana helped prepare the presentation of material in this Note to the Environmental Protection Agency's March 1986 workshop, "Protecting the Ozone Layer." Participants in that workshop, particularly Toby Page, provided helpful feedback. Alyce Shigg oversaw production of the many drafts underlying this Note and Patricia Bedrosian edited the final draft. We thank them all and retain responsibility for any errors that remain.

CONTENTS

PREFACE iii

SUMMARY vii

ACKNOWLEDGMENTS xiii

FIGURES AND TABLES xvii

Section

I. INTRODUCTION 1

II. BACKGROUND: THE NEED TO COMBINE DISTRIBUTIONS FOR POTENTIAL OZONE DEPLETERS 4

Wanted: A Subjective Probability Distribution for Ozone Depletion 5
Scenarios Based on a Proxy for Stratospheric Ozone Depletion 9

III. THE DISTRIBUTION OF THE SCORE FUNCTION 15

Aggregating Chemical Use 16
Deriving Scenarios for Individual Chemicals from the Score Function 18

IV. SUBJECTIVE MARGINAL PROBABILITY DISTRIBUTIONS FOR POTENTIAL OZONE DEPLETERS 22

Methodology 22
Subjective Probability Distribution for the Pre-2000 Period 25
Subjective Probability Distribution for the Post-2000 Period 27
Marginal Distributions for Individual Chemical Production . 31

V. PRODUCTION SCENARIOS BASED ON QUANTILES OF THE SCORE FUNCTION 33

Choosing the Quantiles To Use for Scenario Development 33
Chemical Use Scenarios 35

VI. CONCLUSIONS 39

APPENDIX 43

REFERENCES 51

FIGURES

2.1. Schematic view of potential causes and effects of stratospheric ozone depletion 6

TABLES

S.1. Selected Production Levels for Scenarios Based on Quantiles of the Score Function x

4.1. Parameters of the Subjective Joint Probability Distribution in the Pre-2000 Period 26

4.2. Parameters of the Subjective Joint Probability Distribution in the Post-2000 Period 31

4.3. Production Levels at Specified Quantiles of the Subjective Marginal Probability Distributions for Individual Chemicals 32

5.1. Chemical Weights 34

5.2. z-statistics and β Values for Distributions of the Score Function and Components 36

5.3. Growth Rates for Scenarios Before and After 2000 37

5.4. Selected Production Levels for Scenarios Based on Quantiles of the Score Function 38

I. INTRODUCTION

Over the past 12 years photochemical models of the atmosphere have suggested that global human-caused emissions of certain chlorofluorocarbons (CFCs) and related chemicals may reduce the concentration of stratospheric ozone. We refer to these chemicals as potential ozone depleters or PODs. A sufficient reduction in stratospheric ozone could allow substantially greater amounts of ultraviolet radiation to penetrate to the earth's surface, potentially causing a wide variety of detrimental effects. These effects include significant threats to human health, reductions in crop yields, degradation of certain materials, and other important adverse ecological consequences.[1] Scientists studying the possibility of ozone depletion have not reached a consensus on the likelihood that these adverse effects will occur in the foreseeable future. However, because the PODs survive in the atmosphere for many decades after their release, current emissions may affect stratospheric ozone concentrations well into the next century. Consequently, if the probability that the PODs will cause serious adverse effects is sufficiently high, policies that reduce current human emissions of these chemicals may be warranted.

The U.S. Environmental Protection Agency (EPA) has undertaken a major effort to study these potential effects, to characterize systematically the uncertainties about them, and to examine the likely effects of alternative policies to control the emissions of PODs. Ultimately, this effort will help policymakers compare the social costs of controlling POD emissions with the social benefits. The social costs of controls are represented by the benefits that must be forgone if the commercial use of these chemicals is restricted. The social benefits are amelioration of the kinds of adverse effects mentioned above, where possible expressed in monetary terms.

---

[1]For details, see National Academy of Sciences (1976, 1979, 1982, 1984) or Ramanthan et al. (1985).

The Rand Corporation is participating in this effort by, among other things, studying the market and technological factors that affect current and future human emissions of PODs. We focus on the seven most important of these: CFC-11, -12, and -113, carbon tetrachloride, methyl chloroform, and Halon 1211 and 1301. Rand has developed information on the likely sources of uncertainty associated with production of these seven PODs (Hammitt et al., 1986; Quinn et al., 1986). Previous Rand reports analyze the production of each chemical independently. Given EPA's approach to convoluting uncertainties, however, it is important to analyze the combined effect of all these chemicals on potential ozone depletion. Thus, we must characterize the joint uncertainty about production of the PODs. This Note explains why that is true and develops a simple methodology for doing so.

Our method focuses on uncertainties about *production* over time.[2] However, it is not production but ultimate emissions of the PODs that are relevant to potential ozone depletion. At present, we calculate the time path of emissions for each chemical production trajectory using deterministic algorithms similar to those used in prior Rand work (Palmer et al., 1980) and by the Chemical Manufacturers Association (CMA). Hence, the method does not capture the effect of any uncertainties about the relationship between production and emission of the chemicals.[3]

Section II provides additional background on EPA's policy analytic approach to potential ozone depletion and Rand's role in that approach. It explains the conceptual basis for integrating Rand's information on uncertainties about future chemical production into EPA's approach. Section III describes the specific analytic method we use to convolute uncertainties about the production of individual PODs to derive the probability distribution for the joint production of these chemicals. Our subjective probability distributions for production of individual

---

[2]We treat annual production and use as equivalent, since production inventories over periods of several years are negligible.

[3]The character and importance of these uncertainties is an important topic for future analysis.

chemicals are reported in Sec. IV. These are based on Rand's past work on future production and emissions of PODs. Section V presents production scenarios based on the joint distribution derived from the distributions for each chemical. Conclusions and suggested directions for future work are presented in Sec. VI, and the computer code used to implement our method is documented in the Appendix.

II. BACKGROUND: THE NEED TO COMBINE DISTRIBUTIONS FOR POTENTIAL OZONE DEPLETERS

Many uncertainties impinge on the question of the costs imposed over the next century by continuing emissions of PODs. These range from questions about the future emissions trajectories of PODs and of other gases that influence ozone concentration, to questions about the effect of a specified set of emission paths on actual ozone concentration, to questions about the effects of greater ultraviolet radiation on human health, crop yields, and degradation of materials, and of other consequences of policy interest. Uncertainties about each of these factors contribute to the uncertainty about the magnitude of the potential threat and the effects of alternative global strategies for controlling the emission of PODs. Moreover, the presence of this pervasive uncertainty is an important factor in choosing an appropriate policy, since a more flexible policy may be preferred even to alternatives that would perform better in a more certain environment.

The EPA has designed a strategy for comparing the effects of alternative policies in the face of these many sources of uncertainty. The strategy first reduces the broad range of possible futures to a fairly small set of cases and then examines the effects of alternative policies in each case. The cases are constructed through the following method:

- Isolate the principal factors that contribute to uncertainty.
- For each factor, select a small number of scenarios to represent the range of uncertainty about it.
- Construct cases by taking all possible combinations of the scenarios for the different factors.

The Rand Corporation is analyzing uncertainties about the emissions of seven PODs. To incorporate its work into EPA's framework, Rand must develop scenarios to reflect the nature of uncertainty about future emissions trajectories for these PODs. In this section, we ask what

kinds of scenarios would be appropriate. We begin by noting that an explicit probability distribution for ozone depletion would be preferable to the current use of discrete scenarios if costs allowed. However, because of the extreme complexity of the computer simulation models of the atmospheric chemistry involved, computation costs prevent the use of Monte Carlo analysis to generate a distribution function for ozone depletion. As an alternative, we suggest an analytic method to develop scenarios that approximate the kind of information that would be produced by the preferred focus on a subjective probability distribution for ozone depletion.[1]

WANTED: A SUBJECTIVE PROBABILITY DISTRIBUTION FOR OZONE DEPLETION

The extent of possible ozone depletion lies at the heart of EPA's policy concerns.[2] Essentially, the concern is that certain human activities may lead to ozone depletion, which may in turn affect the quality of human life. Figure 2.1 summarizes, in a very cursory fashion, the EPA's view of the problem and the links that must be understood. To understand it, start at the top of the figure and work down. Market and technological factors and government policies, ranging from the ban on most uses of CFCs as aerosol propellants to workplace safety standards, currently affect POD emissions. The EPA is

---

[1]There are two main alternative interpretations of probability--the frequency interpretation and the subjective interpretation. In the frequency interpretation, which is more widely understood, "the probability of event A" is understood to mean the relative frequency of occurrence of event A in some (invariably hypothetical) infinite sequence of repetitions of the mechanism in question. In the subjective interpretation, "the probability of event A" is a representation of one's belief about the likelihood of event A's occurring. That is, the first presumes the existence of a stochastic process that can be observed to get empirical information about the probability of an event, whereas the second is a formal way of presenting a subjective judgment. In this Note, all references to probability use the second interpretation; we provide a formal method for developing the implications of a set of subjective judgments about the state of the world. We thank James Hodges for emphasizing the importance of distinguishing these interpretations to make our intentions and discussion clearer.

[2]The chemicals analyzed here may also affect general climatic change, an issue that also concerns the EPA.

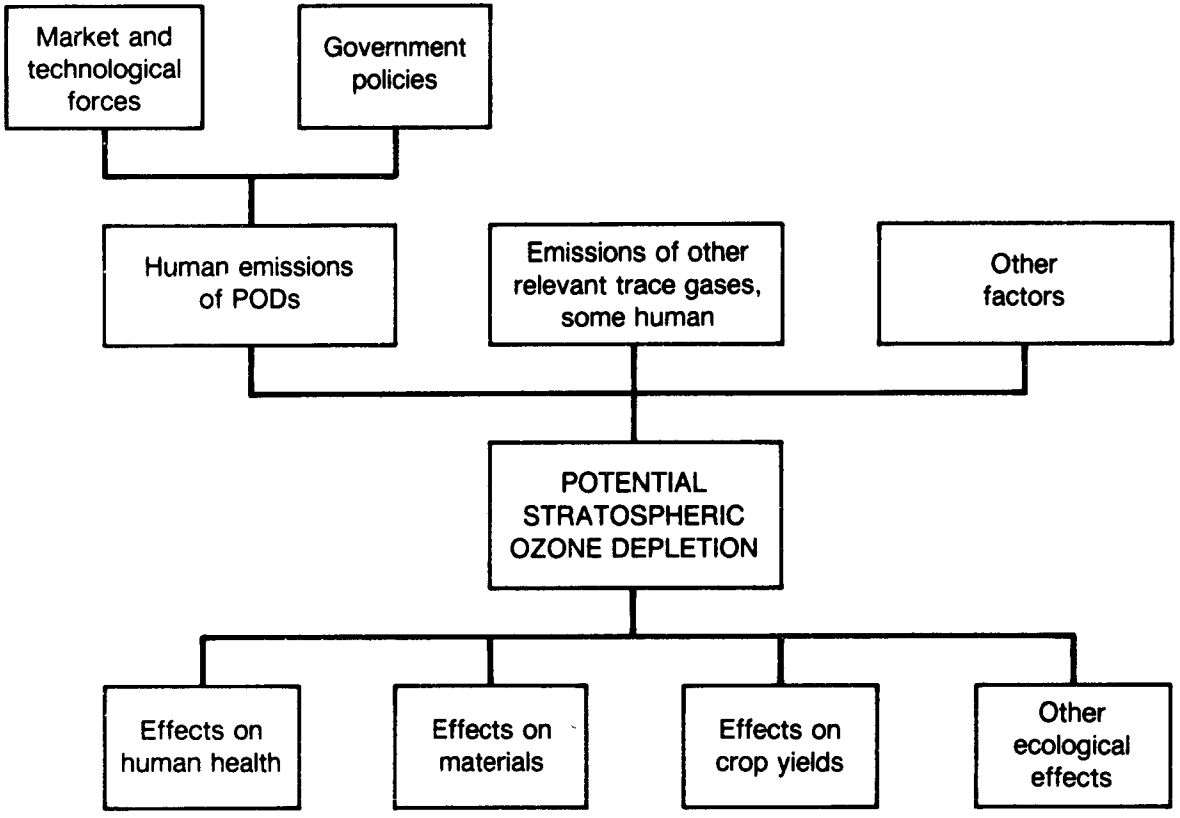


Fig. 2.1.—Schematic view of potential causes and effects of stratospheric ozone depletion

considering new government policies that could also affect emissions. After release to the atmosphere, PODs and other trace gases diffuse and react in a complex fashion that may be influenced by other factors such as global temperatures and the amount of solar radiation. One of the potential results of these complex interactions is a reduction in the concentration of stratospheric ozone. The diffusion and chemical reactions are simulated by computer models that produce time profiles of estimated ozone concentrations at different altitudes and, in some cases, latitudes. These time profiles can in turn be transformed into estimated time profiles of the various effects shown at the bottom of the figure, using a variety of models.

Each box has uncertainties associated with it. As noted above, the EPA plans to account for each of the identified uncertainties by developing scenarios to represent alternative possible outcomes corresponding to each box. For example, it might choose three scenarios to represent market and technological forces, eight to represent two possibilities each for emissions of three "other" gases, four to represent two parameterizations each of two models of the upper atmosphere, and so on. If these numbers of scenarios were used, the analysis would generate 96 alternative possible time profiles for stratospheric ozone. Each of these cases would then be compounded with scenarios that encapsulate information about uncertainties associated with the effects of each time profile, to generate the full number of cases to be analyzed for alternative policies.

So many sources of uncertainty are important that even a simplistic method of allowing each source to be represented by two or three scenarios leads to an unwieldy number of cases to use in policy analysis. However, the structure of the problem lends itself to a simplification that could potentially allow a much less simplistic treatment of uncertainty. Note that all of the information from the top half of the figure funnels through a single time profile--that for the extent of stratospheric ozone depletion--that is the only input required to study the remaining sources of uncertainty.[3] Thus, in theory, it is

[3]This is a slight oversimplification. Certain factors that affect emissions in the top part of the figure may also be important to the

possible to develop a subjective probability distribution for the extent of ozone depletion that summarizes all of the uncertainties in the boxes that feed into the POTENTIAL STRATOSPHERIC OZONE DEPLETION box in Fig. 2.1 that are relevant to the analysis of the effects in the final row of boxes.

A probability distribution for the extent of ozone depletion could be developed by first developing subjective probability distributions for the uncertain quantities in each of the boxes that feed into the POTENTIAL STRATOSPHERIC OZONE DEPLETION box and using Monte Carlo analysis to convolute these distributions. Actually, one would want a set of such ozone-depletion distributions, each conditional on a specified government policy. These distributions would not only summarize the extent of the known information about the factors that may influence depletion but would also allow the assigning of probabilities to particular ozone-depletion scenarios. Thus, one could state that the (subjectively assessed) probability that ozone depletion will fall between two specified levels in a given year is x percent (conditional on the corresponding government policy).

The difficulty with this approach lies in representing the chemical interactions in the atmosphere in a cost-effective way. Current models of the upper atmosphere are too complex and costly to use for more than a limited number of cases.

This difficulty does not eliminate the usefulness of using the concept of a probability distribution for ozone depletion. As we shall see, it can provide a basis for developing emission scenarios used as inputs to the atmospheric models. Ideally, we should be able to interpret cases easily in terms of this subjective probability distribution. For example, a "high" case should be developed from scenarios for market and technological factors, other trace gases, and other factors that together yield a "high" level of ozone depletion, perhaps one consistent with the 75th percentile of the subjective

---

size of effects in the bottom half of the figure. For example, the level of general economic activity could affect the size of crops or quantities of materials that might be harmed by ozone depletion. These kinds of dependencies can be integrated by making the distribution for ozone depletion explicitly a function of general economic growth.

probability distribution for ozone depletion under current government policies. Of course, we cannot accurately estimate the subjective probability distribution without actually running the atmospheric models, which we cannot do often enough to generate the distribution. Nonetheless, if we must choose scenarios for the inputs to the atmospheric models, it makes sense to think about how to choose them in light of what they are ultimately meant to do: Provide the kind of information that a subjective probability distribution for ozone depletion would provide if we could develop it directly.

SCENARIOS BASED ON A PROXY FOR STRATOSPHERIC OZONE DEPLETION

The scenarios developed here are intended to approximate those that would be derived from a subjective probability distribution for the extent of ozone depletion, if one were to be developed. We focus on growth rates for each potential ozone depleter so that a single random variable--the growth rate--can describe a time profile for production. We identify the main independent sources of uncertainty for the growth rate of each chemical, designate them as "component" random variates, and parameterize "component" distributions for these variates. The available information on economic and technological factors that affect growth in use of these chemicals is embodied in the distributions for these component variates. If the production growth rates of two chemicals are related, they will both be dependent on at least one common component variate.

To combine the distributions for the individual chemicals, we develop a "score function" that relates production growth rates of the seven PODs to a scalar value that has some policy relevance. Ideally, the score function would be a monotone transformation of some relevant measure of ozone depletion, so that its subjective distribution could easily be related to the distribution of ozone depletion. Because that is not possible, we seek the best proxy that we can implement in a simple way. We derive the subjective probability distribution for this score function by convoluting the distributions for each of the component variates underlying the POD production growth rates.

We then *define* scenarios in terms of quantiles of the score function. For example, an "upper limit" growth scenario might use the 95th percentile of the distribution; a "high" growth scenario might use the 75th percentile. We then seek the quantile of the distributions for the component random variates that, if chosen for all *component* variates simultaneously, would yield the value of the score function for the quantile used to define the scenario. For example, using the 82nd percentile for each component variate might yield values of growth rates that, when placed in the score function, yield its value at the 95th percentile of its distribution.[4] We then use the production growth rates for each chemical that are consistent with these values of the component variates to define the scenario in terms of the chemicals themselves. The resulting set of production paths for the seven chemicals is a scenario that can be used to generate emissions inputs for the atmospheric models. Consider the key steps of this procedure in turn.

Subjective Probability Distributions for Individual Chemicals

Our approach begins as a standard Monte Carlo analysis would. We seek a set of independent probability distributions and then derive a joint probability distribution for the seven chemicals based on these independent distributions. The joint distribution developed in this Note, discussed in more detail in Sec. IV, is based on the assumption that general economic growth is one source of uncertainty that affects the production of all chemicals. Otherwise, uncertainties about the production of these chemicals are unrelated. The approach, however, could easily accommodate information on other interrelationships by adding additional component variables to the analysis.

---

[4]Note that the quantiles used for the component variates will differ from the quantile of the score function and will be closer to their respective medians, unless all of the component variates are perfectly correlated.

Score Function

The score function is designed to do two things. First, as a practical matter, it provides a scalar value that summarizes the information in the subjective joint probability distribution for the individual chemicals. This single value provides a simple way to relate scenarios to one another. Second, and equally important, the value is designed to have policy significance. Increased production of any of the PODs will increase the value of the score function and should also be associated with greater ozone depletion. Hence, "high" growth scenarios should be associated with high ozone depletion and "low" growth scenarios with low ozone depletion. This relationship between the score function and the extent of ozone depletion is obviously not perfect. If it were, we would not need the atmospheric models. But it is designed to yield scenarios that can be interpreted roughly in terms of the likely corresponding ozone depletion.[5]

One way to think about the score function is as a simple tool that policymakers can use to rank alternative sets of POD production levels. A simple score function would be the sum of POD production in a given year. However, this function would be inadequate because of the widely different effects that a unit of each POD may have on the ozone concentration. The score function we propose weights the production levels of the chemicals, transforming them to a standard value so that a unit of each is believed to have approximately the same effect on the ozone.

The EPA has proposed a similar approach to ozone depletion in the past.[6] Although our analysis does not use exactly the approach EPA proposed, the use of a score function to order policy thinking about chemicals that policymakers do not consider to be equally dangerous is consistent with that approach.

---

[5]Holding other factors, including the emissions of other gases, constant.

[6]See U.S. EPA (1980).

Specifically, of the many different score functions that might be used, we use a simple weighted sum of the production growth rates for individual chemicals. The subjectively chosen weights are intended to reflect the chemicals' relative potential to deplete stratospheric ozone. The ith chemical's weight is defined as

$$w_i \equiv (p_i\ f_i\ e_i)/\Sigma\ (p_i\ f_i\ e_i)$$

where

p_i = the annual global production of the chemical,

f_i = the fraction of production of the ith chemical that is likely to be released to the atmosphere, and

e_i = the estimated effect of an emitted kilogram of the chemical on stratospheric ozone relative to that of CFC-11.

None of these factors can be specified with certainty. We estimate the 1985 production and use levels for each chemical based on the best available data (see Hammitt et al., 1986.) The fraction of production that will ultimately be released is based on detailed study of the applications of each chemical (see Hammitt et al., 1986, and Palmer et al., 1980). The estimated relative ozone-depletion potencies are based on information from atmospheric models (see Quinn et al., 1986). These relative potencies are sensitive to assumptions in the atmospheric models; we use them only to suggest orders of magnitude for the weights.

We construct two sets of weights: one for the period 1985-2000 and another for 2000-2040. The weight for each chemical is proportional to the product of the chemical's annual production at the start of the relevant period and a subjective factor designed to capture the other two terms, f_i and e_i. The factors for CFC-11, -12, and -113 are 1 because, despite their diverse uses, the majority of annual production of each CFC is emitted relatively promptly, and each presents about the same potential threat to ozone per kilogram. For carbon tetrachloride,

the weight is 0.064, the estimated share of production that is emitted (most carbon tetrachloride produced is consumed in the production of CFC-11 and -12). Carbon tetrachloride presents about the same potential threat per kilogram to ozone as the three CFCs. The factor for methyl chloroform is 0.1, since atmospheric models suggest its effect on ozone is an order of magnitude smaller than the three CFCs. Like the CFCs, emissions are typically prompt. Finally, we use a factor of 10 for both Halons. Their effect per kilogram on stratospheric ozone may be an order of magnitude or more greater than that of the CFCs above. We choose a factor at the low end of this scale to reflect the fact that Halons are banked for long periods of time between production and emission, and consequently should not begin to contribute to ozone depletion until much later, and also because a large fraction of the banked Halon 1301 may be recovered and never emitted.

The most important result of using this weighting scheme is that the growth rates of chemicals produced in large volume, or likely to have a larger depletion effect per gram, contribute more to the score function than others. As a result, the score function should serve as a proxy for the potential for ozone depletion.

From Score Function to Component Distributions

Our approach makes ozone depletion the focus of concern, even though it is represented only by a proxy. Any value of the score function could be produced by an infinite variety of production growth rates for individual chemicals. That problem lies at the core of using scenarios; no one seriously expects any one scenario to occur in the sense that all growth rates specified in the scenario persist as expected over the life of the scenario. Scenarios are designed to illustrate the implications of an underlying probability distribution or to represent some general kind of event that the probability distribution suggests has a significant probability of occurring. We need a simple convention to pick the single set of time profiles that make up a scenario.

We seek scenarios that illustrate the different time profiles of ozone depletion that production of the seven PODs might induce. Otherwise, we are indifferent about the specific time profiles chosen

for individual chemicals. It seems reasonable to seek a convention that treats sources of uncertainty equally to avoid any manipulation of the approach aimed at emphasizing one chemical over another. Accordingly, we choose as a convention to use the same quantiles for each of the independent component distributions. Other conventions could be chosen, just as scenarios with similar policy implications can be defined in different ways.

The subjective probability distribution for ozone depletion stands at the heart of EPA policy analysis. If that distribution could be approached directly, that would be the best path to follow. This section presents an alternative approach to take when the best alternative appears too costly. Our approach still focuses on the central point of interest--ozone depletion. It seeks a method to generate scenarios that are likely to capture and illustrate the range of ways in which economic and technological factors relevant to the seven PODs could affect stratospheric ozone depletion.

The approach suggested in this section is conceptual in nature; it could be implemented in many different ways. Section III explains the specific method we have developed to implement this concept.

III. THE DISTRIBUTION OF THE SCORE FUNCTION

To implement our approach, we need explicit subjective probability distributions for production growth rates and for the score function. In this section we develop a formulation that allows us to use a closed analytic solution to convolute the distributions for the individual PODs and to derive the distribution of the score function. The subjective probability distributions for the individual chemicals are described in Sec. IV.

Our method approximates the distribution for the score function that would be developed if all the component variates that describe the growth rates of individual PODs were distributed normally.[1] Normal distributions appear reasonable in all but a few instances, and these can be accommodated without serious difficulty. Our approximation would be exact if the relative production shares of each chemical remained constant over time. These shares change in our analysis but not enough to seriously threaten the integrity of the general results.

The general conceptual approach outlined in Sec. II would allow a more general implementation based on standard Monte Carlo techniques that would require neither an assumption of approximate normality nor the kinds of approximations used here. Whether this approach would justify the additional costs is unclear, since a Monte Carlo analysis requires approximations when continuous distributions are approximated by discrete ones.

The approach presented in this section allows quick, low-cost development of scenarios without sacrificing much accuracy. We discuss in turn the role of linear approximations in aggregating chemical use and the closed analytic solution we use to choose chemical growth rates that are consistent with any scenario chosen using the score function.

---

[1]Equivalently, we assume that the future quantities of PODs are distributed approximately log-normally. The correspondence between a normally distributed growth rate and a log-normally distributed future production level is good for modest growth rates. Let $Y_t = Y_0 (1 + r)^t$ where Y_i is production in year i and r is the growth rate. Then $\log Y_t = \log Y_0 + t \log (1 + r) \approx \log Y_0 + t\, r$ for small r.

AGGREGATING CHEMICAL USE

The growth rate for the production of each chemical is characterized as the sum of the growth rates of general economic activity (GNP) and of the specific intensity of use of each chemical, defined as the level of use relative to the GNP.[2] We focus on the average annual growth rates of GNP and intensity for each chemical. Our subjective probability distributions for the growth rates of these components are normal distributions. Because the score function is a linear combination of the component variables, our uncertainty about its value is also described by a normal distribution. The parameters of the distribution of the score function's value can be expressed as simple functions of the parameters of the distributions of the component variables.

We have subjective distributions for use of the seven PODs before 2000 for different world regions and, for CFC-11 and CFC-12, for product applications. We must aggregate these distributions to derive the distributions for world use of each chemical and similarly aggregate across chemicals to derive the distribution for the score function. We rely on linear approximations in making these aggregations.

First consider the aggregation of growth rates for different uses of a chemical or for total use of a hemical in different world regions. For example, we have developed subjective probability distributions for CFC-12 use in aerosols, foam blowing, refrigeration, air conditioning, and other applications (Hammitt et al., 1986). Let x_i be the amount of CFC-12 used in the ith application. Then the total amount of CFC-12, x, is simply $\Sigma\, x_i$ and the rate of change in x can be related to the rate of change of the $\{x_i\}$ at any instant in time in the following way:

$$(1/x)(dx/dt) = \sum_i [(x_i/x)(1/x_i)(dx_i/dt)] \qquad (3.1)$$

[2]This is an approximation, but one that works well for small growth rates. The exact relationship is $(1 + r_k) = (1 + g)(1 + u_k) = 1 + g + u_k + gu_k$, where r_k is the growth rate for the kth chemical, g is the growth rate for GNP, and u_k is the growth rate for the intensity of use of the kth chemical relative to GNP. For small g and u_k, $gu_k \simeq 0$ and $r_k \simeq g + u_k$. This standard approximation is often used in economics.

If we define r as the growth rate of CFC-12, r_i as the growth rate of the ith application of CFC-12, and a_i as the share of CFC-12 used in the ith application ($a_i = x_i/\Sigma\, x_i$), Eq. (3.1) can be reexpressed as

$$r = \sum_i (a_i\, r_i) \tag{3.2}$$

Given our small growth rates, $r_i \simeq g + u_i$,[3] where g is the percentage growth rate for GNP and u_i is the growth rate for the intensity of use of the ith application relative to GNP. Hence, Eq. (3.2) can be rewritten as

$$r \simeq g + \sum_i (a_i\, u_i). \tag{3.3}$$

The derivation of Eq. (3.3) incorporates two linear approximations. First, it assumes that the growth rates of two factors affecting a variable can simply be summed to calculate the growth rate of the variable itself. Given the small growth rates we are considering, this is adequate. Second, although Eq. (3.2) is exact at any instant, it is not exact over a discrete period of time unless all u_i are equal and hence all a_i remain constant over the period. Since we use the $\{a_i\}$ corresponding to the beginning of the period, we are essentially using a Laspeyres index to approximate aggregated growth rates; this index is adequate so long as the $\{a_i\}$ do not shift too much over the period of interest.[4]

Similarly, to aggregate use across world regions we use a linear formula to approximate the global growth rate. If r_j is the rate of

---

[3]See footnote 2 above.

[4]Alternatives would include using the weights corresponding to the end of the period (a Paasche index) or an intermediate set of weights. As long as the correct weights do not shift much over the period, any of these choices will produce similar results. This is a specific example of the general problem of defining index numbers. For further discussion, see Hirshleifer (1976) or other economics texts.

growth in the jth region and b_j is the share of global use there, the global growth rate

$$r \simeq \sum_j (b_j \, r_j). \tag{3.4}$$

The $\{b_j\}$ are fairly stable as long as uses in different regions do not grow at markedly different rates.

The second place where linear aggregation is important is in the definition of the score function. We *define* the score function as

$$s = \sum_k (w_k \, r_k)$$

$$\simeq g + \sum_k (w_k \, u_k) \tag{3.5}$$

where w_k is the subjective weight for the kth POD, described in Sec. II, and u_k is the growth rate for the intensity of use of the kth POD.

DERIVING SCENARIOS FOR INDIVIDUAL CHEMICALS FROM THE SCORE FUNCTION

If g and u_k in Eq. (3.5) are normally distributed, then s is normally distributed as well. This observation is the key not only to convoluting uncertainties in the components into a distribution for the score function but also to moving in the opposite direction. Once a scenario is defined in terms of a quantile of the distribution for s, we can use the normality of the score function and its components to find the common quantile for the component distributions that is consistent with this scenario.

Start by noting that the mean (m_s) and variance (v_s) of s can be defined in terms of the means (m_k), variances (v_k), and covariances ($v_{\ell k}$) of its components:

$$m_s = m_g + \sum_k (w_k m_k)$$

$$v_s = v_g + \sum_k (w_k^2 \; v_k) + 2 \sum_{k>\ell} (w_k \; w_\ell \; v_{k\ell}) \tag{3.6}$$

The value of the score function at the q_sth quantile of its distribution is

$$s(q_s) = m_s + v_s^{.5} \; z(q_s) \tag{3.7}$$

where $z(q_s)$ is the value of the z-statistic corresponding to the q_sth quantile of the standard normal distribution. Analogously, the q_cth quantiles of the growth rates of GNP and the intensity of use of the ith chemical can be defined as:

$$g(q_c) = m_g + v_g^{.5} \; z(q_c)$$

and (3.8)

$$u_i(q_c) = m_i + v_i^{.5} \; z(q_c).$$

We would like to find the value $z(q_c)$, and thus implicitly the quantile q_c, so that if we fix g and all the u_k at their q_cth quantiles, s will take the value at its q_sth quantile. To do this, for a given value of s, substitute Eq. (3.8) into Eq. (3.5) and Eq. (3.6) into Eq. (3.7) and set Eq. (3.5) equal to Eq. (3.7). Rearranging yields

$$z(q_c) \; [v_g^{.5} + \sum_i (w_i \; v_i^{.5})]$$

$$= z(q_s) \; [v_g + \sum_i (w_i^2 \; v_i) + 2 \sum_{k>\ell} (w_k \; w_\ell \; v_{k\ell})]^{.5} \tag{3.9}$$

or

$$z(q_c) = z(q_s) \;/\; \beta \tag{3.10}$$

where

$$\beta = \frac{v_g^{.5} + \Sigma\,(w_i\, v_i^{.5})}{[v_g + \Sigma\,(w_i^2\, v_i) + 2 \sum_{k>\ell} (w_k\, w_\ell\, v_{k\ell})]^{.5}} \;.$$

Equation (3.10) allows one easily to transform quantiles of the distribution of the score function into the corresponding quantiles of the distributions underlying the POD growth rates. Each scenario is based on a value of q_s, which yields $z(q_s)$, which in Eq. (3.10) yields $z(q_c)$.[5] We know that $\beta > 1$ so that the quantiles for the component distributions are closer to their medians than the corresponding quantiles for the distribution of the score function.[6] That is, the quantiles of the component variates that correspond to a specified subjective probability interval for the score function will span an interval associated with a lower level of subjective probability for the component variates. As shown in Table 5.2 below, the quantiles of the component distributions corresponding to the 90 percent subjective probability interval for the score function approximately span a 62 percent subjective probability interval for each component variate.

---

[5]Note that we need not determine q_c to calculate the growth rates relevant to any scenario. Once $z(q_c)$ is calculated from Eq. (3.10), it can be substituted into Eq. (3.8) and the appropriate values of the component growth rates can be calculated.

[6]To see this, square the expression that defines β in Eq. (3.10) and subtract the denominator from the numerator. This yields an expression

$$2 \sum_i [w_i v_g^{.5} v_i^{.5}] + 2 \sum_{i>j} [w_i w_j\, ((v_i v_j)^{.5} - v_{ij})] \;.$$

The first term must be positive. To sign the second, note that the subjective analog of the Pearson correlation coefficient, $v_{ij}/(v_i v_j)^{.5}$, cannot exceed unity. Hence, the second term is also positive. Therefore the numerator must exceed the denominator and β must exceed one.

Adopting normal distributions for the component growth rates and using linear approximations to convolute uncertainties and thereby construct distributions for aggregations of the component random variates considerably simplifies our analysis. The scenarios generated will reflect the influence of the approximations used. The alternative is to use a simulation technique like Monte Carlo, which itself normally requires that we approximate the underlying distributions. Given the likely sources of error associated with the method presented here, we believe it provides a good, quick, and low-cost method for developing scenarios that reflect the jointness of the underlying subjective probability distribution for production levels of the chemicals of interest to policymakers.

IV. SUBJECTIVE MARGINAL PROBABILITY DISTRIBUTIONS FOR POTENTIAL OZONE DEPLETERS

To construct scenarios from our subjective probability distribution for the production growth rates for the seven chemicals we are studying, we must choose subjectively based parameter values with which to characterize it. This section explains how we choose these parameter values for the period 1985 to 2040.[1] It begins with a brief explanation of the methodology used to develop the distribution based on information reported in other Rand documents. It then summarizes our analysis of the period 1985-2000. Because Hammitt et al. (1986) document our choice of parameter values for this portion of our analysis, we simply outline the approach used and summarize the results. Finally, the section explains how parameters were developed for the period 2000-2040.

METHODOLOGY

The ultimate object of interest in developing the subjective probability distribution is how the production of seven chemicals grows over time. To examine this, we focus on production growth rates. How exactly should we represent correlations among growth rates over time for each chemical? And how exactly should we express relationships among growth rates for different chemicals in any year? Specifying these relationships completely would entail a density of detail not warranted by the extent of our knowledge about the relationships. We seek a simplified specification of the relationships that captures their most important features.

---

[1]It is obviously difficult to think about events this far in the future. We look ahead this far to accommodate the needs of atmospheric modelers. Because the chemicals we are studying can remain in the atmosphere for decades following their emission, atmospheric models rely on long time series of emissions as inputs. We try to reflect the degree of our uncertainty about the far future in our choice of parameter values.

Relationships Across Time

Because our primary concern is with cumulative POD production, we focus on average annual growth rates over long periods of time. Specifically, to choose normal distributions to represent uncertainty about growth rates, we must choose means and variances for our distributions for the secular growth rate for each chemical and covariances among growth rates for different chemicals in each period. Because of our focus on long-term average rates we need not address year-to-year variations associated with the business cycle or temporary market conditions. It is reasonable to ignore these events because their influence on the variance of the average growth rate falls as the length of the period grows and should be quite modest over the 15-year and longer periods we consider.

We break the total period from 1985 to 2040 into two subperiods and examine the means and covariance structure of secular growth within each. Parameter values for the period 1985-2000 are based on analysis in Hammitt et al. (1986), whose results reflect subjective judgments about the range of reasonable growth rates for chemicals in different applications. These judgments are based on a detailed analysis of market trends and potential changes in markets, technologies, and regulations that could affect the use of these chemicals. Parameter values for the period 2000-2040 are based on concepts developed in Quinn et al. (1986). That document looks at historical trends in the relationship between chemical use and income and uses these to project a range of use levels over the period in question. The analysis is necessarily less detailed than that in Hammitt et al. (1986). We draw on results from Hammitt et al. in the later period to assure that our assumptions in the two periods are mutually consistent.

Although the structure of growth rates within each period may be conceived as a set of means and a covariance matrix for each period, the relationship between the periods is more difficult to represent parametrically. We choose a relationship that carries over the implicit assumption of a positive correlation between yearly growth rates across time within the two periods.[2] To construct a high growth scenario for

---

[2]Heuristically, we can think of a growth rate as having two

the full period, we use high growth scenarios in each period. Similarly, low growth scenarios use low growth rates in both periods.

Relationships between Chemicals

We treat the average annual growth rate as the sum of two terms: (1) general economic growth and (2) growth of intensity of use relative to GNP, which includes both growth in the product markets where the chemical is used (relative to GNP) and growth in the use of the chemical in the manufacture of the products. We assume that sources of uncertainty in the intensity of use of each chemical are uncorrelated between chemicals, both within and across periods. With a better empirical understanding of the chemicals markets, it should be possible to identify relationships of this kind in the future. For now, however, we assume them away.

The general economic growth component is common to all of the chemicals and consequently creates a positive covariance among the growth rates for all of the chemicals. Before 2000, we divide the world into regions and specify general economic growth and chemical intensity distributions for each; after 2000, we treat the world as a single unit. When dealing with more than one region, we assume that growth rates in different regions are positively correlated with one another. The next subsection discusses this in more detail.

In sum, our method characterizes a wide variety of factors relevant to uncertainty about the future use of these chemicals. It reflects interrelationships across time and across chemicals. A more complicated framework for relating growth rates could potentially capture subtleties not represented here. However, empirical data of the type and quality necessary even to quantify all of the details of this system in a historical period are not currently available. Until better data are available, a more detailed structure is difficult to justify.

---

components. The first is a secular component that can be represented by a single random variate for each chemical. The second is an annual component that requires separate random variates for each year. These can be independent of one another over time (though not necessarily across chemicals). The first component embodies the positive correlation we wish to capture in our choice of a method to relate the two periods. The second is an additional source of uncertainty that helps explain why the variance of a mean growth rate can decrease for longer periods.

SUBJECTIVE PROBABILITY DISTRIBUTION FOR THE PRE-2000 PERIOD

The subjective probability distribution for the period before 2000 is taken from Hammitt et al. (1986). That source develops explicit 80 percent subjective probability intervals for the use and production of the seven PODs through the end of the century. It divides world use into use in three major regions, and projects future use of CFC-11 and -12 in each of the major products in which they are used. The mean rates of growth are based on analysis of trends and industry forecasts for each application or chemical. Although the reported mean rates are not constant over the period for some of the uses, we have calculated average annual rates over the period for use here.

We aggregate our distributions for growth rates across applications of a single chemical, and across chemical use in different regions, to obtain our distributions for world GNP and chemical intensity growth using the methods described in Sec. III. When aggregating distributions across regions, we use a positive correlation (a coefficient of 0.75) across regions for both GNP and chemical intensity growth rates. The parameters of the resulting distributions are reported in Table 4.1.

The table displays the parameters of the growth rate distributions in two forms. The columns labeled "Intensity" include the mean and standard deviation of our distributions for the rate of growth of intensity of use of each chemical, relative to general economic growth. The last row of the table shows the mean and standard deviation of our distribution for the general economic growth rate itself in these columns. The columns labeled "Production" report the mean and standard deviation of our distributions for growth rates for production of each chemical, including the effects of both general economic growth and intensity of chemical use. The mean of our distribution for the production growth rate is the sum of the means of our distributions for general economic growth and intensity of use. The standard deviation of the distribution for the production growth rate is the square root of the sum of variances for general economic growth and intensity of use.

Table 4.1

PARAMETERS OF THE SUBJECTIVE JOINT PROBABILITY DISTRIBUTION IN THE PRE-2000 PERIOD

(Use in thousands of metric tons, rates in % per year)

		Intensity		Production	
Chemical	1985 Use	Mean	Standard Deviation	Mean	Standard Deviation[a]
CFC-11	341.5	0.02	0.98	3.30	1.51
CFC-12	443.7	-1.00	1.05	2.28	1.56
Carbon tetrachloride	1029.0	-0.49	1.02	2.79	1.54
CFC-113	163.2	3.27	1.67	6.55	2.03
Methyl chloroform	544.6	-0.32	1.10	2.96	1.59
Halon 1301	10.8	1.08	2.29	4.36	2.56
Halon 1211	10.8	0.96	2.33	4.24	2.60
Gross global product		3.28	1.15		

[a] The covariance among the chemical production growth rates is the variance of gross global product or 1.32.

As shown by Table 4.1, we expect use of CFC-113 and the Halons to grow more rapidly during the remainder of the century than do the other chemicals. This reflects a typical pattern of chemical use, in that relatively recently marketed "specialty" chemicals that are produced in limited quantities grow rapidly as they are adopted in applications to which they are well suited. Older chemicals, that are produced in larger quantities, may not grow as quickly because they have already been adopted in the applications for which they are best suited. The covariance among the production growth rates is equal to the variance of general global economic growth because the intensities are uncorrelated with one another and with general economic growth.[3]

[3]The total growth rate for the ith chemical, r_i, equals $g + u_i$, where g is the general growth rate and u_i is the growth of intensity of use of the ith chemical relative to general economic growth. Hence, $cov(r_i,r_j) = cov(g + u_i, g + u_j) = var(g) + cov(g,u_i) + cov(g,u_j) + cov(u_i,u_j) = var(g)$, since all the covariances in the last step are equal to zero.

SUBJECTIVE PROBABILITY DISTRIBUTION FOR THE POST-2000 PERIOD

The subjective probability distribution for the post-2000 period is derived from information from a number of sources. We chose parameter values that reflect the rate of general economic growth based on data from William Nordhaus and Gary Yohe.[4] We chose parameter values to reflect the rate of growth of chemicals relative to general economic growth based on concepts developed in Quinn et al. (1986) and the parameter values chosen for the pre-2000 period. Information from the pre-2000 period is used to assure internal consistency in the distribution. This subsection first considers how information from these sources was used and then reports the resulting distribution for the post-2000 period.

Development of the Subjective Probability Distribution

During the post-2000 period, it is much more difficult to rely on detailed analyses of individual chemical applications and markets than it is in the pre-2000 period. Our basic level of uncertainty about events in this period makes it difficult to imagine the range of events that might occur. Quinn et al. (1986), for example, present the best available analysis of the kinds of events that might be important to the markets for PODs after the turn of the century. But even this analysis generally shows less variation in growth rates after 2000 than before. In particular, it allows for no variation in the rate of general economic growth. As a result, we build on the basic concepts developed in Quinn et al. (1986), but seek a more realistically broad range of uncertainty for the growth of production during this period.

Consider first the parameter values of the distribution for the global economic growth rate. We develop parameters for this distribution based on distributions Nordhaus and Yohe have developed on the projected rates of population and labor productivity growth. We start with a weighted average of their parameters for these distributions over the periods 2000-2025 and 2025-2050. We posit a

---

[4]Personal communication with Gary Yohe, Wesleyan University, Middletown, Connecticut, 8 January 1986.

correlation coefficient of -0.2 between population growth and growth in labor productivity over the period 2000-2040.[5] From these, we calculate parameters for use in our analysis. Since the GNP growth rate is approximately the sum of the population and labor productivity growth rates,[6] our mean GNP growth rate is the sum of the means that Nordhaus and Yohe use for population and labor productivity, and our variance is the sum of the variances that they use for population and labor productivity, less a small quantity to take account of the negative correlation between them.[7]

Now consider parameter values of the distributions for growth rates of intensity of use relative to general economic growth. The most important concept in Quinn et al. (1986) is that the rate of growth in the production of PODs will tend toward the rate of general economic growth over the long run. Quinn et al. use gross national product (GNP) per capita as a measure of general economic income. We believe a more appropriate measure is GNP itself, since this captures growth in the income of individuals and in the population as a whole.[8] Hence, we assume that on average intensity of use will not change over the long run.

---

[5]Global labor productivity and population are likely to be inversely correlated over this period because population increases are likely to be in the poorer nations that suffer from shortages of human and physical capital. Using an input-output model of the world economy, Leontief (1979) simulates how variations in population are likely to be inversely correlated with per capita GNP. His results are consistent with the use of a correlation coefficient of -0.2.

[6]See footnote 2 in Sec. III.

[7]The adjustment term is (-0.2)(2)(standard deviation for population growth rate)(standard deviation for growth rate of labor productivity). This term is small enough so that the choice of a correlation coefficient does not change our results much.

[8]It has been suggested that a rate of growth between that of GNP per capita and GNP itself might be most appropriate. That is because, as indicated above, it is likely that population and GNP per capita are negatively correlated. We recognize that by reflecting this negative correlation in our distribution for GNP itself. Once that relationship is accounted for, GNP is a more useful measure of income than GNP per capita.

For most chemicals, that implies a mean of zero for the rate of growth of intensity. The Halons are treated slightly differently. For Halon 1301, we expect recycle and recovery to become important after 2000, creating a source of Halon 1301 that can compete with new production. As a result, even if the annual demand for new Halon 1301 grows at the rate of growth of the GNP, production will grow more slowly. This implies a negative growth rate of intensity of use. For Halon 1201, we expect penetration of the fire extinguishant market to slow beyond 2000, leading to a slightly negative growth rate for intensity of use.

Appropriate variances are harder to choose for these distributions because the range of uncertainty is difficult to conceptualize in markets for individual chemicals this far into the future. We start with the ranges suggested in Quinn et al. (1986). This document develops ranges of growth rates for CFC-11 and -12 and, to a lesser extent, CFC-113. We then compare these ranges with the ranges for these chemicals developed in Quinn et al. and Hammitt et al. (1986) to the pre-2000 period, a period we understand much better.

Our comparison of the range of growth rates in the two periods is based on a second important concept developed in Quinn et al. Uncertainty in either period reflects the joint probabilities of many individual events over time. In a short time period, the number of events relevant to our analysis--changes in regulation, technology, product line, and so on--is small, leading to a possibility that any one of these could lead to very large changes relative to the mean rate of growth. Over a longer period of time, these events tend to have offsetting effects, suggesting that a reasonable range of average annual growth rates in intensity of use should fall over time if the range of events likely in any fixed length of time remains constant. This is simply a reflection of the fact that the variance of a mean of a set of independent, identically distributed random variables falls as the number of variables rises. Because the pre-2000 period is so much shorter than the post-2000 period, we must adjust variances in the two periods before comparing them.

We can use this view of the uncertainties underlying our distributions for intensity growth rates to choose the variance of growth rates in the post-2000 period based on those in the pre-2000 period. To do so, calculate the variance for the pre-2000 period by squaring the chosen standard deviation for each chemical. Multiply this by 15/40 = 0.375 to find the equivalent variance for the longer post-2000 period.[9] Adjust this variance up by a factor to reflect our belief that uncertainty is higher in the post-2000 period. Choosing this factor is inherently arbitrary; after a review of the analysis of likely trends in the post-2000 period in Quinn et al. (1986) and other available sources, we choose a factor of 1.25. Use this new variance as a basis for the standard deviation of the post-2000 distribution for the rate of growth of intensity of use relative to general economic growth. The standard deviations reported in Table 4.2 are based on this calculation.

Parameters of the Joint Distribution

Table 4.2 presents the parameter values of the subjective probability distribution for growth rates in the post-2000 period. Note that the means of our subjective probability distribution for growth rates are generally lower than for the period before 2000, and the standard deviations are also smaller, as discussed above. The means of our subjective probability distribution for the growth rates for all of the PODs except the Halons are equal. Growth rates for the Halons are lower because we expect growth to slow as the likely new applications

---

[9]The variance of a mean of n independently and identically distributed random variables with variance v is v/n. Hence, the ratio of variances for means based on two groups of these variables with group sizes n_1 and n_2 is n_1/n_2. We are not suggesting that events in individual years are independent of one another. But events in a time period as long as five years probably are more or less independent of events in the next five-year period. The proportionality of the two periods is the same whether we consider events within each period associated with one-year or five-year subperiods. We emphasize here that we are dealing with subjective distributions. We use statistical concepts most commonly associated with a frequency view of statistics to formalize our view of the sources of uncertainty underlying our distributions for the two periods.

Table 4.2

PARAMETERS OF THE SUBJECTIVE JOINT PROBABILITY DISTRIBUTION IN THE POST-2000 PERIOD

(In % per year)

	Intensity		Production	
Chemical	Mean	Standard Deviation	Mean	Standard Deviation[a]
CFC-11	0	0.67	2.4	1.17
CFC-12	0	0.72	2.4	1.20
Carbon tetrachloride	0	0.70	2.4	1.19
CFC-113	0	1.15	2.4	1.50
Methyl chloroform	0	0.75	2.4	1.22
Halon 1301	-0.45	1.57	1.95	1.84
Halon 1211	-0.05	1.60	2.35	1.87
Gross global product	2.4	0.96		

[a] The covariance among the chemical production growth rates is the variance of gross global product or 0.92.

for these chemicals are exhausted. The growth is slowest for Halon 1301 where recovery and reuse of the chemical should significantly affect the need for new production as its likely markets are penetrated. Standard deviations are also similar for all of the PODs but CFC-113 and the Halons. Regulatory uncertainty will remain high for CFC-113. We are significantly less certain in general about the future of the Halons than about the future of the other chemicals.

MARGINAL DISTRIBUTIONS FOR INDIVIDUAL CHEMICAL PRODUCTION

Table 4.3 presents some illustrative quantiles of the marginal distributions for production of individual chemicals in 2000, 2020, and 2040, together with estimated current world use. These results suggest that a wide range of outcomes are possible as we move into the future. To understand the full implications of the subjective probability distribution described here, we must view outcomes for chemicals jointly. The joint results are presented in Sec. V.

Table 4.3

PRODUCTION LEVELS AT SPECIFIED QUANTILES OF THE SUBJECTIVE MARGINAL PROBABILITY DISTRIBUTIONS FOR INDIVIDUAL CHEMICALS

(In thousands of metric tons)

Chemical/ Year	Quantile				
	0.05	0.25	0.50	0.75	0.95
CFC-11					
1985	342	342	342	342	342
2000	386	479	556	644	794
2040	466	907	1435	2263	4326
CFC-12					
1985	444	444	444	444	444
2000	425	532	622	725	901
2040	504	1001	1606	2565	4994
Carbon tetrachloride					
1985	1029	1029	1029	1029	1029
2000	1070	1335	1554	1807	2237
2040	1280	2519	4014	6371	12290
CFC-113					
1985	163	163	163	163	163
2000	262	348	422	512	671
2040	256	605	1091	1956	4476
Methyl chloroform					
1985	545	545	545	545	545
2000	574	721	844	986	1229
2040	672	1349	2179	3506	6893
Halon 1301					
1985	11	11	11	11	11
2000	11	16	20	26	37
2040	7	21	44	92	259
Halon 1211					
1985	11	11	11	11	11
2000	11	16	20	26	37
2040	8	25	53	111	315

V. PRODUCTION SCENARIOS BASED ON QUANTILES OF THE SCORE FUNCTION

Applying the methods described in Sec. III to the subjective probability distribution defined in Sec. IV yields scenarios that we can use to project alternative futures for the seven PODs analyzed here. This section explains how the final calculations are made and presents a set of production scenarios based on our technique.

CHOOSING THE QUANTILES TO USE FOR SCENARIO DEVELOPMENT

A production scenario is based on a particular quantile of the distribution of the score function defined in Sec. III. We use the 5th, 25th, 50th, 75th, and 95th percentiles as a basis for scenarios that represent, respectively, lower limit, low, middle, high, and upper limit cases relevant to policy decisions. Other scenarios could obviously be developed without difficulty using the techniques described here. These five appear to describe the relevant policy space in a way that facilitates analysis.

Viewed in the context of EPA's policy analysis, the middle three scenarios--representing low, middle, and high growth--should be the most useful. The middle case represents a scenario defined such that the effect of these seven PODs on ozone depletion is equally likely to be greater or smaller than the effect corresponding to this scenario. Analogously, the low and high growth scenarios are defined such that the probabilities of greater or lesser effects as a result of these chemicals, conditional on the effect being greater or smaller than the median case, are equal. Thus, these three scenarios encapsulate information on regions of the distribution for ozone depletion that reflect the likely range of outcomes for these seven chemicals. The limiting scenarios at the 5th and 95th percentiles are better used to think about the outer bounds of reasonable results than to convolute with other sources of uncertainty in EPA's planned generation of many cases.

We start the development of scenarios with chemical weights for the score function that reflect relative production levels in 1985. Table 5.1 presents these weights. These weights, together with the values of the standard deviations from Sec. IV and Eq. (3.8) from Sec. III, allow us to calculate the value β with which to transform z-statistics from the distribution for the score function into z-statistics for the component economic-growth and intensity distributions. These identify intensity and general economic growth rates that can be used to calculate a growth rate for each chemical for each scenario during the pre-2000 period. These growth rates, applied to actual production levels in 1985, allow us to calculate the production paths relevant to each chemical for each scenario up to 2000.

The calculations for the post-2000 period are analogous. We use different weights and consequently a different value of β, based on 2000 production levels for the 50th percentile growth scenario. These are also reported in Table 5.1.

Table 5.1

CHEMICAL WEIGHTS

Chemical	1985	2000	Difference
CFC-11	0.265	0.255	-0.010
CFC-12	0.344	0.285	-0.059
Carbon tetrachloride	0.051	0.045	-0.006
CFC-113	0.126	0.193	0.067
Methyl chloroform	0.043	0.038	-0.005
Halon 1301	0.085	0.092	0.007
Halon 1211	0.085	0.092	0.007

NOTE: The concepts underlying these weights are explained in Secs. II and III. They reflect the production level, share of production that is emitted, and potential ozone-depletion risk per gram in the atmosphere of each chemical. Of these factors, we assume that only production levels differ between the periods before and after 2000.

Median growth rates differ enough across chemicals during the pre-2000 period to lead to significant shifts in the chemical weights between 1985 and 2000. This means that our weighting system is only approximate over this period; it effectively represents the use of a Laspeyres index, with its potential problems. Median growth rates after 2000 are equal for all chemicals but the Halons. Although we use a constant set of weights over a significantly longer period of time after 2000, the actual weights do not shift as much over this period as they do from 1985 to 2000.[1]

Applying these weights in Eq. (3.8) yields β values of 1.93 before 2000 and 1.83 afterward. These yield the z-statistics for individual scenarios shown in Table 5.2. The results in this table make it clear how important it is to view chemicals jointly rather than individually. To construct scenarios for the 5th percentile of the score function, we must use z-statistics for component distributions that are consistent with the 18th to 20th percentiles of these distributions. A 25th percentile scenario uses z-statistics consistent with the 36th percentile of the component distributions. Similar adjustments apply for higher percentile scenarios. Viewing these seven chemicals together significantly narrows the range of growth rates represented in the scenarios before and after 2000; the effect is slightly smaller after 2000.

CHEMICAL USE SCENARIOS

Taken together with the parameter values from Sec. IV, the z-statistics in Table 5.2 yield the growth rates in Table 5.3 as the bases for production scenarios. Table 5.4 shows the production levels that result from these growth rates for 1985, 2000, 2020, and 2040. Numbers like these calculated for the intervening years provide the basis for calculating emission scenarios, which in turn can provide inputs to the type of policy analysis EPA is currently pursuing. Moving

[1]The largest difference is about 0.013, for Halon 1301. Weights corresponding to the median growth scenario in 2040 are CFC-11, 0.257; CFC-12, 0.288; carbon tetrachloride, 0.046; CFC-113, 0.196; methyl chloroform, 0.039; Halon 1301, 0.079; and Halon 1211, 0.095.

Table 5.2

Z-STATISTICS AND β VALUES FOR DISTRIBUTIONS OF THE SCORE FUNCTION AND COMPONENTS

Quantile of the Score Function	z-Statistics		
	Score Function	Pre-2000 Components	Post-2000 Components
0.05	-1.645	-.854	-.899
0.25	-0.675	-.351	-.369
0.50	0	0	0
0.75	0.675	.351	.369
0.95	1.645	.854	.899
β value		1.93	1.83

beyond these productions scenarios, however, takes us beyond the scope of this Note.[2]

[2]For information on how to transform production scenarios into emission scenarios, see Palmer et al. (1980).

Table 5.3

GROWTH RATES FOR SCENARIOS BEFORE AND AFTER 2000

(In % per year)

Chemical	Period	Scenarios/Quantiles of the Score Function				
		0.05	0.25	0.50	0.75	0.95
CFC-11	Pre-2000	1.47	2.54	3.29	4.03	5.12
	Post-2000	0.93	1.80	2.40	3.00	3.86
CFC-12	Pre-2000	0.39	1.50	2.27	3.04	4.15
	Post-2000	0.89	1.78	2.40	3.02	3.91
Carbon tetrachloride	Pre-2000	4.15	5.56	6.55	7.54	8.97
	Post-2000	0.51	1.63	2.40	3.18	4.29
CFC-113	Pre-2000	1.03	2.17	2.96	3.74	4.88
	Post-2000	0.86	1.77	2.40	3.03	3.94
Methyl chloroform	Pre-2000	0.93	2.03	2.79	3.55	4.64
	Post-2000	0.91	1.79	2.40	3.01	3.89
Halon 1301	Pre-2000	1.12	2.94	4.07	5.34	7.15
	Post-2000	-0.20	-1.07	2.00	2.92	4.22
Halon 1211	Pre-2000	1.12	2.94	4.07	5.34	7.15
	Post-2000	-0.19	1.51	2.47	3.39	4.72

Table 5.4

SELECTED PRODUCTION LEVELS FOR SCENARIOS
BASED ON QUANTILES OF THE SCORE FUNCTION

(In thousands of metric tons)

Chemical/ Year	Quantile				
	0.05	0.25	0.50	0.75	0.95
CFC-11					
1985	342	342	342	342	342
2000	426	498	556	619	723
2040	617	1017	1435	2022	3295
CFC-12					
1985	444	444	444	444	444
2000	471	555	622	696	817
2040	671	1124	1606	2287	3788
Carbon tetrachloride					
1985	1029	1029	1029	1029	1029
2000	1183	1391	1554	1736	2032
2040	1701	2827	4014	5686	9343
CFC-113					
1985	163	163	163	163	163
2000	300	367	422	485	591
2040	367	700	1091	1695	3174
Methyl chloroform					
1985	545	545	545	545	545
2000	636	752	844	946	1113
2040	897	1517	2179	3123	5217
Halon 1301					
1985	11	11	11	11	11
2000	13	17	20	24	31
2040	12	26	44	76	162
Halon 1211					
1985	11	11	11	11	11
2000	13	17	20	24	31
2040	14	31	53	91	196

VI. CONCLUSIONS

The EPA faces a difficult policy problem. The agency needs to understand the many uncertainties that affect the relationship between decisions to reduce the global use of PODs and the effects that such reduction might have on human health, materials degradation, crop yields, and other activities of interest. We address only a small subset of these uncertainties in this Note. But the relationship of these uncertainties to other parts of this policy problem provides the basic motivation. On the one hand, the problem is so complex that it must be broken into pieces if we hope to produce useful results. On the other, the characterization of uncertainties in any part of this problem is likely to be more useful if it properly reflects the concerns of the problem as a whole. We offer a way to build scenarios relevant to one piece of the problem that relates them back to the problem as a whole.

This Note addresses uncertainties associated with production of seven PODs. Ideally, we would like to develop a subjective probability distribution for these chemicals and convolute the uncertainties reflected in this distribution with other sources of uncertainty relevant to stratospheric ozone depletion. In such an approach, developing a probability distribution for the PODs would be one step in a process to develop a distribution for ozone depletion itself. This cannot be done because the cost of calculating ozone-depletion profiles is too high to allow extensive use of the Monte Carlo methods needed to convolute all of the uncertainties relevant to ozone depletion in a complete and detailed way.

Calculation costs dictate that only a limited number of cases be considered in the atmospheric models used to study ozone depletion. Hence, we must assure that the cases considered embody as much information as possible. That is, whether we examine it in detail or not, a distribution for ozone depletion exists that is consistent with our assumptions about the uncertainties associated with inputs to the atmospheric models and with the models themselves. Since we cannot investigate this distribution of ozone depletion directly and in detail,

the cases we use to examine parts of the distribution should tell us something about where they lie in the distribution and about the probability density of the distribution in their vicinity. Our method provides a way to relate scenarios for the future production of seven PODs to the probability distribution for ozone depletion.

The specific method we use is simple; the concept it is based on could be used to develop more complex methods that might be more satisfactory. It remains for future analysis to determine how much improvement additional complexity would allow. For now, the specific method we offer can be thought of as an illustration of a more general conceptual approach and a practical way to implement that approach until a better method is developed.

Here is a quick overview of the approach. Characterize uncertainty about the growth rates of general economic activity and intensity of use of chemicals relative to it with independent normal probability distributions. Choose values for the means and variances of these distributions. Define a policy-relevant score function as a linear combination of these growth rates. Calculate the mean and variance of its subjective probability distribution. Define scenarios in terms of quantiles of the distribution of the score function. Identify growth rates in the component distributions that are compatible with the value of the score function for the quantile defining each scenario; use a simple convention to do this. Use the growth rates of the component distributions for a scenario to calculate the growth rates for each chemical in that scenario.

The key to this approach is the score function. It provides a policy-relevant scale with which to compare alternative scenarios for seven chemicals along a single dimension. The dimension chosen is one that should be related to the ozone depletion likely to result from the scenarios it is used to describe. The relationship is probably crude, but the scale reflects the kind of simple weighting scheme that EPA policymakers have found useful in the past to specify the relative danger associated with different chemicals and hence the joint danger associated with any set of production levels of these chemicals. More complicated score functions could be considered if we were interested in using a Monte Carlo technique to convolute uncertainties. Ironically,

as the score function comes closer to approximating the actual joint effect of a set of chemicals on ozone depletion, using it to develop scenarios may become less attractive. That is because a direct approach to the subjective probability distribution for ozone depletion becomes more attractive, eliminating the need for developing scenarios.

Restricting our subjective distributions to normal distributions and relying on linear approximations simplifies the analysis considerably and in fact makes a closed analytical solution to the convolution of uncertainties possible. Abandoning normality, or some other parametric distributions, would give us greater freedom to reflect uncertainties as we see them but would require the use of a simulation technique like Monte Carlo to convolute uncertainties. Once this step is taken, we probably no longer need to rely on linear approximations. Simulations themselves, of course, typically require simplifying assumptions and approximations to implement them at a reasonable cost. Whether the approximations associated with normal distributions and linear aggregations here induce more serious errors than the simplifications and approximations required by a technique like Monte Carlo is an empirical question. It deserves closer attention if this approach is to be used often in the future.

Whether an analytical approach like that used here or a Monte Carlo approach is taken, the interrelationships among chemicals deserve more attention. For example, CFC-11 and -12 are produced together. Although the proportions in which they are produced are variable, it would be surprising if cost considerations did not induce a positive correlation in their production rates. Alternatively, CFC-113 and methyl chloroform are substitutes, but both are subject to a similar set of government regulations. Changes in markets and regulations that underlie the scenarios used here could induce either a negative or positive correlation in their growth rates. These considerations and others like them suggest that future efforts to build scenarios for these chemicals should give closer attention to the relationships in intensity of use for different chemicals. Our technique makes that simple to do.

The techniques proposed here can produce a wide variety of scenarios. They are based on simple quantiles of the score function. The low, middle, and high growth scenarios associated with the 25th,

50th, and 75th percentiles of its distribution characterize the relevant policy space and should properly represent a reasonable range of effects of market and technological developments in the larger context of EPA's policy analysis. Developing scenarios for other factors conditional on the rate of general economic growth might also be worth exploring. That is because the level of the effects of ozone depletion on human activities like materials degradation and crop yields is likely to depend on the general rate of economic growth: Higher chemical growth rates will presumably have larger effects on ozone depletion which, in turn, will have more effect on crop yields if high economic growth has created a demand for more crops. Such relationships may prove to be quite important in sorting out the joint effects of different sources of uncertainty. Our technique could accommodate scenarios conditioned on general economic growth by calculating the moments for score functions conditional on economic growth rates; how those growth rates would be chosen remains a problem.

In the end, the approach taken in this Note offers a simple solution to a complex problem. More complex solutions may well justify their additional costs but that is not immediately clear. Additional attention to substantive issues associated with the construction of scenarios for application to the issue of potential ozone depletion is likely to be more productive in the short run.

Appendix

BASIC CODE USED TO IMPLEMENT AGGREGATIONS AND CONVOLUTION

This appendix documents four BASIC programs that we employ to convolute the distributions corresponding to different applications of CFC-11 and CFC-12, and to total use of each chemical. In general, variable names follow a few rules. Those beginning with "mid" indicate mean growth rates; those beginning with "sig" indicate standard deviations. The suffix ".g" refers to GNP, ".int" to intensity of use, and ".com" to total use (combined GNP and intensity effects).

The first program is used to derive the means and standard deviations of the distributions of the intensity growth rates for CFC-11 and CFC-12 from the information presented in Hammitt et al. (1986). That source projects use in each major application for the United States and the other CMA reporting countries separately. It provides a baseline projected use for each application and region together with factors that, when multiplied by the base projected use in 2000, characterize an 80 percent subjective probability interval for use. The program uses the estimated 1985 use, the projected base use in 2000, the factors characterizing the uncertainty range, and the parameters of the subjective distribution for GNP growth to calculate the parameters of the intensity growth rates for each region and application. It also convolutes these distributions to calculate the parameters of the distribution of rate of growth of intensity of total CFC-11 or CFC-12 use by region.

The second program is used to aggregate chemical use across regions. It takes as input the estimated 1985 use, projected baseline 2000 use, and factors characterizing the 80 percent subjective probability interval to calculate the parameters of the intensity growth rates by region, and convolute these to find the parameters of the world intensity growth rate. A similar program that uses the parameters of the intensity growth rate distributions for each region is used to calculate the parameters of the distribution of world intensity growth rates for CFC-11 and -12.

The third program calculates the parameters of the score function distribution. As input, it requires the parameters of the distribution of world GNP growth, world intensity growth for each chemical, and weights that reflect the relative ozone-depletion potency of each chemical. We run this program twice to calculate the parameters corresponding to each period separately.

The last program is used to calculate the production of each chemical corresponding to different quantiles of the score function, and to quantiles of the marginal distributions for individual chemical growth. As input it requires the intensity and GNP growth rates for the pre- and post-2000 periods and the values of β for each period. Variable names ending in ".e" indicate first (early) period values whereas names ending in ".l" indicate values in the later period. These suffixes are sometimes combined with the suffixes mentioned earlier; for example, ".eg" refers to GNP growth in the first period.

A listing of the program code follows:

PROGRAM 1: BASIC CODE TO CALCULATE PARAMETERS OF CFC-11 AND CFC-12 INTENSITY GROWTH RATES, BY REGION AND APPLICATION, 1985-2000

```
100     rem  file cfc.bas to calculate CFC-11 and 12 intensity
110     rem  for US and non-US reporting companies
120     open "incfc" for input as #1
130     input#1,n,mid.g,sig.g
140     for i = 1 to n
150     input#1,b0(i),bn(i),lofact(i),hifact(i)
160     next
170     base = 0
180     for i = 1 to n
190     lorate(i) = (bn(i) * lofact(i) / b0(i))^(1/15)
200     lorate(i) = (lorate(i) - 1) * 100
210     hirate(i) = (bn(i) * hifact(i) / b0(i))^(1/15)
220     hirate(i) = (hirate(i) - 1) * 100
230     mid(i) = (lorate(i) + hirate(i)) / 2 - mid.g
240     sig(i) = (hirate(i) - lorate(i)) / (2 * 1.2816)
241     sig(i) = (sig(i)^2 - sig.g^2)^0.5
250     base = base + b0(i)
260     next
270     mid.int = 0
280     sig.int = 0
290     for i = 1 to n
300     share(i) = b0(i) / base
310     midterm(i) = share(i) * mid(i)
320     sigt(i) = share(i) * sig(i)
```

```
330     sigtsq(i) = sigt(i)^2
340     mid.int = mid.int + midterm(i)
350     sig.int = sig.int + sigtsq(i)
360     next
370     mid.com = mid.int + mid.g
380     sig.com = (sig.int + sig.g^2)^0.5
390     sig.int = sig.int^0.5
400     open "outcfc" for output as #2
410     print "mid.int = ",mid.int
420     print "sig.int = ",sig.int
430     print#2,"mid.int = ",mid.int
440     print#2,"sig.int = ",sig.int
450     print#2,"mid.g = ",mid.g
460     print#2,"sig.g = ",sig.g
470     print#2,"mid.com = ",mid.com
480     print#2,"sig.com = ",sig.com
490     print#2,"  share(i)";"  mid(i)  ";"  sig(i)"
500     for i = 1 to n
510     print#2,using"#####.####";share(i),mid(i),sig(i)
520     next
530     print#2,"b0","bn","lofact","hifact","lorate","hirate"
540     for i = 1 to n
550     print#2,b0(i),bn(i),lofact(i),hifact(i),lorate(i),hirate(i)
560     next
```

PROGRAM 2: BASIC CODE TO CALCULATE PARAMETERS OF WORLD INTENSITY GROWTH RATES FOR OTHER CHEMICALS, 1985-2000

```
100     rem  file chm.bas to calculate world intensity for other chemicals
110     open "inchm" for input as #1
120     input#1,n
130     rho(1) = 1.00
140     rho(2) = 0.75
150     mid.g(1) = 3.0
160     sig.g(1) = 1.17
170     mid.g(2) = 3.5
180     sig.g(2) = 1.17
190     mid.g(3) = 3.0
200     sig.g(3) = 1.56
210     for i = 1 to n
220     input#1,b0(i),bn(i),lofact(i),hifact(i)
230     next
240     base = 0
250     for i = 1 to n
260     lorate(i) = (bn(i) * lofact(i) / b0(i))^(1/15)
270     lorate(i) = ((lorate(i) - 1) * 100) - mid.g(i)
280     hirate(i) = (bn(i) * hifact(i) / b0(i))^(1/15)
290     hirate(i) = ((hirate(i) - 1) * 100) - mid.g(i)
300     mid(i) = (lorate(i) + hirate(i)) / 2
310     sig.c(i) = (hirate(i) - lorate(i)) / (2 * 1.2816)
320     sig(i) = ((sig.c(i)^2) - (sig.g(i)^2))^0.5
330     base = base + b0(i)
340     next
```

```
350     mid.int = 0
360     sig.int = 0
370     for i = 1 to n
380     share(i) = b0(i) / base
390     midterm(i) = share(i) * mid(i)
400     sigt(i) = share(i) * sig(i)
410     sigtsq(i) = sigt(i)^2
420     mid.int = mid.int + midterm(i)
430     sig.int = sig.int + sigtsq(i)
440     next
450     if n = 3 then goto 480
460     crossprd = 2 * sigt(1) * sigt(2)
470     goto 490
480     crossprd = 2 * (sigt(1)*sigt(2) + sigt(1)*sigt(3) + sigt(2)*sigt(3))
490     for i = 1 to 2
500     sig.int(i) = (sig.int + rho(i) * crossprd)^0.5
510     next
520     open "outchm" for output as #2
530     print "mid.int = ",mid.int
540     print "rho,std dev"
550     for i = 1 to 2
560     print rho(i),sig.int(i)
570     next
580     print#2,"mid.int = ",mid.int
590     print#2,"rho,std dev"
600     for i = 1 to 2
610     print#2,rho(i),sig.int(i)
620     next
630     print#2,"mid(i)","sig(i)","share(i)"
640     for i = 1 to n
650     print#2,mid(i),sig(i),share(i)
660     next
670     print#2,"b0","bn","lofact","hifact","lorate","hirate"
680     for i = 1 to n
690     print#2,b0(i),bn(i),lofact(i),hifact(i),lorate(i),hirate(i)
700     next
```

PROGRAM 3: BASIC CODE TO CALCULATE PARAMETERS OF THE DISTRIBUTION OF THE SCORE FUNCTION

```
100     rem  file joint.bas to calculate joint scenarios for all chemicals
110     rem  uses world gnp and world intensity distributions for each chemical
120     open "injoint" for input as #1
130     input#1,n,mid.g,sig.g
140     base = 0
150     for i = 1 to n
160     input#1,wgt(i),b0(i),mid(i),sig(i)
170     share(i) = wgt(i) * b0(i)
180     base = base + share(i)
190     next
200     mid.int = 0
210     sig.int = 0
220     beta = 0
```

```
230     for i = 1 to n
240     share(i) = share(i) / base
250     midterm(i) = share(i) * mid(i)
260     mid.int = mid.int + midterm(i)
270     sigt(i) = share(i) * sig(i)
280     sig.int = sig.int + sigt(i)^2
290     beta = beta + sigt(i)
300     next
310     mid.com = mid.int + mid.g
320     sig.com = (sig.int + sig.g^2)^0.5
330     sig.int = sig.int^0.5
340     beta = (beta + sig.g) / sig.com
350     open "outjoint" for output as #2
360     print "mid.com = ",mid.com
370     print "sig.com = ",sig.com
380     print "mid.int = ",mid.int
390     print "sig.int = ",sig.int
400     print"mid.g= ",mid.g
410     print"sig.g= ",sig.g
420     print "beta = ",beta
430     print#2,"mid.com = ",mid.com
440     print#2,"sig.com = ",sig.com
450     print#2,"mid.int = ",mid.int
460     print#2,"sig.int = ",sig.int
470     print#2,"mid.g = ",mid.g
480     print#2,"sig.g = ",sig.g
490     print#2,"beta = ",beta
500     print#2,"mid(i)","sig(i)","share(i)"
510     for i = 1 to n
520     print#2,mid(i),sig(i),share(i)
530     next
540     print#2,"wgt(i)","b0(i)","midterm(i)","sigt(i)"
550     for i = 1 to n
560     print#2,wgt(i),b0(i),midterm(i),sigt(i)
570     next
```

PROGRAM 4: BASIC CODE TO CALCULATE CHEMICAL PRODUCTION CORRESPONDING TO QUANTILES OF THE SCORE FUNCTION AND TO QUANTILES OF MARGINAL CHEMICAL USE DISTRIBUTIONS

```
100     rem  file scenar.bas to calculate quantiles of joint and individual
110     rem  chemical production distributions over time
120     rem  subscript 1--CFC-11, 2--CFC-12, 3--CT, 4--CFC-113, 5--MC,
130     rem  6--Halon 1301, 7--Halon 1211, 0--Joint weighted production
140     open "inscen" for input as #1
150     dim g(5,11),q(5,7,11),c(5,7,11),year(11)
160     input#1,beta.e,beta.l
170     input#1,mid.eg,sig.eg,mid.lg,sig.lg
180     for i = 0 to 7
190     input#1,b0(i),mid.e(i),sig.e(i),mid.l(i),sig.l(i)
200     next
210     data -1.645,-0.675,0.0,0.675,1.645
220     for j = 1 to 5
```

```
230     read zj(j)
240     zc.e(j) = zj(j) / beta.e
250     zc.l(j) = zj(j) / beta.l
260     rate.eg(j) = mid.eg + zc.e(j) * sig.eg
270     rate.e(j,0) = mid.e(0) + zj(j) * sig.e(0)
280     for t = 0 to 3
290     g(j,t) = (1 + rate.eg(j)/100)^(t * 5)
300     q(j,0,t) = b0(0) * (1 + rate.e(j,0)/100)^(t * 5)
310     next t
320     rate.lg(j) = mid.lg + zc.l(j) * sig.lg
330     rate.l(j,0) = mid.l(0) + zj(j) * sig.l(0)
340     for t = 4 to 11
350     tm3 = t - 3
360     g(j,t) = g(j,3) * (1 + rate.lg(j)/100)^(tm3 * 5)
370     q(j,0,t) = q(j,0,3) * (1 + rate.l(j,0)/100)^(tm3 * 5)
380     next t
390     for i = 1 to 7
400     rate.e(j,i) = mid.e(i) + zc.e(j) * sig.e(i) + rate.eg(j)
410     rc.e(j,i) = mid.e(i) + mid.eg + (zj(j) * (sig.e(i)^2 + sig.eg^2)^0.5)
420     for t = 0 to 3
430     q(j,i,t) = b0(i) * (1 + rate.e(j,i)/100)^(t * 5)
440     c(j,i,t) = b0(i) * (1 + rc.e(j,i)/100)^(t * 5)
450     next t
460     rate.l(j,i) = mid.l(i) + zc.l(j) * sig.l(i) + rate.lg(j)
470     rc.l(j,i) = mid.l(i) + mid.lg + (zj(j) * (sig.l(i)^2 + sig.lg^2)^0.5)
480     for t = 4 to 11
490     tm3 = t - 3
500     q(j,i,t) = q(j,i,3) * (1 + rate.l(j,i)/100)^(tm3 * 5)
510     c(j,i,t) = c(j,i,3) * (1 + rc.l(j,i)/100)^(tm3 * 5)
520     next t
530     next i
540     next j
550     open "outscen" for output as #2
560     print#2,"zj(k)","zc.e(k)","zc.l(k)"
570     for k = 1 to 5
580     print#2,zj(k),zc.e(k),zc.l(k)
590     next k
600     print#2,"  "
610     print#2,"GNP"
620     print#2,"Components of Joint Quantiles"
630     print#2,"year","g(.05)","g(.25)","g(.50)","g(.75)","g(.95)"
640     for t = 0 to 11
650     year(t) = t * 5 + 1985
660     print#2,year(t),g(1,t),g(2,t),g(3,t),g(4,t),g(5,t)
670     next t
680     for i = 0 to 7
690     print#2,"  "
700     if i = 0 then print#2,"Joint weighted chemical production"
810     if i = 1 then print#2,"CFC-11"
820     if i = 2 then print#2,"CFC-12"
830     if i = 3 then print#2,"Carbon tetrachloride"
840     if i = 4 then print#2,"CFC-113"
```

```
850     if i = 5 then print#2,"Methyl chloroform"
860     if i = 6 then print#2,"Halon 1301"
870     if i = 7 then print#2,"Halon 1211"
880     print#2,"Components of Joint Quantiles"
890     print#2," year";"       c(.05)";"       c(.25)";"       c(.50)";
                "       c(.75)";"       c(.95)"
900     for t = 0 to 11
910     print#2,using"#####       ";year(t),q(1,i,t),q(2,i,t),q(3,i,t),
                q(4,i,t),q(5,i,t)
920     next t
930     next i
940     for i = 1 to 7
950     print#2,"  "
960     if i = 1 then print#2,"CFC-11"
970     if i = 2 then print#2,"CFC-12"
980     if i = 3 then print#2,"Carbon tetrachloride"
990     if i = 4 then print#2,"CFC-113"
1000    if i = 5 then print#2,"Methyl chloroform"
1010    if i = 6 then print#2,"Halon 1301"
1020    if i = 7 then print#2,"Halon 1211"
1030    print#2,"Quantiles of Chemical Production"
1040    print#2," year";"       c(.05)";"       c(.25)";"       c(.50)";
                "       c(.75)";"       c(.95)"
1050    for t = 0 to 11
1060    print#2,using"#####       ";year(t),c(1,i,t),c(2,i,t),c(3,i,t),
                c(4,i,t),c(5,i,t)
1070    next t
1080    next i
```

REFERENCES

Hammitt, James K., Kathleen A. Wolf, Frank Camm, William E. Mooz, Timothy H. Quinn, and Anil Bamezai, *Product Uses and Market Trends for Potential Ozone-Depleting Substances: 1985-2000*, The Rand Corporation, R-3386-EPA, May 1986.

Hirshleifer, Jack, *Price Theory and Applications*, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1976

Kahneman, Daniel, Paul Slovic, and Amos Tversky, *Judgment Under Uncertainty: Heuristics and Biases*, Cambridge University Press, Cambridge, 1982.

Leontief, Wassily, "Population Growth and Economic Development: Illustrative Projections," *Population and Development Review*, Vol. 5, No. 1, 1979.

National Academy of Sciences, *Halocarbons: Effects on Stratospheric Ozone*, Washington D.C., 1976.

National Academy of Sciences, *Protection against Depletion of Stratospheric Ozone*, Washington D.C., 1979.

National Academy of Sciences, *Causes and Effects of Stratospheric Ozone Depletion: An Update*, Washington D.C., 1982.

National Academy of Sciences, *Causes and Effects of Changes in Stratospheric Ozone: Update 1983*, Washington D.C., 1984.

Palmer, Adele R., William E. Mooz, Timothy H. Quinn and Kathleen A. Wolf, *Economic Implications of Regulating Chlorofluorocarbon Emissions from Nonaerosol Applications*, The Rand Corporation, R-2524-EPA, June 1980.

Quinn, Timothy, Kathleen A. Wolf, William E. Mooz, James K. Hammitt, Thomas W. Chesnutt, and Syam Sarma, *Projected Use, Emissions and Banks of Potential Ozone-Depleting Substances*, The Rand Corporation, N-2282-EPA, January 1986.

Ramanthan, V., R. J. Cicerone, H. B. Singh, and T. J. Kiehl, "Trace Gases and Their Potential Role in Climatic Change," *J. Geophysical Res.*, Vol. 90, June 20, 1985.

U.S. Environmental Protection Agency, "Ozone-Depleting Chlorofluorocarbons, Proposed Production Restriction," *Federal Register*, Vol. 45, No. 196, October 7, 1980, pp. 66726-66734.