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SYNTHESIS REPORT

(Integration of the four assessment panels reports by the Open-ended Working Group of the Parties to the Montreal Protocol)

13 November 1989

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1.0 INTRODUCTION

The Montreal Protocol on Substances that Deplete the Ozone Layer entered into force on 1 January 1989. Article 6 of the Protocol: Assessment and Review of Control Measures requires that

> "Beginning in 1990, and at least every four years thereafter, the Parties shall assess the control measures provided for in Article 2 on the basis of available scientific, environmental, technical, and economic information. At least one year before each assessment, the Parties shall convene appropriate panels of experts qualified in the fields mentioned and determine the composition and terms of reference of any such panels. Within one year of being convened, the panels will report their conclusions, through the Secretariat, to the Parties."

On 17-18 October 1988, at The Hague, Netherlands, in compliance with Article 6 and in anticipation of the coming into force of the Protocol, an Ad Hoc Working Group of Legal and Technical Experts for the Harmonization of Data on Production, Imports, and Exports of Substances that Deplete the Ozone Layer established four review panels and outlined their terms of reference and timetables for completing reviews of available scientific, environmental, technical, and economic information. This process was approved by the Parties to the Protocol at their first meeting in Helsinki, Finland on 2 - 5 May 1989. The Parties also confirmed UNEP as the Secretariat for the Vienna Convention for the Protection of the Ozone Layer and its Montreal Protocol.

The reports of the assessment panels contain the main conclusions reached by those panels and represent the judgement of several hundred experts of appropriate disciplines and selected from 21 developed and 9 developing countries. The reports of each of the four panels incorporated an extensive peer-review process in their original language (English). They will be published and distributed by UNEP in the latter part of 1989. Copies will be made available to Parties to the Vienna Convention and Montreal Protocol; all other member states of the United Nations; and to interested organizations, institutions, and individuals worldwide.

The panel reports were chaired as follows:

- The report of the Ozone Scientific Assessment Panel, chaired by Dr. Robert Watson and Dr. Daniel Albritton (United States of America) 136 scientists from 25 countries contributed to the preparation and review of the report (87 scientists from 15 countries prepared the report, and 78 scientists from 23 countries participated in the peer review process). World Meteorological Organization (WMO) assisted in this effort.

- The report of the Environmental Effects Panel chaired by Dr. Jan van der Leun (The Netherlands) and Dr. Manfred Tevini (Federal Republic of Germany). 48 scientists from 17 countries participated in the preparation and peer review of the report (20 scientists from 8 countries prepared the report, and 28 scientists from 12 countries peer reviewed the report).

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- The report of the Technology Review Panel chaired by Mr. Victor Buxton (Canada) and Dr. Stephen Andersen (United States of America). 110 experts from 22 countries prepared the report. An even greater number, involving experts from additional countries, participated in the peer review process.

- The report of the Economic assessment Panel chaired by Mr. George Strongylis (European Economic Community), and co-chaired by Dr. Stephen Andersen and Mr. John Hoffman (United States of America). 24 experts from 12 countries prepared the report that was peer reviewed by 25 experts from 18 countries.

The Technology Review Panel Report is a summary of five-detailed Technical Options Reports prepared by international subcommittees of sector specific experts. The five technical reports are:

- Refrigeration, Air Conditioning and heat Pumps, chaired by Dr. Lambert Kuijpers (The Netherlands),

- Rigid and Flexible Foams, chaired by Ms. Jean Lupinacci (USA)

- Electronic, Degreasing and Dry Cleaning Solvents, chaired by Dr. Stephen Andersen (USA)

- Aerosols, Sterilants and Miscellaneous Uses of CFCs, chaired by Mrs. Ingrid Kokeritz (Sweden), and

- Halon Fire Extinguishing Agents, chaired by Mr. Gary Taylor (Canada).

This document is based on the key findings of the four Panel reports (science, environmental effects, technology, and economics).

2.0 ASSESSMENT SUMMARIES

The major findings of the four assessment reports are summarized in the following subsections.

2.1 Scientific Assessment of Stratospheric Ozone

Recent Findings

Remarkable progress has been made in stratospheric ozone science in the past few years. There have been highly significant advances in the understanding of the impact of human activities on the Earth's protective ozone layer. Since the Montreal Protocol was signed, there have been four major findings each of which heightens the concern that chlorine- and bromine-containing chemicals can lead to a significant depletion of stratospheric ozone:

- Antarctic Ozone Hole: The weight of scientific evidence strongly indicates that chlorinated (largely man-made) and brominated chemicals are primarily responsible for the recently discovered substantial decreases of stratospheric ozone over Antarctica in springtime.

- Perturbed Arctic Chemistry: While at present ozone changes over the Arctic are not comparable to those over the Antarctic, the same potentially ozone-destroying processes have been identified in the Arctic stratosphere. The degree of any future ozone depletion will probably depend on the particular meteorology of each Arctic winter and future atmospheric levels of chlorine and bromine.

- Long-Term Ozone Decreases: The analysis of the total-column ozone data from ground-based instruments show measurable downward trends from 1969 to 1988 of 3 to 5.5 per cent in the northern hemisphere (30 to 64°N latitudes) in the winter months that cannot be attributed to known natural processes.

- Model Limitations: These findings have led to the recognition of major gaps in theoretical models used for assessment studies. Assessment models do not simulate adequately polar stratospheric cloud (PSC) chemistry or polar meteorology. The impact of these shortcomings for the prediction of ozone layer depletion at higher latitudes is uncertain. Not all models include consideration of the effects of carbon dioxide atmospheric accumulation. Those models that do include this effect show somewhat lower ozone depletion compared to those that do not include the effect.

These and other findings are based upon the results from several major ground-based and aircraft field campaigns in the polar regions, a reanalysis of ground-based ozone data from the past thirty one years, a reanalysis of satellite ozone and PSC data, laboratory studies of gas-phase and surface-induced chemical processes, and model simulations incorporating these new laboratory data and observations.

Other Important Scientific Findings:

- Table 1 shows calculated values of the Ozone Depleting Potentials (ODP) and Global Warming Potentials (GWP)for the CFCs and halons currently included in the Montreal Protocol, carbon tetrachloride (carbon tetrachloride), methyl chloroform (CH_3CCl_3) and potential HCFC and HFC substitutes. In general, the ODPs and GWPs of the potential substitutes and methyl chloroform are significantly lower than those of the controlled substances because of their shorter atmospheric life times. Even for the lower ODP and GWP chemicals, the volume of use needs to be considered.

Implications

The findings and conclusions from the intensive and extensive ozone research over the past few years have several major implications as input to public policy regarding restrictions on man-made substances that lead to stratospheric ozone depletion:

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- The scientific basis for the 1987 Montreal Protocol on Substances that Deplete the Ozone layer was the theoretical prediction that, should CFC and halon abundances continue to grow for the next few decades, there would eventually be substantial ozone layer depletion. The research of the last few years has demonstrated that actual ozone loss due to man-made chlorine (i.e., CFCs) and bromine has already occurred, i.e., the Antarctic ozone hole.

- Even if the control measures of the Montreal Protocol were to be implemented by all nations, today's atmospheric abundance of chlorine (about 3 parts per billion by volume (ppbv)) will at least double to triple during the next century. If the atmospheric abundance of chlorine reaches about 9 ppbv by about 2050, ozone depletions of 0-4 per cent in the tropics and 4 - 12 per cent at high latitudes would be predicted, even without including the effects of heterogeneous chemical processes known to occur in polar regions, which may further increase the magnitude of the predicted ozone depletion.

- The surface-induced, PSC-induced chemical reactions which cause the ozone depletion in Antarctica and also occur in the Arctic, represent additional ozone-depleting processes that were not included in the stratospheric ozone assessment models used to guide the Montreal Protocol. Recent laboratory studies suggest that similar reactions involving chlorine compounds may occur on sulfate particles present at lower latitudes, which could be particularly important immediately after a volcanic eruption. Hence, future global ozone layer depletions could well be larger than originally predicted.

- Large-scale ozone depletions in Antarctica appear to have started in the late 1970s and were initiated by atmospheric chlorine abundance of about 1.5-2 ppbv, compared to today's level of about 3 ppbv. To return the Antarctic ozone layer to levels of the pre-1970s, and hence to avoid the possible ozone dilution effect that the Antarctic ozone hole could have at other latitudes, one of a limited number of approaches to reduce the atmospheric abundance of chlorine and bromine is a complete elimination of emissions of all fully halogenated CFCs, halons, carbon tetrachloride, and methyl chloroform, as well as careful considerations of the HCFC substitutes. Otherwise, the Antarctic ozone hole is expected to recur seasonally, provided the present meteorological conditions continue.

2.2 Environmental Effects

With depletion of the ozone layer, the intensity of the UV-B radiation reaching the ground increases and the wavelength composition is shifted to shorter wavelengths. Most effects of ultraviolet radiation depend strongly on the wavelength, with the largest impacts associated with the shorter wavelengths.

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UV-B radiation is known to have a multitude of effects on humans, animals, plants, and materials. Most of these effects are damaging. The knowledge required for quantitative predictions of the effects, however, is available only for a few of these damages. Even with the present limited level of quantification, it is clear that some of these effects could pose significant environmental threats.

The potential effects of increased levels of UV-B radiation due to ozone depletion include the following:

Human Health

Exposure to increased UV-B radiation can cause suppression of the body's immune system, which might lead to an increase in the occurrence or severity of infectious diseases such as herpes, leishmaniasis and malaria and a possible decrease in the effectiveness of vaccination programmes.

Enhanced levels of UV-B radiation can lead to increased damage to the eyes, especially cataracts the incidence of which is expected to increase by 0.6 per cent per 1 per cent total column ozone depletion. Therefore, each 1 per cent total column ozone depletion is, in the long run, expected to lead to a worldwide increase of 100,000 blind persons due to UV-B induced cataracts, other things being equal (e.g. population, age distribution, availability of medical care, etc.). Damage to the eyes and possible increases in incidence or severity of infectious diseases would be serious, particularly where these diseases occur most, even now.

Non-melanoma skin cancer will increase with any long-term increase of the surface UV-B radiation, without a threshold value. Every 1 per cent decrease of total column ozone is predicted to lead to a 3 per cent rise of the incidence of non-melanoma skin cancer; other things being equal - e.g. the exposure of people to sunlight. There is concern that an increase of the more dangerous cutaneous malignant melanoma could also occur. The current incidence of non-melanoma skin cancer is much higher than for melanoma skin cancer, but the current annual number of deaths attributable to the two types of cancer is about the same. Increase of skin cancer would mainly affect people with little protective pigment in their skin, i.e. light-skinned people.

Terrestrial Plants

Of the plant species investigated (approximately 80 varieties of 12 species), about half were found to be sensitive to enhanced UV-B radiation, the impact being that plants typically have reduced growth and smaller leaves. This sensitivity applies, for instance, for certain varieties of soybeans and wheat. In some cases, these plants also show changes in their chemical composition, which can affect food quality and the availability of mineral nutrients. Within species, varieties have different UV-B sensitivities, as is also demonstrated in soybeans. While some varieties of soybeans are not sensitive at all, increased UV-B reduces food yield by up to 25 per cent in certain economically important varieties, for exposures simulating 25 per cent

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total column ozone depletion. Even small decreases in food production from UV-B effects on agriculture would significantly affect people in areas where food shortages occur even now. There is an urgent need for development of biotechnology for replacement of sensitive crops.

Aquatic Ecosystems

Increased UV-B irradiance has been shown to have a negative influence on aquatic organisms, especially small ones such as phytoplankton, zooplankton, larval crabs and shrimp, and juvenile fish. Because many of these small organisms are at the base of the marine food web, increased UV-B exposure may have a negative influence on the productivity of fisheries.

Increased exposure to UV-B radiation could lead to decreased nitrogen assimilation by prokaryotic microorganisms and, thereby, to a possible nitrogen deficiency for rice paddies. The potential loss in yield has not yet been quantified.

Since phytoplankton fix carbon dioxide in photosynthesis, damage to phytoplankton by increased UV-B radiation would indirectly contribute to the radiative forcing of predicted global warming induced by greenhouse gases.

Tropospheric Air Quality

Enhanced levels of surface UV radiation could cause increased atmospheric abundances of several chemically reactive compounds, notably ozone, hydrogen peroxide, and acids. It is also possible that the atmospheric abundance of particulates could be enhanced. This would aggravate the environmental pollution problems already present in many urban and rural areas and increase the negative influences of air pollution on human health and agricultural productivity, assuming that existing pollution controls are not strengthened.

Materials Damage

Exposure to UV radiation is a significant cause of degradation of many materials, particularly plastics that are used outdoors. The impact is mainly economic. The increased damage will be most severe in tropical locations, where the degradation may be enhanced by high ambient temperatures and sunshine levels.

Global Warming

The present atmospheric abundance of controlled substances contribute 20 per cent to 25 per cent of the anthropogenic radiative forcing of global warming.

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Key Areas of Uncertainty

The key areas of uncertainty are in the following areas:

- Quantification of the primary effects on food production and quality, on forestry, and natural ecosystems.
- Clarification and quantification of influences on human health, especially the immune system, and occurrences of melanomas and cataracts.
- Effects on biota of the enhanced UV radiation during the Antarctic springtime ozone depletion.

2.3 Technology Review

The goal of the Technology Assessment Panel was to determine and quantify the technical feasibility of reductions of ozone depleting substances.

Technical feasibility in this respect is defined as the possibility to provide substitutes or alternative processes without substantially affecting properties, performance and reliability of goods and services from a technical and environmental point of view.

Taking into account the current state of the technological development, it is technically feasible to phase down the production and consumption of the five CFCs controlled under the Montreal Protocol, as well as carbontetrachloride, by at least 95 per cent by the year 2000.

The remaining demand after the year 2000 would be from refrigeration and air conditioning (principally automotive) systems that were designed to use CFCs and are still in service (and not amenable to near "drop in" substitutes) and minor uses. These remaining uses are expected to be eliminated within 5-10 years thereafter. Figure 1 shows the technically feasible phase-down projections for any year for each of the major use categories.

It is assumed that HFCs and HCFCs currently under testing will be environmentally acceptable and commercially available. The time scale for full commercialization for some chemicals remain uncertain at this time but chemical manufacturers are working on many chemical substitutes. Three Programmes for Alternative Fluorocarbon Toxicity Testing (PAFT I, II and III) and the programme AFEAS on the environmental acceptability have been defined; the results will be published as soon as they are available in open literature. Final results of testing of these substitute chemicals will not be available for three or more years.

The key conclusions from the technology assessment are:

- The refrigeration, air conditioning, and heat pump sector represents 25 per cent of global consumption of the controlled CFCs. Globally, under 8 per cent is used for food preservation and developing countries' share of this is less than one quarter. Domestic refrigeration worldwide accounts for 1 per cent. Evidence suggest that for developing countries, a 30 per cent annual growth rate in the manufacture of domestic refrigerators can be assumed. Thus demand from developing countries (including India and the Peoples' Republic of China) for CFC-12 for refrigerators only, will at the year 2000 represent less than 2 per cent annually of the global 1986 CFC consumption level. The assessment also assumes recycling and reuse of 60 per cent of existing CFC refrigeration fluids in the year 2000.

It is necessary to distinguish between new and existing equipment. New designs using alternative refrigerants are possible in many, but not all subsectors now, but existing equipment will have to be upgraded and replaced slowly, with full substitution taking up to 15-20 years. One major problem is that automotive air conditioning represents a large use of CFCs and some automobiles produced before a switch to new environmentally acceptable refrigerants will be in use well after the year 2000.

- 25 per cent of the world's CFCs are used in foam production. It is technically feasible to reduce consumption by 60-70 per cent by 1993 with a phase out of at least 95 per cent by 1995. These reductions are dependent to a large degree on the availability of new HCFCs.

- CFC-113 solvent use in electronic, precision, metal, and dry cleaning represents about 16 per cent of the global consumption of the controlled CFCs. There is no single universal substitute for all CFC-113 solvent uses, but rather a myriad of options. The most predominant use is in the electronics subsector. All CFC-113 solvent uses can be phased out by the year 2000. The CFC-113 phase out is only partially dependent on the availability of HCFCs, due to the large variety of non-HCFC alternatives including: product and process substitutes, water cleaning, hydrocarbons (e.g., terpenes, alcohol, and white spirits), cleaning processes that do not require the use of solvents, etc.

- Sufficient technical options exist now to phase out CFC use as aerosol propellants with the exceptions being some medical products and other minor uses. CFC-12 use in sterilization can be substantially reduced using existing alternatives and can be phased out by 1995 in developed countries and somewhat later in developing countries. In food freezing applications, substitution is technically feasible and several techniques are commercially available.

- Methyl Chloroform (1,1,1 Trichloroethane) is a widely used all purpose solvent. It has an ozone depletion potential of between .10-.16 and a lifetime of 6.3 years. Because of its large production, it contributes to current ozone depletion to about the same degree as CFC-11, CFC-12 or carbon tetrachloride, since much of the depletion associated with the current production and consumption of these longer-lived gases lies in the future. Substitutes currently exist in each of the three major uses of methyl chloroform: cleaning solvent; adhesives; and aerosols. Reductions of 90-95 per cent of current usage appear feasible.

- Carbon tetrachloride has an Ozone Depletion Potential of 1.0-1.2. It is primarily used as a feedstock for CFCs, but may also be used for example, as a constituent of pesticides, as a solvent in the manufacture of synthetic rubber and dyes, as a dry cleaning agent and as a grain fumigant. These uses in many countries have been eliminated in recent years due to toxicity concerns. As a result, subtitutes currently exist for the majority of its uses.

- Based on projections of the chemical industry at the year 2000, HCFCs are estimated to capture up to 30 per cent of the current CFC market. An additional 10 per cent of demand could be captured by HFCs with the remaining 60 per cent of demand satisfied by product and process substitutes. The use of HCFCs and HFCs will be essential in achieving early reductions and eventual phase-out of CFCs.

- There are currently no substitute chemicals with equivalent characteristics to halons. Other fire protection techniques (including carbon dioxide and water sprinkler systems) are, however, available in most applications that offer adequate fire protection. In addition, proper fire protection is also dependent on other features, such as detection systems, fire restrictive enclosures, cable and wire insulation, proper construction planning, etc. A timetable for phasing down halon consumption has been discussed by experts in the Review Panel Committee. No consensus was reached on a possible timetable, although the majority of experts felt that conservation practises and the afore mentioned protection measures alone are adequate to allow an orderly and complete phaseout by the year 2005. Some believed a reduction of 60 per cent, at the most, was achievable within 5 years with a total phaseout possible if alternative chemicals became available. Others concluded that a reduction schedule was premature until substitutes became available.

- Technology is currently available to capture, recycle, and destroy CFCs and halons. However, more cost effective techniques are currently under development.

Since substitutes currently exist for most of their uses, it is technically feasible by the year 2000 to:

- Phase down by at least 95 per cent the production and consumption of the five controlled CFCs.

- Phase out totally the production and consumption of carbon tetrachloride since this has been possible in many countries.

- Phase down by at least 90 per cent the production and consumption of methyl chloroform.

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Reductions for CFCs and methyl chloroform require that substitutes currently available or under development are environmentally acceptable and are made commercially available throughout the world.

Production of all of the substances referred to above would not be restricted for subsequent use as a chemical feedstock.

2.4 Economic Implications

A review of the Protocol measures requires an appraisal of the costs of substitution of CFCS and halons and the benefits of avoiding ozone depletion.

Canada, United States of America, Europe, and Japan account for approximately 80 per cent of the total consumption of controlled chemicals. The per capita consumption in developed economies is in many cases more than ten times the per capita consumption in most developing countries. Economic implications have to be considered in the context of developed and developing economies separately.

Economic/Environmental Benefits of Reduced CFC/halon Use.

Reducing the use of ozone-depleting substances could have enormous beneficial impacts on human health and the environment in both developed and developing countries. The current state of scientific knowledge makes it very difficult to quantify the magnitude of many of these impacts. Nevertheless, the scientific evidence is mounting that predicted stratospheric ozone depletion will cause increased levels of skin cancers, cataracts, immune suppression, and other human health impacts, plus additional effects on plants and animals, among others. Many factors associated with proper valuation procedures vary from one region of the world to another and between people alive today and generations to come. These issues make it inherently difficult, if not impossible, to assign a monetary value to the harmful impacts avoided as a result of the reduction in use of ozone-depleting substances.

This difficulty in economic quantification does not change the basic conclusion of the economics panel that, on a global basis, the monetary value of the benefits of safeguarding the ozone layer is undoubtedly much greater than the costs of CFC and halon reductions. However, developing countries are less able to pay the costs of reducing or phasing out CFCs and halons and may have other, more immediate concerns such as food supply and economic development. Given the fact that a global CFC reduction is essential for the protection of the ozone layer, diffusion of CFC and halon replacement technology, including recovery and recycling, is necessary and is in the interest of both developed and developing countries alike.

The Costs of Technical Substitution

The costs of reducing or eliminating CFCs and halons depend on a variety of factors including capital costs, research and development costs, operational costs (such as energy and labour costs), and safety and toxicity risks. Differences in national development and in the extent of development of CFC and halon producing and consuming industries result in large differences in transition costs for each country. Detailed estimates of the changeover costs cannot at present be made for many options. Consequently, global cost estimates are difficult to make with reasonable accuracy.

The development of options for replacing CFCs and halons is progressing rapidly. As economically feasible safe substitutes become available on a global basis, the current costs of CFC and halon reductions are expected to be reduced.

Most technical options require initial capital investments, but ultimately, some are less expensive to operate or offer improvements in product quality. The first 50 per cent reduction in the global use of CFCs will require modest new capital investment, will incur little or no net cost, will result in some business disruption, and will require very little capital abandonment. This relatively easy step will be accomplished through reduction in the use of CFCs in the manufacture of flexible foams and as aerosol propellants, the more efficient use of CFCs as solvents, and by reductions in many other applications. Cost estimates for the remaining reductions - mainly in the fields of refrigeration, air conditioning, rigid foam, solvents, and fire protection - vary widely and depend on the availability of near term drop-in and other substitutes, costs of re-engineering equipment and products, and the price, safety and energy efficiency of the substitutes.

The time-path for phasing out some CFCs can substantially affect costs. A very rapid transition (much less than 10 years) would result in substantially higher costs due to capital abandonment. Individual governments and industries have significant opportunities to reduce costs, save money and improve energy efficiency if the best reduction strategy is chosen. Higher energy efficiency would reduce greenhouse gas emissions for an equivalent provision of service.

Technology Transfer

Developing countries have special needs and concerns as part of a global effort to protect stratospheric ozone. These concerns include: (1) the cost of CFC supply; (2) the cost of chemical substitutes; (3) the cost of imported products made now with CFCs and which, later, will be made with substitutes; (4) the cost of access to new technology; and (5) maintenance of trade with Parties to the Protocol in products made with or containing CFCs and halons.

- Even low-use developing countries will want to adopt new technologies that cost about the same as or less than the old CFC technologies. For example, the potential cost savings from more energy efficient refrigerators may be more important in developing countries where income is low and energy costs are high. All countries can avoid new capital investment that would make them more dependent on CFCs and would result in later costs from abandonment of CFC capital when they begin their phase-down.

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- Developing countries which are Party to the Protocol, need to be able to purchase CFCs for important needs such as food preservation until the alternatives are available. These countries may be able to purchase allowable quantities of CFCs at reasonable prices as production capacity becomes surplus in developed countries due to the CFC phase-down. New investment in CFC production technology is now imprudent since there may not be time to depreciate the new capital and since ample supplies of CFCs may be available at low prices as developed countries phase-down production. Some coordination may be necessary to assure a reliable reasonable price and supply. A low-cost adequate supply to developing countries which are Party to the Protocol can avoid the cost of investment in old CFC technology.

- The new chemical substitutes (HFCs and HCFCs) are estimated to cost two to five times as much as CFCs when they become generally commercially available due to the increased cost of chemical ingredients, manufacturing costs, and capital cost. In some cases, the new chemicals may provide cost-offsetting advantages such as improvements in energy efficiency or other product performance.

  However, developing countries may need development assistance including capital grants and other technology transfer to afford these new chemicals. Countries that now produce CFCs, including developing countries may decide to become producers of some of the new chemicals. UNEP should carefully monitor this situation as new chemicals become available, mostly after 1993.

- To the extent that new products (refrigerators, electronics, etc.) cost more due to increases in research-and-development, capital investment, chemical ingredients, and other costs; countries that import these products may need supplementary technical assistance or financial aid.

Currently, the lack of technical knowledge and financial resources of developing countries inhibits the adoption of certain CFC/halon replacement technologies and the definition and implementation of the best national options for the transition to CFC-free technologies.

Some CFC replacement technologies will be adopted in the usual course of economic growth, but at a slow rate. Development assistance will be required in most cases. Funding is needed for the transfer of technology during the transition period because currently available resources are already strained as a result of the world debt problem and the dire economic situation of many countries. Examples of methods of raising funds for financial assistance vary from charging for CFC use to contributing a small percentage of GNP. Financial assistance can be either bilateral or multilateral, for example, as a contribution to an international fund.

3.0 REPORTING AND SYSTEMATIC OBSERVATION REQUIREMENTS

Reporting and systematic observations of all chlorine and bromine containing chemicals that can contribute to the chlorine and bromine loading of the stratosphere (hence potential stratospheric ozone depletion), or to the predicted global warming, is strongly recommended. This should include all fully halogenated CFCs currently not included in the Montreal Protocol, as well as carbon tetrachloride, methyl chloroform, and the proposed substitute chemicals, hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs) Reporting and systematic observation requirements for these chemicals should be similar to those required for the substances currently controlled by the Montreal Protocol, which should meet the needs of the scientific community to evaluate the environmental impacts of these chemicals.

A "monitoring" network that could evaluate the global abundances and trends of the HCFCs and HFCs would require more stations than the current network that is used to monitor the long-lived CFCs. This is because the atmospheric distributions of the HCFCs and HFCs will exhibit greater variability since their atmospheric lifetimes are shorter than those of the CFCs. A quantitative evaluation of the impact of atmospheric chlorine and bromine on the stratosphere could be achieved if a sub-set of the stations in this network also monitored the chemical composition and physical structure of the stratosphere.

4.0 CONCLUSIONS

Ozone depletion is a global problem: It is caused by those nations producing and consuming CFCs, halons, and other chlorine- and bromine-containing chemicals which are eventually released into the Earth's atmosphere. Ozone depletion increases the amount of harmful ultraviolet radiation reaching the Earth's surface and, among other things, can result in adverse consequences for human health and may cause a reduction in food production. While the largest ozone depletions are predicted to occur at high latitudes in both the hemispheres, enhanced levels of ultraviolet radiation will have adverse effects on people from all nations, independent of geographical position, e.g., northern or southern hemisphere, or economic status, e.g. developed or developing. While peoples with lightly pigmented skins are most susceptible to melanoma and non-melanoma skin cancer, all peoples are susceptible to contracting eye disorders and a suppression of the immune response system. Unfortunately, those people with inadequate health services are placed at the greatest risk, e.g. some of the developing countries. Agricultural and fisheries productivities could decrease because of enhanced levels of ultraviolet radiation, and again those people likely to be affected most, live where shortages of food now exist.

Developed/Developing Nations Partnership Needed: The current and historic use of CFCs, halons, and other chlorine and bromine containing chemicals in developed nations is the primary cause of this problem. However, it is clear that protection of the ozone layer will require a full partnership between developed countries that have caused the problem and those in developing countries who would now like to improve their standard of living by

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using these chemicals for uses such as refrigeration. The lack of technical knowledge and financial resources of developing countries inhibits the adoption of certain CFC/halon replacement technologies and the definition and implementation of the best national options for the transition to CFC-free technologies. Funding is needed to assist the transfer of technology to developing countries during the transition period because currently available resources are already strained as a result of the world debt problem and the dire economic situation of many countries.

Current Montreal Protocol: The total chlorine and bromine loadings of the atmosphere are predicted to approximately triple by the year 2050 and lead to total column ozone depletions of 0 to 4 per cent in the tropics and 4 to 12 per cent at high latitudes (without consideration of the effects of surface induced chemistry, which could increase these estimates, at least in polar regions). The Antarctic ozone depletion would be expected to be comparable or worse than at present and significant Arctic ozone losses would become more likely. Significant adverse human health consequences would be expected.

Stabilizing atmospheric chlorine and bromine: Stabilizing atmospheric chlorine and bromine to today's levels can be achieved through a phase-out of the CFCs, carbon tetrachloride, methyl chloroform and the halons. (Other control options may also do this). If the total chlorine and bromine loading of the atmosphere is stabilized, the seasonal Antarctic ozone hole would recur for the forseeable future, but no additional significant ozone depletion would be expected either in the Arctic of globally. Indeed, if the stabilized chlorine and bromine levels are accompanied by increased atmospheric abundances of carbon dioxide and methane then minor increases in ozone might even be expected. This assumes that increases in carbon dioxide and methane will not significantly decrease the temperature of the lower polar stratosphere and change polar meteorology and PSC abundances.

Antarctic Ozone "Hole": The Antarctic ozone hole will not disappear until the atmospheric abundance of chlorine is reduced to the levels of the early 1970's: 1.5-2 ppbv assuming present climate. In addition, the atmospheric abundance of bromine should remain at, or be reduced below, today's level and this implies a reduction in bromine emissions. This could be achieved by a complete phase-out of the fully halogenated CFCs, halons, carbon tetrachloride, and methyl chloroform, and careful consideration of what emission rates of the HCFCs are acceptable. Even if all anthropogenic sources of atmospheric chlorine were to be eliminated today, the time taken for the abundance of atmospheric chlorine to be reduced below 2 ppbv would be many decades, hence the seasonal Antarctic ozone hole will recur for a long time to come.

Long Atmospheric Recovery Times: Once chemicals, such as the chlorofluorocarbons with long atmospheric lifetimes, are emitted into the atmosphere, the time for the atmosphere to fully recover is many decades to centuries. Compliance (100 per cent participation by all nations), broad scope of control (inclusion of chemicals such as carbon tetrachloride and

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methyl chloroform), and stringency (a complete phaseout of these chemicals) are of paramount importance in protecting the ozone layer. Almost any level of non- compliance or reduction in the scope and stringency below a complete phase-out of CFCs, methyl chloroform, and carbon tetrachloride would effectively eliminate the possibility of reducing the atmospheric abundance of chlorine below today's level. It should be noted, however, that timing is also important. For every year that fully halogenated chlorofluorocarbons are emitted into the atmosphere at the present rate, it will take about an additional five years for the abundance of atmospheric chlorine to be reduced below 2 ppbv. Therefore, the sooner the fully halogenated CFCs and carbon terachloride are phased out of production, the "quicker" the Antarctic ozone hole might recover. In contrast, the atmospheric loading of chlorine from chemicals with shorter atmospheric lifetimes, such as the HCFCs and methyl chloroform, decreases much more quickly once their emissions into the atmosphere are terminated.

<u>CFC Phase Out Technically Feasible</u>: Since substitutes currently exist for most of their uses, it is technically feasible by the year 2000 to:

- Phase down by at least 95 per cent the production and consumption of the five controlled CFCs.
- Phase out totally the production and consumption of carbon tetrachloride since this has been possible in many countries.

- Phase down by at least 90 per cent the production and consumption of methyl chloroform.

Reduction for CFCs and methyl chloroform require that substitutes currently available or under development are environmentally acceptable and are made commercially available throughout the world.

Production of any of the substances referred to above would not be restricted for subsequent use as a chemical feedstock.

<u>High Economic Costs with Rapid Phase-outs</u>: A rapid phase-out of some CFCs over a period much less than 10 years will substantially increase costs due to abandonment of capital investment in CFC producing and using technologies and by the rush to change technologies. Major sectors including the foam industry, would lose market to product alternatives resulting in jobs losses in some areas and gains in others. The costs of technology transfer and capital investment in developing countries would also increase substantially if reduction schedules under the special provisions of the Protocol are also shortened. A rush to market selected technologies that were more expensive to buy or operate would also increase the costs in developed and developing countries. For example, a faster phase-out schedule may not allow time to develop more energy efficient domestic refrigerators. This could increase product cost without off-setting decreases in electricity costs and would have global climate implications from increased CO_2 emissions.

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Table 1. Range of Ozone Depletion Potentials (ODPs) and halocarbon Global Warming Potentials (GWPs) *.**

species	ODPs		GWPs**
	This Assessment	Montreal Protocol	This Assessment
CFC-11	1.0	1.0	1.0
CFC-12	0.9 - 1.0	1.0	2.8 - 3.4
CFC-113	0.8 - 0.9	0.8	1.3 - 1.4
CFC-114	0.6 - 0.8	1.0	3.7 - 4.1
CFC-115	0.3 - 0.5	0.6	7.4 - 7.6
HCFC-22	0.04 - 0.06		0.32 - 0.37
HCFC-123	0.013 - 0.022		0.017 - 0.020
HCFC-124	0.016 - 0.024		0.092 - 0.10
HFC-125	0		0.51 - 0.65
HFC-134a	0		0.24 - 0.29
HCFC-141b	0.07 - 0.11		0.084 - 0.097
HCFC-142b	0.05 - 0.06		0.34 - 0.39
HFC-143a	0		0.72 - 0.76
HFC-152a	0		0.026 - 0.033
CCL_4	1.0 - 1.2		0.34 - 0.35
CH_3CCl_3	0.10 - 0.16		0.022 - 0.026
halon 1301*	7.8 - 13.2	10.0	
halon 1211*	2.2 - 3.0	3.0	
halon 2402*	5.0 - 6.2	6.0	

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* The ODPs for the halons are sensitive to the atmospheric abundance of chlorine. The values shown in the table are for present day conditions (i.e. a chlorine abundance of about 3 ppbv). The ODPs for the halons increase at higher chlorine abundances.

** The halocarbon GWPs are all normalized to a value of unity for CFC-11. An equally valid alternate set of values can be obtained by normalization to CFC-12 (this was done in the Technology Assessment report). Normalization to CFC-12 requires dividing all the GWP values shown in the table by 3.1 (the average value for the GWP for CFC-12). The benefit gained by substitution of a CFC with an HCFC (or an HFC) is computed by ratioing the GWP values of the HCFC (or HFC) to the CFC.

*** The ODPs and GWPs are defined in Sections 4.3.2 and 4.4.2 in the Scientific Assessment of Stratospheric Ozone: 1989, Panel for Scientific Assessment.

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Appendix A

The various scenarios for controlling the ozone-depleting substances are not summarized directly from the assessment report but are derived from the findings of the panels. The purpose of their inclusion is to provide the linkage so as to facilitate policy consideration from the findings of the four panels.

EXAMPLE SCENARIOS

Scenarios for controlling the emissions of chlorine containing chemicals. The following section presents possible scenarios for controlling chlorine containing chemicals. For each scenario, there is a brief description of (i) how the atmosphere is predicted to respond in terms of chlorine loading and stratospheric ozone depletion (polar and globally) by the year 2050, (ii) environmental effects, (iii) technical feasibility, and (iv) economic costs. Figure 2 presents the total chlorine concentrations in the stratosphere from 1986 through 2100 that would result from each of these five possible scenarios for controlling chlorine containing chemicals. In each of the following scenarios a number of assumptions have been made. These include, (i) 100 per cent global participation, (ii) an average annual growth in goods and services that currently use CFCs of 3 per cent between 1986 and 2050 and constant thereafter, (iii) an increase in methyl chloroform and HCFC-22 emissions of 3 per cent between 1986 and 2050 and constant thereafter, and (iv) no growth in the emissions of carbon tetrachloride. This last assumption may be optimistic given that the atmospheric abundance of carbon tetrachloride has recently been increasing at about 1 per cent per year.

Scenarios for controlling the emissions of halons. For the purposes of discussing these Scenarios it was assumed that the halons currently covered by the Montreal Protocol were treated in a manner consistent with the CFCs, i.e., the CFC phase-out was accompanied by a halon phase-out. (The technology assessment did not result in a conclusion that the schedule for the phase down of halons could be accomplished at the same rate for currently controlled CFCs without a potential increased fire risk.)

Environmental consequences. There is a general lack of quantitative information available for most of the environmental effects discussed in Section 2.2. Therefore, specific quantified projections of the magnitude of the effects to be predicted for each of the different scenarios discussed below is unwarranted. However, two human health impacts that can be quantified are, (i) that for every 1 per cent decrease in total column ozone there would be a 3 per cent increase in the incidence of non-melanoma skin cancer, and (ii) that for every 1 per cent decrease in total column ozone there would be a 0.6 per cent increase in the incidence of cataracts. These relationships apply to all of the predicted ozone changes in the scenarios discussed below:

Model predictions of ozone depletion. There are two key points to be noted about the model calculations of ozone depletion; (i) none of the models considered the effects of ice crystal chemistry, which could increase the estimates of ozone depletion, at least in polar regions, and (ii) the model results shown for each of the five scenarios, except scenario 1, do not include the effect of temperature feedback. Increasing abundances of atmospheric carbon dioxide decrease stratospheric temperatures, which, in turn, lead to a decrease in the destruction of ozone through temperature feedback. While there are still open questions regarding the quantitative treatment of the influence of carbon dioxide (temperature feedback), those models that do not include the carbon dioxide effect are almost certainly overestimating the magnitude of ozone depletion by chlorine - and bromine-containing chemicals compared to models including temperature feedback (the results shown in option 1 demonstrate the magnitude of this effect).

1 Current Montreal Protocol (Figure 2, Scenario)

<u>Science</u>: As seen in Figure 2, the total chlorine loading of the atmosphere is expected to increase to about 8 ppbv by the year 2050 (triple today's level) and about 10 ppbv by the end of the next century. An increase from 2.7 ppbv to above 8 ppbv of total chlorine is predicted to lead to an additional total column ozone depletion of 1 to 4 per cent in the tropics and 4 to 12 per cent at high latitudes. These models did not take into account the impact of increasing atmospheric abundances of carbon dioxide. For models that did include the effect of carbon dioxide, predicted column ozone reductions were somewhat less, i.e., 0 to 1.5 per cent in the tropics and from 3.5 per cent to 7 per cent at high latitudes in late winter. None of these models considered the effects of ice crystal chemistry which could increase the estimates of ozone depletion, at least in polar regions. Higher ozone layer depletions would occur after the year 2050 as atmospheric chlorine abundances increase. The Antarctic ozone hole would be expected to be comparable to or worse than at present, and significant Arctic ozone losses would become more likely.

<u>Technology</u>: There is a large choice of product, chemical, and process control systems available to accomplish much more than a 50 per cent reduction in CFCs and a freeze in halons, even with no new substitute chemicals.

<u>Economics</u>: The economic benefits of the Montreal Protocol in developed and developing countries include reduced loss of life from cancer, health improvement, and the associated savings in medical costs. There are also benefits of increased worker productivity and longevity. In addition, there are savings stemming from longer product life of UV-sensitive plastics and other materials exposed to sunlight. Fewer losses in agricultural and marine productivity--with possibly far greater changes in some regions than others--are particularly important economic factors in developing countries where food price increases would have to be at the expense of other essential spending.

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(a) Developed Countries: A 50 per cent reduction in production and consumption of CFCs and a freeze in halon production and use will require modest new capital investment, will incur little or no net cost, will result in some disruption, and will require very little capital abandonment. User industries will have to adjust to a reduced supply of CFCs, but relatively modest amounts of new capital investment will be required and capital redundance is not expected to be particularly significant. Aerosols, foam, solvent, automobile air conditioning, and other sectors will be most affected. Which industries will be most affected in any country will depend on how reductions in consumption are implemented, for example, by voluntary agreements, market forces, or national regulation. There is a substantial opportunity for cost savings from international and national industrial cooperation. The use of CFCs in foam insulation and refrigeration could preserve current energy efficiency. Equal fire protection can be provided at similar costs if industry reduces fire risk and the consequences of fires through architectural design, fire-resistant construction, lower flammable loads in high-value areas and by backup of computer systems and records.

(b) Developing Countries: Special provisions of the Montreal Protocol allow low-use, developing countries to increase annual CFC consumption as much as 0.3 kilograms per capita for up to ten years. However, these countries will naturally want to adopt new technologies that cost about the same or less than the old CFC technologies. All countries can avoid new capital investment that would make them more dependent on CFCs and would result in later costs from abandonment of CFC capital when they begin their 50 per cent phase-down. For example, new investment in CFC production technology is imprudent since there may not be time to depreciate the new capital and since ample supplies of CFCs may be available at lower prices as developed countries phase-down production. In most CFC applications substantial reductions are possible with technical options that require some initial capital investment, but actually save money in the long run by reduced operating costs and by improved product quality. However, investment funds must be available for the transfer of these technologies to developing countries including the funds for the purchase of new capital. Some of these funds can be repaid from the operating cost savings of the new investment and from costs that are recovered from export sales, but some investment will need to be grants from developed countries.

2 CFC Phaseout, no controls on methyl chloroform (50 per cent substitution of CFCs with HCFCs with an average ODP of 0.05) (Figure 2, scenario 2)

Science: Atmospheric chlorine abundances in the year 2050 is predicted to be 1.8 ppbv lower than scenario 1, i.e. about 6 ppbv, or twice today's level, increasing to about 7 ppbv by the end of the century. An increase from 2.7 ppbv to about 6 ppbv of total chlorine is predicted to lead to an ozone depletion of 1 to 2.5 per cent near the equator and 4 to 6 per cent at high latitudes (without considering the effects of ice crystal chemistry, which could increase these estimates, at least in polar regions). As in scenario 1, the Antarctic ozone depletion would be expected to comparable or worse than at present, and significant Arctic ozone losses would become more likely.

Technology: Phase out of at least 95-98 per cent of production and consumption is possible by the year 2000 based on today's knowledge and total phase out within 5-10 years thereafter. The commercialization of chemicals currently under test would allow a phase-out by the year 2000. In this case, drop-in substitutes are needed for in-use equipment and substitutes are needed for medical products. The existing capital stock of refrigeration and air conditioning can be serviced from recycled CFCs if aggressive recycling programs recover CFCs during servicing and from decommissioned equipment and from equipment where the CFCs are replaced by near "drop-in" chemical blends. A phase-out of CFCs is dependent on the availability of HCFCs and HFCs, particularly for rigid insulating foam, refrigeration/air conditioning, and medical/hospital sectors.

Economics: (a) Developed countries, Capital investment for a complete phase-out will be higher than for the current Montreal Protocol. The net cost of the first 50 per cent reduction can be made with existing technical options at little or no net cost but investment is necessary. Additional cost-effective technologies will be developed prior to the year 2000 if a phase-out is scheduled. The marginal cost of final reductions may be very expensive. There will be significant business disruption with increasing cost of final phase-out unless new technologies are developed in time. Major product substitution is likely in the foam sectors. Product substitutes are currently available at similar cost but require some redesign and changes in construction practices to accommodate thicker insulating materials. Capital abandonment will be higher than under the current Protocol. Substantial research and development is needed to avoid unacceptable losses in energy efficiency.

(b) Developing countries: Very ambitious technology transfer is necessary to developing countries including financing of capital to use new chemical alternatives, the retrofit of existing capital equipment to minimize CFC emissions, and for recycling and recovery. Countries qualifying for special use provisions will also want new cost-saving technology as soon as it is available.

3 CFC Phaseout, freeze on methyl chloroform (50 per cent substitution of CFCs by HCFCs with an average ODP of 0.05) (Figure 2, scenario 3)

Science: Freezing methyl chloroform at its 1986 levels, in conjunction with a CFC phaseout, is predicted to lead to an atmospheric abundance of chlorine in the year 2050 of about 4.5 ppbv, or one and one half today's level, then staying constant throughout the rest of the century. An increase from 3 ppbv to 4.5 ppbv of total chlorine is predicted to lead to little change in total column ozone in the tropics and a decrease of up to 4 per cent at high latitudes (without considering the effects of ice crystal chemistry, which could increase these estimates, at least in polar regions). The Antarctic ozone layer depletion would be expected to remain similar to that of today, with Arctic ozone losses becoming somewhat more likely.

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Technology: Comments relating to scenario 2 also apply to CFCs in scenario 3. Substitutes currently exist that would permit at least 90 per cent reduction of methyl chloroform. Therefore, a freeze should pose few insurmountable problems. Methyl chloroform is a low cost effective solvent. Methyl chloroform is widely used, with varying workplace precautions, in most regions of the world. Concern for the ozone layer has already stimulated the development of alternatives that clean as well or better than CFC-113. These alternatives include aqueous, terpene and alcohol cleaners. These alternatives to CFC-113 are also alternatives for methly chloroform in most uses.

Economics: This scenario has the same economic implications as scenario 2 above plus the following additional implications.

(a) Developed countries: Based on analysis in the Electronic, Degreasing, and Dry Cleaning Solvents report and the Technology panel report, a freeze in carbon tetrachloride emissions in countries where it is already prohibited due to toxicity will have no economic effects. In other countries a freeze in carbon tetrachloride emissions and a freeze in methyl chloroform production and use would provide increased benefits of ozone protection and benefits resulting from reduced health and environmental exposure to carbon tetrachloride. The economic benefits of increased product durability and performance, particularly in electronics, are far more valuable than small changes in cleaning cost that are an inconsequential part of final product cost. Some alternatives such as aqueous and terpene cleaning alternatives require moderate capital investment but new HCFC solvents are near "drop-in" replacements. Costs of cleaning are an extremely small part of final product cost except in the case of dry cleaning. Use of methyl chloroform is more important to small solvent users in both developed and developing countries because it is low cost and relatively safe to use. Little if any capital abandonment is necessary if HCFCs are commercialized promptly and no new investment is made in CFC solvent equipment.

(b) Developing Countries: New low-cost/no cost solvent alternatives will allow a freeze in carbon tetrachloride and methyl chloroform at low net cost world-wide if technology is promptly transferred to developing countries. Methyl chloroform will be less economically important when technologies are transferred to developing countries. Increased technical assistance and investment funds are necessary for investment in the new technologies.

4 CFC Phaseout, Phaseout of both carbon tetrachloride and methyl chloroform (50 per cent substitution of CFCs by HCFCs with an average ODP of 0.05) (Figure 2, scenario 4)

Science: Phaseout of both carbon tetrachloride and methyl chloroform in conjunction with a CFC phase out is predicted to lead to an atmospheric abundance of chlorine in the year 2050 of about 3.5 ppbv, or slightly above today's level, then staying constant throughout the rest of the

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century. An increase from 3 ppbv to 3.5 ppbv of total chlorine is predicted to lead to little change in total column ozone in the tropics and decreases limited to about 3 per cent at high latitudes (without considering the effects of ice crystal chemistry, which could increase these estimates, at least in polar regions). The Antarctic ozone depletion would be expected to be unchanged, but additional significant Arctic ozone losses would be expected to be small. Thus, this scenario describes keeping approximately the status quo with regard to the present state of the ozone layer.

Technology: Substitutes exist for almost all methyl chloroform solvent uses, with the exception of a few uses such as methyl chloroform in waterborne adhesive products. The phase out of mechanisms for carbon tetrachloride should have as its end point the phase-out of emissions, because carbon tetrachloride is needed as feedstock for the production of HCFCs. Substitutes exist for current uses of carbon tetrachloride other than as a feedstock chemical.

Economics: This scenarios is the same as scenarios 2 and 3 above, plus additional human health advantages from the carbon tetrachloride reductions. Carbon tetrachloride use as a solvent is prohibited in many countries because it is a highly toxic and carcinogenic. Carbon tetrachloride can be safely used as an economically important chemical feedstock that is transformed during chemical production and therefore need not be regulated in feedstock uses that have no emissions. The United States, Europe, and Japan already limit carbon tetrachloride use in non-feedstock applications to 3-9 per cent of total production. Additional research will be necessary to understandminor uses and to develop alternatives and substitutes. New capital investment is moderate since existing capital can be used by some new alternatives. Capital abandonment will be minimal because many solvent machines will be replaced in the normal course of business. Increased technology transfer is necessary in developing countries, including financing of additional capital investment to use new alternatives and substitutes. More economic analysis on carbon tetrachloride and methyl chloroform should be conducted in the near future.

5 CFC Phaseout, Phaseout of both carbon tetrachloride and methyl chloroform, (20 per cent substitution of CFCs by HCFCs with an average ODP of 0.02) (Figure 2, scenario 5).

Science: Phaseout of both carbon tetrachloride and methyl chloroform in conjunction with a CFC phaseout, but with HCFC substitution being limited to 20 per cent with an average ODP of 0.02 is predicted to lead to an atmospheric abundance of chlorine in the year 2050 slightly less than today's level. The Antarctic ozone depletion would be expected to be unchanged, and significant Arctic ozone losses would be expected to be somewhat less likely than today. Eventually, with this scenario (beyond the year 2100) the atmospheric abundance of chlorine would drop below about 2 ppbv and ozone in Antarctica may be expected to return to normal (all other things being equal, e.g. climate). Although no model calculations were performed using this scenario, it is likely that all models would predict an increase in global total column ozone beyond the middle of the next century due to the effects of the increasing atmospheric abundances of carbon dioxide and methane.

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Technology: All of previous comments apply. HCFCs and HFCs are needed for phasing-out CFCs before the year 2000. HCFCs such as HCFC-22, 124, 142b, are ingredients in the proposed high energy efficiency refrigerant blends. HCFC-22 is already commercialized as an energy efficient refrigerant in small and medium sized air conditioning systems and some refrigeration equipment. Emission controls for the existing and new future equipment may be desirable; these should be realizable taking into account the experience obtained in emission controls for CFC refrigeration equipment. In the short term, HCFCs are the only candidates for the highest quality rigid foam insulation (energy efficient) in applications such as refrigerators where thickness cannot be easily increased to provide equivalent insulation. In the long-term, vacuum insulation may provide greater insulation value, and instead of HCFCs, new HFC refrigerants such as HFC-134a and HFC-152a might be blended for use in certain refrigeration equipment.

Economics: This scenario has the same economic implications as scenarios 2, 3, and 4 above plus it has a higher risk of increases in energy use if alternative insulation of equivalent value is not used, if insulating foam made without HCFCs ages more rapidly, or if the choice of refrigerants not including HCFC ingredients results in lower energy efficiency. Higher energy use has implications for resource use, pollution, climate change, national costs, and consumer prices. However, HCFCs may not be essential in these uses if more energy efficient alternatives are developed that are not dependent on HCFCs. It may not be economically or technically feasible to phase-out CFCs while providing some products such as medical aerosols and low pressure, non-flammable ethylene oxide sterilization if HCFCs are not available.

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Figure 1

Technically Feasible Phasedown Projections for Major CFC Use Categories

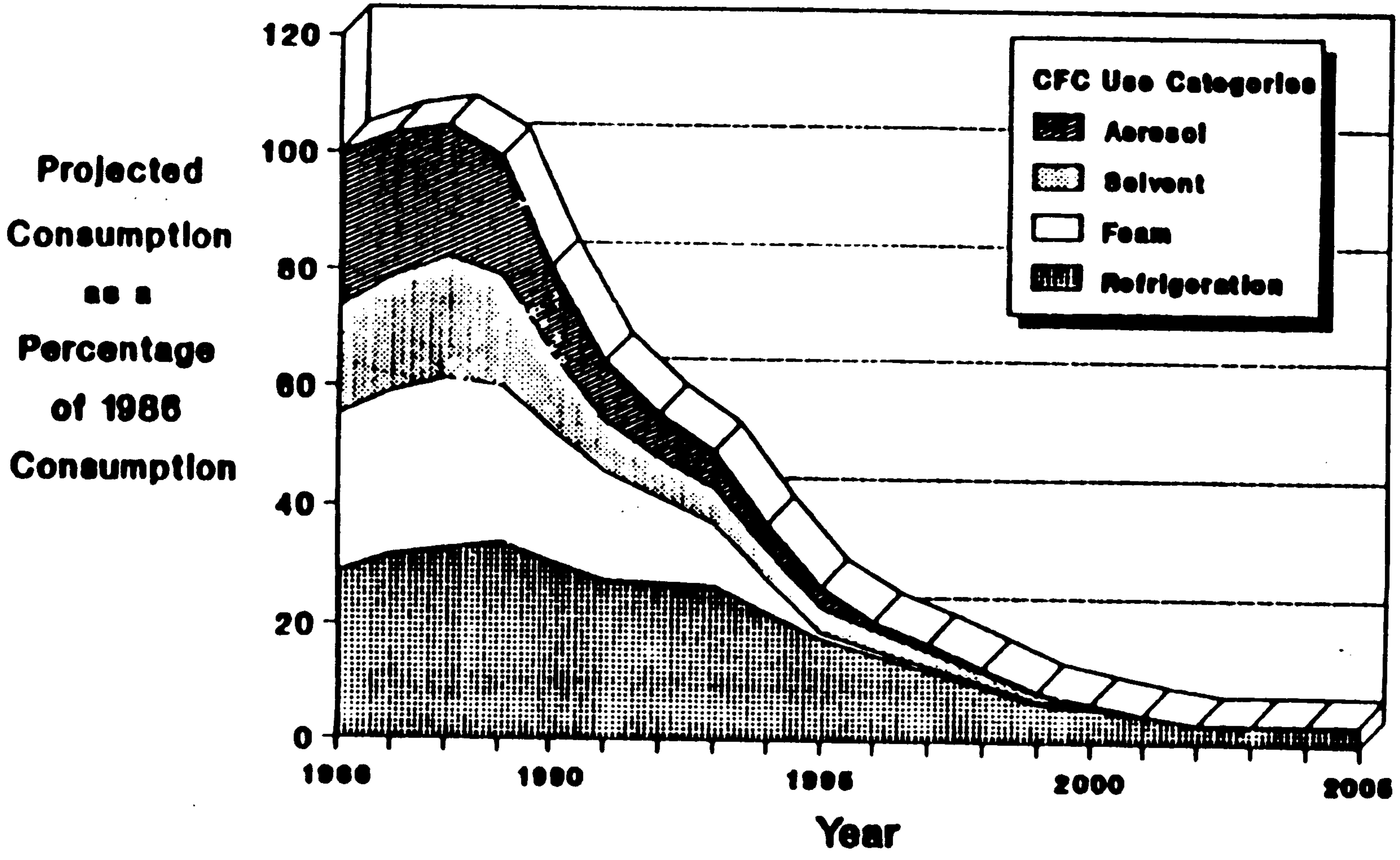
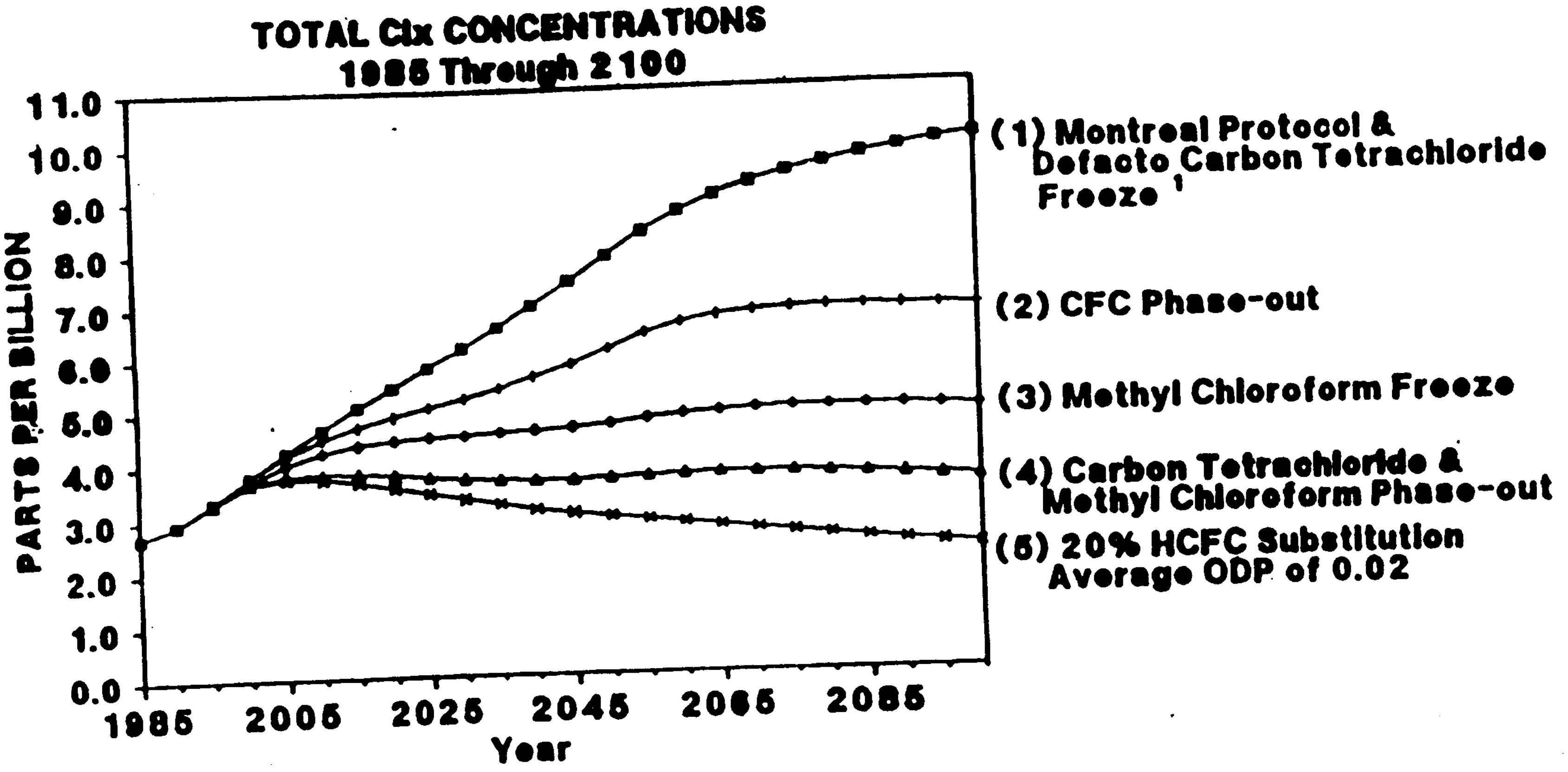


Figure 2

ATMOSPHERIC CHLORINE CONCENTRATIONS WITH DIFFERENT CHEMICAL CONTROL OPTIONS



Assumptions:

- 2000 Phase-out of Fully Halogenated CFCs (Except Curve 1)
- HCFCs Capture 50% of What CFC Market Would Have Been Without Regulation (Except Curve 1); Assumed Annual Average Growth Rates for Fully Halogenated CFCs, Baseline HCFC-22 (non-substitute) and Methyl Chloroform are Approximately 3% for the Period 1985 to 2050. After 2050 Use is Assumed to be Constant.
- Average ODP of Substitutes is 0.05 (Except Curve 5)
- 100% Global Participation

Notes:

[1] While possibilities exist for an increase in carbon tetrachloride use, such growth is unlikely given the awareness of carbon tetrachloride's potential contribution to stratospheric ozone depletion.

APPENDIX B

Transient Scenarios for Atmospheric Chlorine and Bromine

INTRODUCTION

The rise in atmospheric chlorine levels due to the industrial production and emission of chlorofluorocarbons (CFCs) and other halocarbons is now believed to be the cause of the dramatic appearance of the Antarctic ozone hole in the late 1970s. Further increases in the chlorine and bromine content of the stratosphere are inevitable over the next decade, and the consequences for ozone abundances over the Antarctic, Arctic and the globe are uncertain. Only stringent controls over the production of chlorine-containing hydrocarbons will enable our atmosphere to return to chlorine abundances prevalent prior to the occurrence of the ozone hole, about 2 ppb (molecules per 1,000,000,000 molecules of air).

Bromine in the stratosphere, present at concentrations of about 0.02 ppb, also contributes globally to ozone loss. The role of bromine, as BrO, in formation of the Antarctic ozone hole has been demonstrated but not yet been fully quantified. Catalytic cycles involving BrO and ClO are greatly enhanced in the Antarctic ozone hole relative to the rest of the stratosphere. During the austral spring of 1987, bromine is estimated to be responsible for 10 to 30% of the ozone depletion with chlorine alone responsible for the majority.

A sensitivity study of chlorine-loading scenarios is presented for a range of global emissions for compounds currently regulated under the Montreal Protocol (CFC-11 = $CFCl_3$, CFC-12 = CF_2Cl_2, CFC-113 = $CF_2ClCFCl_2$, CFC-114 = CF_2ClCF_2Cl, CFC-115 = CF_3CF_2Cl), for other gases not specified in the Montreal Protocol (carbon tetrachloride = CCl_4, methyl chloroform = CH_3CCl_3, HCFC-22 = CHF_2Cl), and for possible new hydro-halocarbon substitutes (HCFCs). A subset of these scenarios is also shown for atmospheric bromine loading, being driven by the increases in the halons listed under the Montreal Protocol (CF_3Br, CF_2ClBr, $C_2F_4Br_2$) with fixed levels of CH_3Br.

After complete cessation of all halocarbon emissions, the decline in atmospheric chlorine levels below 2 ppb is determined by the decay of the long-lived CFCs produced prior to the phaseout and would not occur until the latter half of the 21st century. We show here that the use of short-lived HCFC substitutes would not significantly affect this time scale if the substitutes were eliminated sometime between 2030 and 2050, depending on the lifetime of the substitute. The elimination of the Antarctic ozone hole sometime in the future relies predominantly on reducing chlorine levels to 2 ppb or less, but will also depend in part on the local meteorology and changes in other trace gases such as methane.

The maximum concentration of atmospheric chlorine that will be reached in the next several decades is controlled by the amount of chlorine-containing halocarbons (CFCs, CCl_4, CH_3CCl_3, and HCFC-22) added to the atmosphere thus far, and by the amount that will be produced and eventually released to the atmosphere prior to a complete phaseout. The scenarios shown here demonstrate the obvious result that the key factor in reducing the peak chlorine loading is the rapid cutback in CFC emissions. They also show the less evident result that substitution of modest amounts of short-lived HCFCs for the CFCs will not increase the maximum chlorine levels.

Largest ozone depletions in the future are expected to coincide with the peak chlorine loading of the atmosphere. Global-scale losses, largest in the upper stratosphere, are predicted from the gas-phase chemical reactions of chlorine monoxide with atomic oxygen. Ozone depletion throughout the stratosphere in the southern mid-latitudes may become more extensive if the Antarctic ozone hole enlarges. Over Antarctica, and possibly in the Arctic, losses are driven by chlorine-catalyzed destruction of ozone following heterogeneous reactions on polar stratospheric clouds in winter. The rapid appearance of the ozone hole over the last decade demonstrates the extremely non-linear response of polar ozone to increasing chlorine levels. We must be prepared for new thresholds of accelerated ozone loss in the Arctic as chlorine concentrations continue to rise above the current (record) levels of about 3 ppb.

CHLORINE LOADING AND ODPs

The atmospheric chlorine loading is calculated here as the instantaneous, bulk tropospheric mixing ratio (ppb) of chlorine atoms in the form of all the halocarbons noted above, plus the natural source CH_3Cl (0.6 ppb). This definition of chlorine loading of the atmosphere is a conservative (maximum) measure of the amount of stratospheric chlorine that may be active in catalytic ozone destruction because not all of the chlorine will be available (i.e., photochemically released from the halocarbon source gas). For the year 1985, the Table below gives the relative contribution of the individual gases to the total chlorine loading (3.0 ppb). The projected chlorine loading can be used to demonstrate the contribution of individual halocarbons to overall chlorine levels as a function of time.

Table. Atmospheric Chlorine Loading in the Year 1985

industrial sources	
CFC-11	22 %
CFC-12	25 %
CFC-113	3 %
CFC-114	<1 %
CFC-115	<1 %
HCFC-22	3 %
carbon tetrachloride	13 %
methyl chloroform	13 %
natural sources	
methyl chloride	20 %

The Ozone Depletion Potential (ODP) of a halocarbon is calculated with a chemical model for stratospheric ozone, assuming that the gas is in steady state between emissions and atmospheric loss. For most CFCs the time to approach within 10% of steady-state conditions is more than a century. The ODP of a halocarbon is defined relative to CFC-11 (dimensionless) rather than in absolute units (e.g., % ozone loss per kg of gas emitted). Greenhouse Warming Potentials (GWP) are calculated similarly with a model for steady-state climate change. ODPs (or GWPs) therefore reflect the relative chronic ozone destruction (or warming potential) of CFCs after nearly constant emissions for a century. Transient ozone depletion potentials have also been used, but they do not clearly reflect the contribution of different halocarbons to the amount of chlorine in the atmosphere over the next century.

Even in the limit of steady state, the relative chlorine loading of a halocarbon can differ from its ODP because the calculation of an ODP includes the effectiveness of the gas in releasing its chlorine within the stratosphere. Most of the chlorine atoms in CFC-11 are released by photolysis in the lower stratosphere and thus are available to participate in the catalytic destruction of ozone at all altitudes in the stratosphere. Other CFCs, such as CFC-12 and HCFC-22, are more slowly photolyzed; in the lower stratosphere much of their chlorine is retained in the halocarbon; and most of their chlorine atoms are available only in the upper stratosphere or in the winter polar stratosphere. (Air in the winter polar stratosphere appears to be photochemically aged, having descended from the upper stratosphere.) For such compounds, the model derived ODPs (relative to CFC-11) will be less than the relative chlorine loading in these scenarios. A warning about the accuracy of ODP calculations must made: the current assessment models are limited to gas-phase chemistry and predict future ozone depletion predominantly in the middle stratosphere; they do not predict the Antarctic ozone hole or the possibility of similar heterogeneously driven ozone loss in the Arctic lower stratosphere.

The following scenarios were constructed as a sensitivity study to examine several possible approaches to limiting atmospheric chlorine content. The scenarios for the halocarbon source gases are similar, but not identical, to those used to calculate ozone depletion by the UNEP / WMO assessment. Two particular differences are that the lifetime of HCFC-22 is assumed here to be 15 years (rather than 20 years) based on more recent analyses of HCFC lifetimes, and that the assumed CFC cutback in emissions occurs entirely at the end of a given year rather than being phased in over 5 years from 1996 to 2000.

THE MODEL FOR CHLORINE/BROMINE LOADING

The data for halocarbons used in the model for chlorine and bromine loading are based on compilations from the recent ozone assessment (WMO, 1989) and the workshop on alternative fluorocarbons (AFEAS, 1989). The data and method of calculating the mean abundance of the halocarbons are given in Table 1. The atmospheric lifetimes in Table 1 are taken from these recent reports and have an estimated uncertainty of 25 %. Lifetimes for those species destroyed predominantly in the troposphere (CH_3CCl_3 and HCFC-22) are based on the AFEAS review. The fluxes in Table 1 (1 kt/yr = 1,000 metric tons per yr) are based on estimates of production in the year 1985 and total 1,000,000 metric tons for CFCs alone. Growth in production from 1985 through 1990 (kt/yr per yr) is assumed to be 4 %/yr for all industrial halocarbons; such increases are consistent with growth in the production of CFC-11 and CFC-12, compounds for which we have reliable estimates. The initial concentrations in 1985 (parts per trillion = 1/1,000,000,000,000) represent a tropospheric average based on available observations (IOTP, 1989). The factor (kt/ppt) used to convert mixing ratio (ppt) to total abundance (kt) assumes the compound is well mixed throughout 95 % of the atmosphere.

A simple numerical model is used: for example, the concentration in 1986 is calculated by reducing the 1985 value by a factor equal to exp[-1/lifetime(yr)] and then by adding the total emissions in 1986 which have also been reduced by a factor depending on the lifetime (see notes in Table 1). Thus, concentrations refer to the end of the specified year. Fluxes of CFCs and all other chlorine- and bromine-containing species, except CH_3Cl and CH_3Br, are defined according to the scenario, and cuts are assumed to take place instantly at the end of the specified year. More accurate numerical models for the calculation of halocarbon concentrations are available. For example, such models might include the effects of the delay between production and emission of CFCs according to use, of shifts in atmospheric circulation due to climate change, or of changes in tropospheric chemistry (e.g., HCFC and CH_3CCl_3 losses) due to increasing concentrations of other gases such as methane. However, increasing the complexity of the model is not justified for this work because uncertainties (e.g., lifetimes, see Objective 7; release of chlorine in the stratosphere, see ODP discussion) overwhelm the differences between such models

The reference scenario assumes control over atmospheric emissions of all industrial halocarbons as a group (CFCs, CCl_4, HCFC-22, CH_3CCl_3 and the halons). It begins in 1985, assumes growth for the years 1986 through 1990, freezes emissions into the atmosphere at the 1990-rate, and cuts all emissions to zero at the end of the year 2000. From then on the atmospheric abundance of chlorine or bromine is determined solely by the slow decay of gases already in the atmosphere in this reference scenario. Under the current Montreal Protocol the cutback to 50% of CFC emissions refers to 1986 production levels. Also, the earlier implementation of these reductions may result in smaller emissions during the period 1990-2000 than in this scenario.

TIME DELAYS AND BANKING OF CFCs

The absolute timing of the atmospheric response in these calculations may be imprecise not only due to the basic uncertainties in modeling atmospheric composition, but also because certain simplifying assumptions have been made. For example, stratospheric destruction of halocarbons (predominant loss for the long-lived CFCs) will lag emissions by about 2 years, the time it takes for air to travel from the upper troposphere to the middle stratosphere. This effect will be important only when tropospheric concentrations are changing rapidly and is not included here. Furthermore, the ozone depletion in response to halocarbons will also be delayed by the time for tropospheric air to circulate through the stratosphere. Air over the winter pole may represent a mix of tropospheric halocarbons from as long ago as 5 years previous.

A more important and obviously systematic omission in these calculations is the failure to simulate the delay between halocarbon production and emissions (see CMA, 1988). Depending on use, the halocarbons produced in a given year may not be emitted into the atmosphere until several years later. For examples, CFC-11 used in blowing closed-cell insulating foams may take more than 10 years to escape into the atmosphere, and CFC-12 used in hermetically sealed refrigeration systems will not be released until the refrigerant coils break, on average 20 years later. The accumulation, or banking, of the CFCs makes it difficult to stop emissions (as in the reference scenario) immediately upon cessation of production. On the other hand, CFC-113 and CH_3CCl_3 are used primarily as cleaning agents, and their production reflects the amount lost during the cleaning process, presumably to the atmosphere. Most of the CFCs are used in products that release the gases to the atmosphere within 3 years of production. The total bank of CFCs as of 1987 in products with average retention times greater than 2 years is estimated to be less than 2 years of the annual production of all CFCs (CMA, 1988). The net effect of CFC banking may look similar to the scenario in which there is a 15-year delay in compliance with CFC cuts (Objective 4 below); however, the banking may be offset by partial cuts in CFCs before the year 2000 as already agreed upon in the current Montreal Protocol.

In spite of these uncertainties in the timing of atmospheric effects, we expect that the comparison between scenarios, such as the difference in peak chlorine loading or the variance in times to reach 2 ppb chlorine, will be accurate. These scenarios describe controls over emissions rather than production and, with this caveat, the calculations provide a useful relative measure of the potential damage to stratospheric ozone associated with each option.

SUBSTITUTION

Substitution for the phased-out halocarbons is considered in many scenarios. In such cases we assume a kg-per-kg replacement (in %) of the sum of halocarbon cuts referenced to their 1985 emission levels (1,000 kt/yr of CFCs, 80 kt/yr of CCl_4, 140 kt/yr of HCFC-22, 600 kt/yr of CH_3CCl_3). We are interested here only in substitutes containing chlorine or bromine. The chemical industry has estimated that replacement with chlorinated compounds would capture about 30% of the CFC market (350 kt/yr in 1985). Substitution for CCl_4, HCFC-22 and CH_3CCl_3--if these compounds were phased out--are likely not to involve chlorinated replacements. Hence, in the reference scenario with a complete cut in all halocarbons (1,820 kt/yr in 1985), the industry estimates would correspond to a substitution rate of about 20% in these scenarios. We have not considered the possibility of bromine-containing compounds as substitutes for the halons.

Two substitute chemicals are considered as replacements for the reductions in the industrial halocarbons (CFCs, CCl_4, HCFC-22, and CH_3CCl_3):

- compound X has a 15 year lifetime (like HCFC-22) with a single chlorine atom and a mean molecular weight of 115, corresponding to a steady-state chlorine loading factor of 0.10 relative to CFC-11;
- compound Y has a 6 year lifetime (like CH_3CCl_3) with a single chlorine atom and a mean molecular weight of 115, corresponding to a steady-state chlorine loading factor of 0.04 relative to CFC-11.

These substitutes are examples of the types of alternative halocarbons included by AFEAS (1989) in its review of alternative fluorocarbons, but do not correspond to any specific compound. Choosing substitute X to replace some of the cutbacks in CFCs, CCl_4, CH_3CCl_3, and HCFC-22, is almost equivalent to continuing, and possibly expanding, the use of HCFC-22. The chlorine loading of HCFC-22 is slightly larger, 0.13, but its ODP is currently modelled to be smaller, 0.05, as discussed above. Thus substitute X would mimic the temporal behavior of HCFC-22 with a slightly different scale factor for its emissions (in kg). Similarly, substitute Y would mimic CH_3CCl_3 but has only one chlorine.

OBJECTIVES

Possible environmental goals might be based on the levels of atmospheric chlorine in the past. Some key chlorine abundances to remember are: (1) the natural abundance of chlorine is 0.6 ppb; (2) chlorine levels in the Antarctic stratosphere before the ozone hole were 1.5 to 2.0 ppb; and (3) today's abundance of chlorine is about 3.0 ppb.

One could not expect the depletion of Antarctic ozone to cease much before the middle of the next century when atmospheric chlorine concentrations would reach 2 ppb or less under the most stringent controls over halocarbon emissions. In order to return to near pristine conditions below 1 ppb chlorine, however, we must wait for the longest-lived CFCs to be almost completely destroyed in the atmosphere. Even without further emissions, this condition would not be met until well into the 22nd century. Without the ozone hole, the difference between 1 and 2 ppb of chlorine is predicted to lead to small, less than 2%, changes in global column ozone (IOTP, 1989).

A number of scenarios were performed to understand what possible actions control the peak chlorine loading, the rate at which the atmospheric abundance of chlorine decreases, and the date at which the atmospheric abundance of chlorine drops below 2 ppb. Specific objectives involve the testing of the impact of:

1. the timing of a phaseout (100% cut) in CFCs, CCl_4, CH_3CCl_3, and HCFC-22 (complete phaseout without substitution in 1995, 2000 [reference case] and 2005);
2. incomplete phaseout (cut in 2000 to 10%, 20%, 50% of 1985 emissions, or freeze the 1990 emissions);
3. different substitution scenarios for compound X and compound Y (phaseout of all halocarbons in 2000 with varying % substitution of X and Y by weight continued until 2015, 2030 [reference], 2045 and even 2100);
4. delayed compliance of phaseout by some countries (cut back to 10% or 20% of 1985 emissions in 2000, complete phaseout in 2015, any substitution is similarly lagged by 15 years);
5. graduated phase-in of halocarbon cuts (cut halocarbon emission to 50% of 1985 emissions in 1995 and completely phaseout in 2000; substitutes have similar 5 yr phase lag);
6. continued use of CH_3CCl_3 (freeze emissions of CH_3CCl_3 at 1990 levels, phaseout in 2030);
7. current uncertainties in the atmospheric lifetimes of halocarbons;
8. halon emissions on bromine loading (cut emissions of CF_3Br and CF_2ClBr in 2000 to 0%, 10%, 20%, 50% of 1985 emissions, or freeze at 1990 levels).

The chlorine loading from these scenarios is summarized in Tables 2a-h and the bromine loading in Table 3. Figures 1-12 display the evolution of chlorine from 1985 to 2100 for a selection of these cases and always compare with the reference calculation (complete phaseout of CFCs, CCl_4, CH_3CCl_3, and HCFC-22 emissions in the year 2000 with no substitutions).

OBJECTIVE 1. Test the impact of the timing of a phaseout (100% cut) in CFCs, CCl_4, CH_3CCl_3, and HCFC-22

This objective was examined by eliminating the emissions of all halocarbons as a group (CFCs, CCl_4, CH_3CCl_3 and HCFC-22) at the end of years 1995, 2000 (reference case), and 2005, all without substitution of any new chlorine containing compound.

Table 2a and Figure 1 show the results of these scenarios. It is evident that each 5 year delay in the total phaseout of these chemicals results in the peak chlorine loading increasing by about 0.5 ppb (87% of it due to the CFCs) and in the date taken for the atmospheric abundance of chlorine to drop below 2 ppb increasing by about 18 years. The delay in reaching an atmospheric loading of 2 ppb is due to the timing of the phaseout of the long-lived halocarbons (CFCs and CCl_4) and is not influenced by the timing of the phaseout of short-lived halocarbons (CH_3CCl_3 and HCFC-22). Banking of these gases, especially the long-lived CFCs, and possible non-compliance (see Objectives 2 and 4), make the effective dates for cessation of CFC emissions slip further into the future.

The key information from these scenarios is that an early phaseout of these substances results in a lower peak chlorine loading (0.1 ppb per year earlier phaseout) and in an earlier date for the atmospheric chlorine loading to drop below 2 ppb (3.6 years per year earlier phaseout), corresponding to the most optimistic time for elimination of the Antarctic ozone hole. The Table below summarizes the peak chlorine loading and the date of 2 ppb chlorine for these scenarios.

Peak Chlorine Loading and Time to Reach 2 ppb

scenario (phaseout=100% cut)	peak chlorine (ppb)	year when chlorine falls below 2 ppb
1995 phaseout	4.24	2055
2000 phaseout (ref*)	4.78	2073
2005 phaseout	5.28	2091

OBJECTIVE 2. Test the impact of incomplete phaseout.

This objective examined the impact of a partial phaseout (90%, 80%, 50%, 0%) in the emissions of all halocarbons as a group (CFCs, CCl_4, CH_3CCl_3 and HCFC-22) without substitution of any new chlorine containing compound. All reductions (90%, 80% and 50%) were made to reach a fraction of the year 1985 emissions (10%, 20% and 50% respectively), ~~and~~ all occurred at the end of year 2000. The calculation with no reductions continued the year 1990 emission levels of all halocarbons until the year 2100.

Table 2a and Figure 2 show the results of these scenarios. For partial phaseouts of 90% and 80% the peak chlorine loading is not affected, but the rate of decrease in the atmospheric chlorine and its long-term steady state value are significantly impacted. In the reference case (100% reduction) the atmospheric abundance of chlorine has decreased to 2 ppb by the year 2073. With a 90% reduction the chlorine abundance reaches 2.4 ppb in the year 2100 and is not expected to decrease to 2 ppb until after the year 2175. With an 80% reduction the chlorine abundance is 3.1 ppb in the year 2100 and will eventually approach its steady-state limit of about 2.8 ppb. With 50% reductions the peak chlorine loading drops briefly after the year 2000 and then continues to rise above 5.3 ppb by the year 2100. Without a cutback in the 1990 emissions the chlorine abundance in the atmosphere is expected to rise rapidly, exceeding 8.5 ppb by the year 2050 and 10.5 ppb by the end of the 21st century.

The key conclusion to be drawn from these scenarios is that a complete phaseout of almost all emission of halocarbons (CFCs, CCl_4, CH_3CCl_3, and HCFC-22) as a group is needed in order to decrease the atmospheric abundance of chlorine below 2 ppb before the year 2100. The required timing of these phaseouts will depend on the lifetime of the specific halocarbon. The long-term decline in chlorine abundances is controlled by the long-lived CFCs and CCl_4. Therefore, a long-term non-compliance with the 100% reduction, by even as little as 5 to 10%, limits our chance of eliminating the Antarctic ozone hole before the year 2100. The Table below summarizes the peak chlorine loading and the date of 2 ppb chlorine for these scenarios.

Peak Chlorine Loading and Time to Reach 2 ppb

scenario (phaseout=100% cut)	peak chlorine (ppb)	year when chlorine falls below 2 ppb
2000 phaseout (ref*)	4.78	2073
2000 (90% cut)	4.78	2175
2000 (80% cut)	4.78	never

OBJECTIVE 3. Test the impact of different substitution scenarios for compound X and compound Y

This objective was examined by eliminating the emissions of the halocarbons (CFCs, CCl_4, CH_3CCl_3 and HCFC-22) as a group in the year 2000 (reference case) and then by substituting for a fraction of these emissions (1,820 kt/yr) with either compound X (15 year lifetime, ODP = 0.1) or compound Y (6 year lifetime, ODP = 0.04). Substitution of either X or Y begins in the year 2001 at a level of 25%, 50% or 100%, corresponding to annual fluxes of 455, 910 and 1,820 kt, respectively. In addition, a scenario with 50% substitution is considered in which use of the substitute (X or Y) is allowed to grow annually at a compounded rate of 3 %/yr (denoted by *50%). In general, the time period of substitution is assumed to be 30 years, from year 2001 through year 2030. In some cases the period of substitution is shortened to 15 years or extended to 45 or even 100 years.

Tables 2b-d and Figures 3-6 show the results of these many scenarios. We discuss only a few of them below.

For the levels of substitution and the limits on their growth considered in these scenarios, the peak chlorine loading occurs at the phaseout of CFCs and is not affected by the substitution. In the case of 100% substitution of compound X, however, the chlorine loading remains high, above 4 ppb, out to the year 2032 (Figure 3). Equivalent substitution of compound Y has a much smaller impact on atmospheric chlorine because of the shorter lifetime (Figure 4). Substitution by either compound X or Y at 50% of the halocarbon emissions followed by 3 %/yr compounded growth becomes equivalent to 100% substitution by the year 2030 and would greatly exceed that level if continued for another 15 years (Figures 3 and 4).

Substitution between the years 2000 and 2030 with compound X at less than 25%, or compound Y at less than 50% of all halocarbon emissions, results in a rapid decrease in peak chlorine loading. The increase in atmospheric chlorine abundance above the base case (no substitution) is greatest in the year 2030 and never exceeds 0.3 ppb under these conditions. The assessment of the International Technical Panel (part of the UNEP assessment) is that about 30% of the current CFC market will be replaced by short-lived substitutes containing chlorine, and that this market will grow at 3 %/yr until terminated. Such a scenario is about equivalent to following the 25% substitution-curve in the early years (2000-2010) and increasing to chlorine levels slightly above the 50% substitution-curve by the year 2030.

When compound X is phased out before the year 2030 or compound Y before the year 2045, the earliest date when the atmospheric abundance of chlorine falls to 2 ppb is delayed by at most 4 years relative to the reference case with no substitutions (Figure 5). With indefinite substitution of compound X or Y, even at 50% of the halocarbon emissions, it is difficult or impossible to achieve chlorine concentrations below 2 ppb by the end of the 21st century (Figure 6).

The key conclusions to be drawn from these scenarios are that substitution of all halocarbons (CFCs, CCl_4, CH_3CCl_3 and HCFC-22) as a group, between the years 2000 and 2030 by compound X, and between the years 2000 and 2045 by compound Y, would have little influence on the date when the atmospheric abundance of chlorine can be expected to fall below 2 ppb, approximately the year 2073. With a limited period of substitution of the short-lived substitutes, the chlorine loading of the atmosphere beyond the year 2075 is governed by the CFCs and CCl_4 emitted prior to their phaseout. Furthermore, such substitutions can still result in a rapid decrease in the peak chlorine abundance if substitution rates close to 25% for X or 50% for Y are used. Substitution by compound Y is preferable to substitution by compound X because of its shorter lifetime.

compound Y makes a smaller contribution to the chlorine loading and in addition allows for more rapid recovery of atmospheric chlorine following cessation of emissions.

OBJECTIVE 4. Test the impact of delayed compliance of phaseout by some countries.

This objective was examined by reducing emissions of all halocarbons (CFCs, CCl_4, CH_3CCl_3 and HCFC-22) to a fraction (10% or 20%) of their 1985 levels in the year 2000 and allowing this fraction of emissions to continue for 15 years until the end of year 2015. Substitution of compounds X and Y was also considered as above for a 30-year time period. The final phaseout of CFCs in the year 2015 was followed by a similar period of fractional substitution until the year 2045. This form of delayed compliance would allow a fraction of the world community further time to implement a complete halocarbon phaseout.

Table 2e and Figures 7-8 show the results of these scenarios. There is no additional penalty in the peak chlorine loading for a 15-year lag in the final 10% or 20% of the halocarbon cuts. However, the 15-year lag in 10% of the phaseout results in a 6-year delay in the time to reach 2 ppb chlorine, and the lag in 20% adds 11 years to this time. The effects of substitution of compounds X or Y are similar to the reference case (complete phaseout) except that the baseline of total chlorine is higher during the substitution period, by a maximum in the year 2015 of about 0.2 ppb (10%) and 0.4 ppb (20%). The 15-year delay in the phaseout does extend the duration of higher chlorine levels. In the case where only 80% of the CFCs are cut and replaced 100% by compound X, the peak chlorine loading in the year 2000 (4.78 ppb) is maintained out to the year 2015 (4.72 ppb).

The key point here is that a 15-year lag in compliance of the phaseout of CFCs by a SMALL FRACTION, 10-20%, of the community should have no effect on peak chlorine levels and have only a small delay in the time to reach 2 ppb total chlorine. The average chlorine levels in the first half of the next century would be higher in this scenario, but may be compensated for by reducing use of the longer-lived of the two substitutes, compounds X. The Table below summarizes the peak chlorine loading and the date of 2 ppb chlorine for these scenarios.

Peak Chlorine Loading and Time to Reach 2 ppb

scenario (phaseout=100% cut)	peak chlorine (ppb)	year when chlorine falls below 2 ppb
2000 phaseout (ref*)	4.78	2073
2000/2015 (90/10%)	4.78	2079
2000/2015 (80/20%)	4.78	2084

OBJECTIVE 5. Test the impact of a graduated phase-in of halocarbon cuts.

This objective was examined by reducing the emissions of all halocarbons (CFCs, CCl_4, CH_3CCl_3 and HCFC-22) to 50% of their 1985 levels at the end of year 1995 and completely to zero at the end of year 2000. Substitution of compound X or Y for a period of 30 years (staggered 5 years as for halocarbon cuts) at 50% of the 1985 halocarbon emissions is also considered. This complex scenario for phaseout of CFCs may be a more realistic approach to elimination of halocarbon emissions, recognizing the ability of some parts of the CFC market to phaseout earlier than others and also the net impact of banking in delaying release of CFCs to the atmosphere.

Table 2f and Figure 9 show the results of these scenarios. As expected, the history of chlorine abundance from the 50%/50% scenario lies between that of the year-1995 phaseout and that of the year-2000 phaseout. Peak chlorine loading occurs in 1995, and the year when chlorine levels fall below 2 ppb is 2063, about 10 years earlier than in the reference case. Moderate substitution (50% of cuts) with compounds X or Y until the year 2030 give chlorine histories that resemble the reference case without substitution for the first half of the 21st century.

The key result from this scenario is that an earlier partial phaseout of CFCs has distinct advantages: reducing the peak chlorine loading, approaching more rapidly the 2 ppb level (probably eliminating the Antarctic ozone hole), and allowing for substitution without significant increase in the average chlorine levels over the next 50 years. The Table below summarizes the peak chlorine loading and the date of 2 ppb chlorine for these scenarios.

Peak Chlorine Loading and Time to Reach 2 ppb

scenario (phaseout=100% cut)	peak chlorine (ppb)	year when chlorine falls below 2 ppb
2000 phaseout (ref*)	4.78	2073
1995/2000 (50/50%)	4.24	2063

OBJECTIVE 6. Test the impact of continued use of CH_3CCl_3

This objective was examined by eliminating the emissions of CFCs, CCl_4, and HCFC-22 at the end of year 2000, but continuing CH_3CCl_3 emissions (1990 levels) until the year 2030. Substitution of compound X or Y for a period of 30 years is considered as above, but substitution percentages now refer to a lesser halocarbon budget of 1,220 kt/yr. This scenario recognizes that methyl chloroform is a short-lived halocarbon (about 6 yr) and has properties similar to those of possible CFC substitutes (i.e., compound Y).

Table 2g and Figure 10 show the results of these scenarios. Compared with the reference scenario, there is no increase in peak chlorine loading and little change in the date at which the atmospheric abundance of chlorine drops below 2 ppb. Substitutions for the phased-out compounds (CFCs, CCl_4 and HCFC-22) show similar properties as in Objective 3, although 100% replacement with compound X maintains near-peak chlorine levels above 4.5 ppb out to the year 2020. Continued use of methyl chloroform is equivalent to substitution with 1,800 kt/yr of compound Y.

When the cuts in CH_3CCl_3 and CFC production are simultaneous the emissions of CH_3CCl_3 are expected to drop rapidly but those of CFCs will continue at some reduced level as the bank of CFCs is released (see previous discussion). The bank of CFCs as of 1987 (CMA, 1988) would produce only a modest extension of CFC release following a cut in production: emissions would drop to about 30% of production levels in 3 years and continue at an average level of less than 10% out to 20 years. Details of the CFC banking in relation to the timing of the cut in CH_3CCl_3 may slightly affect the peak chlorine loading.

The key point from this scenario is that the phaseout of CH_3CCl_3 production is expected to lead to a rapid cessation of emissions and would result in a relatively rapid decrease of as much as 0.5 ppb in atmospheric chlorine.

OBJECTIVE 7. Test the impact of current uncertainties in the atmospheric lifetimes of halocarbons;

This objective was examined by increasing or decreasing the recommended atmospheric lifetimes of the halocarbons by 25% for the reference scenario (phaseout of all halocarbons in the year 2000). These limits are extreme (e.g., CFC-11 lifetimes from 45 yr to 75 yr) and cover the most probable range in CFC lifetimes from the best current atmospheric models and from the budget analyses using observations and historical emissions. Assuming that future halocarbon emissions are known, this scenario represents the largest uncertainty in the absolute abundance of atmospheric chlorine from these calculations.

Table 2h and Figure 11 show the results of these scenarios. When halocarbon lifetimes are reduced by 25%, the more rapid destruction of these compounds lowers the peak chlorine concentration by about 0.3 ppb (to 4.5 ppb) and reduces the time to reach 2 ppb chlorine by 20 years (to the year 2053). When halocarbon lifetimes are increased by 25%, the slower destruction of these compounds raises the peak chlorine concentration by about 0.2 ppb (to 5.0 ppb) and increases the time to reach 2 ppb chlorine by 22 years (to the year 2095).

The key point from these calculations is that the uncertainty in predicting atmospheric chlorine levels in the future, given the history of atmospheric emissions, is not large. More specifically, all of the options to the reference scenario considered above (Objectives 1-6) may need to be shifted up or down, by less than 0.3 ppb, as our understanding and modeling of the atmospheric chemical losses of these compounds improves.

OBJECTIVE 8. Evaluate the impact of halon emissions on bromine loading.

The atmospheric abundance of bromine in these scenarios is predicted to result from emissions of methyl bromide (CH_3Br) and the halons 1301 (CF3Br) and 1211 (CF2ClBr). The other halon specified in the current Montreal Protocol, halon-2402 or C2F4Br2, is assumed to be negligible at present and in the future. (The short-lived compound bromoform, CHBr3, is observed occasionally at high concentrations near the ocean surface, but is expected to contribute little to stratospheric bromine.) This scenario is similar to that for chlorine loading and examines the effects of cutting halon emissions to 0%, 20% and 50% of 1985 levels, as well as freezing emissions at their 1990 levels (see Table 3). The assumption here that production and release of halons occurs simultaneously is also incorrect as discussed for CFCs above.

Results are shown in Table 3 and Figure 12. In 1985 the halons 1301 and 1211 together contributed about 3 ppt to the atmospheric abundance of bromine (18 ppt). If their emissions continued at the estimated 1990 production levels then the atmospheric abundance of bromine in the future would approximately triple from about 18 ppt (3 ppt halons) in the year 1985 to 53 ppt (38 ppt halons) by the year 2100.

To relate the impact of increases in atmospheric bromine to that of chlorine increases, it would be useful to define a factor relating bromine to chlorine. Such a simple factor is difficult to derive because bromine-catalyzed destruction of ozone is important both globally and in the special environment of the Antarctic ozone hole. Furthermore, much of the loss is coupled to the chlorine abundance as noted above. Currently, one estimate of this factor is about 30 (with a large uncertainty ranging from 10 to 50), and thus the rise in bromine with a freeze on 1990 emissions (increase of 33 ppt) would be about the equivalent of adding 1 ppb of chlorine to the atmosphere.

These calculations, however, assumed that CH_3Br remains constant. There is clear evidence that a substantial fraction of atmospheric CH_3Br is associated with northern continental sources and human activity (e.g., grain fumigation), and thus its concentration may increase in the future.

The key result of these bromine scenarios is that a phaseout or 80% reduction of halon emissions in the near future would stabilize the atmospheric abundance of bromine at about 24 ppt (9 ppt of halons).

CONCLUSIONS

In order to minimize future ozone depletion, or the potential of damage to the protective stratospheric ozone layer, and to facilitate the elimination of the Antarctic ozone hole it is desirable to:

phase out production/emission of long-lived halocarbons (CFCs and CCl_4) as soon as possible,

achieve as great as possible compliance with such a phaseout of CFCs and CCl_4 at the expense of substituting short-lived HCFCs,

if it becomes necessary to rapidly reduce the peak chlorine loading, make significant cutbacks in the emissions of abundant, short-lived, non-banked halocarbons, particularly CH_3CCl_3,

phase out in addition the halocarbon substitutes sometime in the middle of the next century if the Antarctic ozone hole is expected to disappear before the end of the next century,

stabilize the atmospheric bromine concentration at today's level or below.

REFERENCES

AFEAS, 1989.
CMA, December, 1988.
IOTP, 1989.
WMO/UNEP, 1989.
UNEP/Technical Panel, 1989.

Table 1. Halocarbon Data for Model

halocarbon		Lifetime (yr)	Flux (kt/yr)	Growth (kt/yr/yr)	Concentration (ppt)	Factor (kt/ppt)
CFC-11	$CFCl_3$	60	360.	14.4	220	23.2
CFC-12	CF_2Cl_2	120	450.	18.0	375	20.4
CFC-113	$C_2F_3Cl_3$	90	165.	6.6	30	31.6
CFC-114	$C_2F_4Cl_2$	200	15.	0.6	5	28.9
CFC-115	C_2F_5Cl	400	10.	0.4	4	26.1
carbon tetrachloride	CCl_4	50	80.	3.2	100	25.9
HCFC-22	CHF_2Cl	15	140.	5.6	80	14.6
methyl chloroform	CH_3CCl_3	6	600.	24.0	130	22.4
methyl chloride	CH_3Cl	1.5			600	
(sub X)	C_xCl	15			0	19.3
(sub Y)	C_xCl	6			0	19.3
halon-1211	CF_2BrCl	15	10.	0.40	1.5	27.9
halon-1301	CF_3Br	110	9.	0.36	1.7	25.1
methyl bromide	CH_3Br	1.5			15	

Lifetime (yr) is the global abundance divided by the annual average loss rate.
Flux (kt/yr = 1,000 tons per year) equals the atmospheric emissions during 1985.
Growth (kt/yr/yr) equals the increment to the flux each year from 1986 through 1990.
Concentration (ppt = parts per trillion = 1/1,000,000,000,000) is the average (well mixed) tropospheric abundance in 1985.
Factor (kt/ppt) relates concentration (ppt) to global content (kt).
Methyl chloride and methyl bromide concentrations are fixed.
The concentration (conc) in year+1 is calculated from the equation
conc[year+1] = conc[year] x decay + flux[year+1] x (1-decay) x lifetime / factor.
where decay = exp(-1 / lifetime).

Table 2a. Atmospheric Chlorine (ppb = 1/1,000,000,000) following Cut in all Halocarbon Emissions without Substitutes

year cut	1995 100%	2000 100%#	2005 100%	2000 90%	2000 80%	2000 50%	2000 0%
1985	2.98	2.98	2.98	2.98	2.98	2.98	2.98
1990	3.62	3.62	3.62	3.62	3.62	3.62	3.62
1995	4.24	4.24	4.24	4.24	4.24	4.24	4.24
2000	3.71	4.78	4.78	4.78	4.78	4.78	4.78
2005	3.38	4.21	5.28	4.30	4.39	4.65	5.28
2010	3.14	3.84	4.67	3.99	4.15	4.63	5.74
2015	2.95	3.57	4.27	3.78	4.00	4.65	6.17
2020	2.78	3.35	3.97	3.62	3.89	4.69	6.57
2025	2.64	3.16	3.73	3.48	3.79	4.74	6.95
2030	2.51	2.99	3.52	3.35	3.71	4.79	7.30
2035	2.39	2.84	3.33	3.24	3.64	4.84	7.64
2040	2.28	2.71	3.16	3.14	3.58	4.89	7.95
2045	2.18	2.58	3.00	3.05	3.52	4.94	8.25
2050	2.09	2.46	2.86	2.97	3.47	4.99	8.53
2055	2.00	2.35	2.72	2.89	3.42	5.04	8.80
2060	1.92	2.25	2.60	2.81	3.38	5.08	9.05
2065	1.84	2.15	2.48	2.75	3.34	5.12	9.28
2070	1.77	2.06	2.38	2.68	3.30	5.16	9.51
2075	1.70	1.98	2.27	2.63	3.27	5.20	9.72
2080	1.64	1.90	2.18	2.57	3.24	5.24	9.92
2085	1.58	1.83	2.09	2.52	3.21	5.28	10.11
2090	1.53	1.76	2.01	2.47	3.18	5.31	10.28
2095	1.48	1.70	1.93	2.43	3.16	5.35	10.45
2100	1.43	1.64	1.86	2.39	3.13	5.38	10.61

reference case in all following tables = ref#

Table 2b. Halocarbon Cuts (100% in 2000) with Substitutes to 2030 (* = +3%/yr growth in substitute)

subs %	none ref#	X 25%	X 50%	X 100%	X *50%	Y 25%	Y 50%	Y 100%	Y *50%
1985	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98
1990	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62
1995	4.24	4.24	4.24	4.24	4.24	4.24	4.24	4.24	4.24
2000	4.78	4.78	4.78	4.78	4.78	4.78	4.78	4.78	4.78
2005	4.21	4.31	4.41	4.61	4.43	4.29	4.37	4.53	4.38
2010	3.84	4.01	4.18	4.53	4.25	3.95	4.07	4.30	4.12
2015	3.57	3.79	4.02	4.47	4.16	3.70	3.83	4.09	3.93
2020	3.35	3.61	3.87	4.40	4.12	3.49	3.62	3.90	3.78
2025	3.16	3.45	3.74	4.32	4.12	3.30	3.44	3.72	3.67
2030	2.99	3.30	3.61	4.23	4.15	3.14	3.28	3.56	3.59
2035	2.84	3.07	3.29	3.73	3.67	2.91	2.97	3.09	3.10
2040	2.71	2.86	3.02	3.34	3.30	2.73	2.76	2.81	2.82
2045	2.58	2.69	2.81	3.03	3.00	2.59	2.60	2.63	2.63
2050	2.46	2.54	2.62	2.79	2.76	2.47	2.47	2.48	2.48
2055	2.35	2.41	2.47	2.58	2.57	2.35	2.35	2.36	2.36
2060	2.25	2.29	2.33	2.42	2.40	2.25	2.25	2.25	2.25
2065	2.15	2.18	2.21	2.27	2.26	2.15	2.15	2.15	2.15
2070	2.06	2.09	2.11	2.15	2.14	2.06	2.06	2.06	2.06
2075	1.98	2.00	2.01	2.04	2.04	1.98	1.98	1.98	1.98
2080	1.90	1.91	1.93	1.95	1.94	1.90	1.90	1.90	1.90
2085	1.83	1.84	1.85	1.86	1.86	1.83	1.83	1.83	1.83
2090	1.76	1.77	1.77	1.78	1.78	1.76	1.76	1.76	1.76
2095	1.70	1.70	1.71	1.71	1.71	1.70	1.70	1.70	1.70
2100	1.64	1.64	1.64	1.65	1.65	1.64	1.64	1.64	1.64

Table 2c. Halocarbon Cuts (100% in 2000) & 100% Substitution for different periods: until 2015, 2030 & 2045

subs until	none ref#	X 2015	X 2030	X 2045	Y 2030	Y 2045
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1985	2.98	2.98	2.98	2.98	2.98	2.98
1990	3.62	3.62	3.62	3.62	3.62	3.62
1995	4.24	4.24	4.24	4.24	4.24	4.24
2000	4.78	4.78	4.78	4.78	4.78	4.78
2005	4.21	4.61	4.61	4.61	4.53	4.53
2010	3.84	4.53	4.53	4.53	4.30	4.30
2015	3.57	4.47	4.47	4.47	4.09	4.09
2020	3.35	3.99	4.40	4.40	3.90	3.90
2025	3.16	3.62	4.32	4.32	3.72	3.72
2030	2.99	3.33	4.23	4.23	3.56	3.56
2035	2.84	3.08	3.73	4.14	3.09	3.41
2040	2.71	2.88	3.34	4.04	2.81	3.28
2045	2.58	2.70	3.03	3.94	2.63	3.15
2050	2.46	2.55	2.79	3.43	2.48	2.71
2055	2.35	2.41	2.58	3.05	2.36	2.46
2060	2.25	2.29	2.42	2.75	2.25	2.30
2065	2.15	2.19	2.27	2.51	2.15	2.17
2070	2.06	2.09	2.15	2.32	2.06	2.07
2075	1.98	2.00	2.04	2.16	1.98	1.98
2080	1.90	1.91	1.95	2.03	1.90	1.90
2085	1.83	1.84	1.86	1.92	1.83	1.83
2090	1.76	1.77	1.78	1.83	1.76	1.76
2095	1.70	1.70	1.71	1.75	1.70	1.70
2100	1.64	1.64	1.65	1.67	1.64	1.64
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Table 2d. Halocarbon Cuts (100% in 2000) & Substitution to 2100

subs %	none ref#	X 25%	X 50%	Y 25%	Y 50%	X&Y 50%
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1985	2.98	2.98	2.98	2.98	2.98	2.98
1990	3.62	3.62	3.62	3.62	3.62	3.62
1995	4.24	4.24	4.24	4.24	4.24	4.24
2000	4.78	4.78	4.78	4.78	4.78	4.78
2005	4.21	4.31	4.41	4.29	4.37	4.57
2010	3.84	4.01	4.18	3.95	4.07	4.41
2015	3.57	3.79	4.02	3.70	3.83	4.28
2020	3.35	3.61	3.87	3.49	3.62	4.14
2025	3.16	3.45	3.74	3.30	3.44	4.02
2030	2.99	3.30	3.61	3.14	3.28	3.90
2035	2.84	3.17	3.49	2.99	3.13	3.78
2040	2.71	3.04	3.37	2.85	2.99	3.65
2045	2.58	2.92	3.26	2.72	2.86	3.54
2050	2.46	2.80	3.15	2.60	2.75	3.44
2055	2.35	2.70	3.05	2.49	2.64	3.34
2060	2.25	2.60	2.95	2.39	2.53	3.23
2065	2.15	2.51	2.86	2.30	2.44	3.15
2070	2.06	2.42	2.77	2.21	2.35	3.06
2075	1.98	2.34	2.69	2.12	2.27	2.98
2080	1.90	2.26	2.61	2.05	2.19	2.90
2085	1.83	2.19	2.54	1.97	2.12	2.83
2090	1.76	2.12	2.48	1.91	2.05	2.77
2095	1.70	2.06	2.41	1.84	1.98	2.69
2100	1.64	2.00	2.35	1.78	1.92	2.63
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Table 2e. Developed/Undeveloped Scenarios:

100% cut & substitution of all halocarbons, but delay
10% to 20% of cuts (& substitution) by 15 yr.

cut 2000 cut 2015 subs	100% ref# none	90% 10% none	90% 10% 100%X	90% 10% 100%Y	80% 20% none	80% 20% 100%X	80% 20% 100%Y
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1985	2.98	2.98	2.98	2.98	2.98	2.98	2.98
1990	3.62	3.62	3.62	3.62	3.62	3.62	3.62
1995	4.24	4.24	4.24	4.24	4.24	4.24	4.24
2000	4.78	4.78	4.78	4.78	4.78	4.78	4.78
2005	4.21	4.30	4.66	4.59	4.39	4.71	4.64
2010	3.84	3.99	4.62	4.41	4.15	4.71	4.52
2015	3.57	3.78	4.60	4.25	4.00	4.72	4.42
2020	3.35	3.53	4.51	4.06	3.71	4.63	4.21
2025	3.16	3.32	4.43	3.87	3.47	4.54	4.02
2030	2.99	3.14	4.34	3.70	3.28	4.45	3.84
2035	2.84	2.98	3.88	3.25	3.11	4.02	3.41
2040	2.71	2.83	3.51	2.98	2.95	3.69	3.15
2045	2.58	2.69	3.22	2.79	2.81	3.42	2.96
2050	2.46	2.57	2.95	2.61	2.67	3.11	2.74
2055	2.35	2.45	2.72	2.47	2.55	2.86	2.58
2060	2.25	2.34	2.54	2.35	2.44	2.66	2.45
2065	2.15	2.24	2.38	2.24	2.33	2.49	2.33
2070	2.06	2.15	2.25	2.15	2.23	2.35	2.23
2075	1.98	2.06	2.13	2.06	2.14	2.22	2.14
2080	1.90	1.98	2.03	1.98	2.05	2.11	2.05
2085	1.83	1.90	1.94	1.90	1.97	2.01	1.97
2090	1.76	1.83	1.85	1.83	1.89	1.92	1.89
2095	1.70	1.76	1.78	1.76	1.82	1.84	1.82
2100	1.64	1.70	1.71	1.70	1.76	1.77	1.76
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Table 2f. Phased Halocarbon Cuts:

50% in 1995 and remaining 50% in 2000
Substitutes similarly cut in 2025 and 2030

subs	ref#	none	50%X	50%Y
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1985	2.98	2.98	2.98	2.98
1990	3.62	3.62	3.62	3.62
1995	4.24	4.24	4.24	4.24
2000	4.78	4.16	4.26	4.24
2005	4.21	3.72	4.00	3.92
2010	3.84	3.43	3.83	3.67
2015	3.57	3.20	3.69	3.47
2020	3.35	3.02	3.57	3.30
2025	3.16	2.86	3.46	3.14
2030	2.99	2.71	3.24	2.92
2035	2.84	2.58	2.96	2.67
2040	2.71	2.46	2.73	2.50
2045	2.58	2.35	2.54	2.36
2050	2.46	2.24	2.38	2.25
2055	2.35	2.15	2.25	2.15
2060	2.25	2.05	2.13	2.06
2065	2.15	1.97	2.02	1.97
2070	2.06	1.89	1.93	1.89
2075	1.98	1.82	1.85	1.82
2080	1.90	1.75	1.77	1.75
2085	1.83	1.69	1.70	1.69
2090	1.76	1.63	1.64	1.63
2095	1.70	1.57	1.58	1.57
2100	1.64	1.52	1.52	1.52
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Table 2g. CH3CCl3 continued until 2030:

All other halocarbons cut 100% in 2000 with subs until 2030
(* = +3%/yr growth, compounded)

subs	none	none	X	X	X	Y	Y	Y
%	ref#	0%	25%	100%	*50%	25%	100%	*50%
1985	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98
1990	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62
1995	4.24	4.24	4.24	4.24	4.24	4.24	4.24	4.24
2000	4.78	4.78	4.78	4.78	4.78	4.78	4.78	4.78
2005	4.21	4.48	4.55	4.75	4.63	4.53	4.70	4.60
2010	3.84	4.23	4.34	4.70	4.51	4.30	4.54	4.42
2015	3.57	4.01	4.16	4.62	4.41	4.10	4.36	4.25
2020	3.35	3.81	3.99	4.52	4.33	3.91	4.18	4.11
2025	3.16	3.64	3.83	4.42	4.28	3.73	4.01	3.98
2030	2.99	3.47	3.68	4.31	4.25	3.57	3.86	3.88
2035	2.84	3.05	3.20	3.65	3.61	3.09	3.22	3.23
2040	2.71	2.80	2.90	3.22	3.19	2.81	2.87	2.87
2045	2.58	2.62	2.69	2.92	2.90	2.63	2.65	2.65
2050	2.46	2.48	2.53	2.70	2.68	2.48	2.49	2.49
2055	2.35	2.36	2.40	2.52	2.50	2.36	2.36	2.36
2060	2.25	2.25	2.28	2.36	2.36	2.25	2.25	2.25
2065	2.15	2.15	2.17	2.23	2.23	2.15	2.16	2.16
2070	2.06	2.06	2.08	2.12	2.12	2.06	2.06	2.06
2075	1.98	1.98	1.99	2.02	2.02	1.98	1.98	1.98
2080	1.90	1.90	1.91	1.93	1.93	1.90	1.90	1.90
2085	1.83	1.83	1.84	1.85	1.85	1.83	1.83	1.83
2090	1.76	1.76	1.77	1.78	1.78	1.76	1.76	1.76
2095	1.70	1.70	1.70	1.71	1.71	1.70	1.70	1.70
2100	1.64	1.64	1.64	1.65	1.65	1.64	1.64	1.64

Table 2h. Uncertainty in halocarbon lifetimes

	ref#	25% shorter	25% longer
1985	2.98	2.98	2.98
1990	3.62	3.49	3.71
1995	4.24	4.01	4.40
2000	4.78	4.47	5.01
2005	4.21	3.87	4.46
2010	3.84	3.50	4.10
2015	3.57	3.22	3.82
2020	3.35	2.99	3.61
2025	3.16	2.80	3.43
2030	2.99	2.62	3.27
2035	2.84	2.46	3.13
2040	2.71	2.32	3.00
2045	2.58	2.18	2.88
2050	2.46	2.06	2.76
2055	2.35	1.95	2.66
2060	2.25	1.85	2.56
2065	2.15	1.76	2.46
2070	2.06	1.68	2.37
2075	1.98	1.60	2.29
2080	1.90	1.53	2.21
2085	1.83	1.47	2.13
2090	1.76	1.41	2.06
2095	1.70	1.35	2.00
2100	1.64	1.30	1.93

Table 3. Atmospheric Bromine (ppt = 1/1,000,000,000,000) following Cut in all Halocarbon Emissions without Substitutes

year cut	1995 100%	2000 100%	2005 100%	2000 90%	2000 80%	2000 50%	2000 0%
1985	18.2	18.2	18.2	18.2	18.2	18.2	18.2
1990	21.4	21.4	21.4	21.4	21.4	21.4	21.4
1995	24.4	24.4	24.4	24.4	24.4	24.4	24.4
2000	23.0	27.0	27.0	27.0	27.0	27.0	27.0
2005	22.0	25.3	29.3	25.7	26.0	27.0	29.3
2010	21.2	24.1	27.4	24.7	25.3	27.1	31.3
2015	20.6	23.1	26.0	24.0	24.8	27.3	33.2
2020	20.1	22.4	24.9	23.4	24.5	27.6	35.0
2025	19.7	21.8	24.0	23.0	24.2	27.9	36.6
2030	19.4	21.2	23.3	22.7	24.1	28.3	38.1
2035	19.1	20.8	22.7	22.4	23.9	28.6	39.5
2040	18.9	20.5	22.2	22.2	23.9	29.0	40.9
2045	18.6	20.1	21.7	22.0	23.8	29.3	42.2
2050	18.5	19.9	21.3	21.8	23.8	29.6	43.4
2055	18.3	19.6	21.0	21.7	23.8	30.0	44.5
2060	18.1	19.4	20.7	21.6	23.7	30.3	45.6
2065	18.0	19.2	20.4	21.4	23.7	30.6	46.6
2070	17.8	19.0	20.1	21.3	23.7	30.9	47.6
2075	17.7	18.8	19.9	21.3	23.7	31.2	48.6
2080	17.6	18.6	19.7	21.2	23.7	31.5	49.5
2085	17.5	18.4	19.5	21.1	23.7	31.7	50.3
2090	17.3	18.3	19.2	21.0	23.8	32.0	51.2
2095	17.2	18.1	19.1	20.9	23.8	32.2	51.9
2100	17.1	18.0	18.9	20.9	23.8	32.4	52.7

Fig. 1. 100% cut of all halocarbons

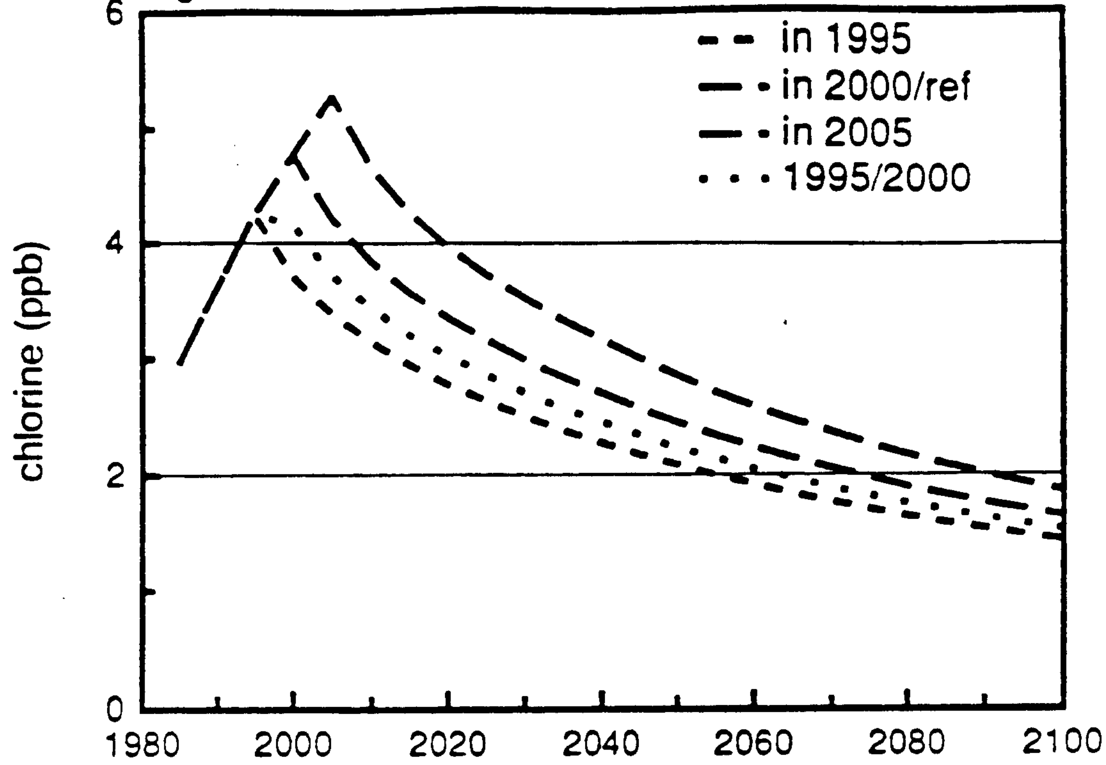

Fig. 2. Cut all halocarbons in 2000

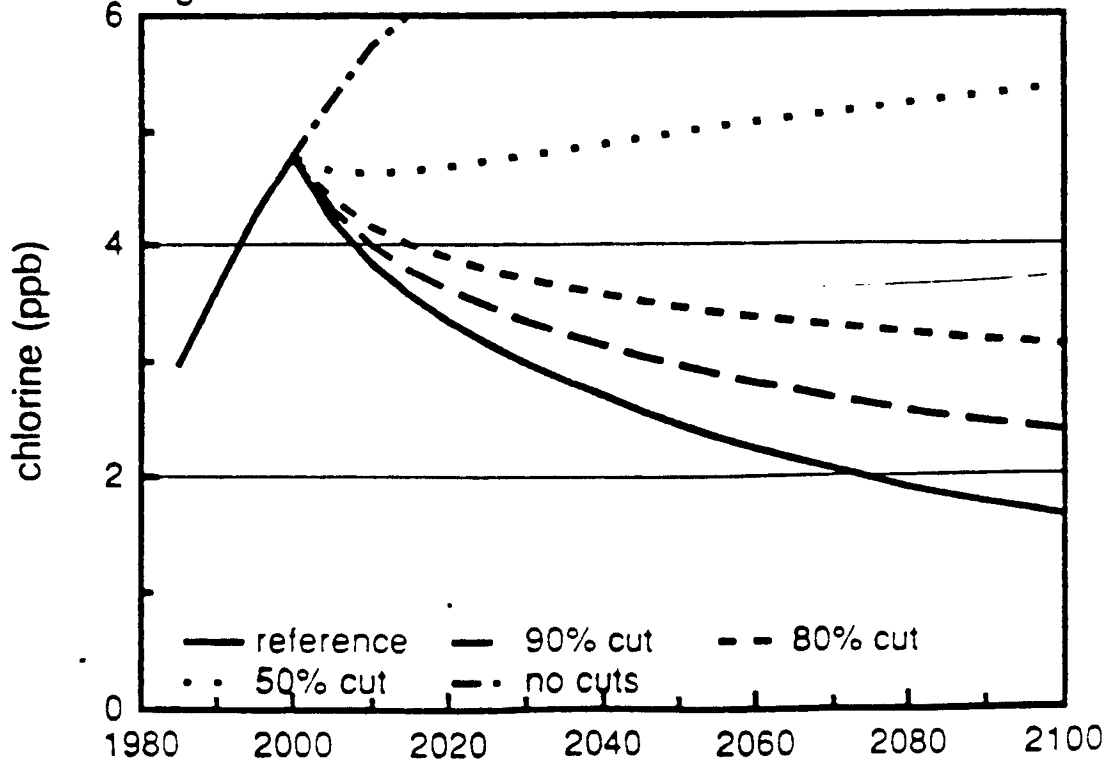

Fig. 3. Substitution for 30 yrs (*=growth)

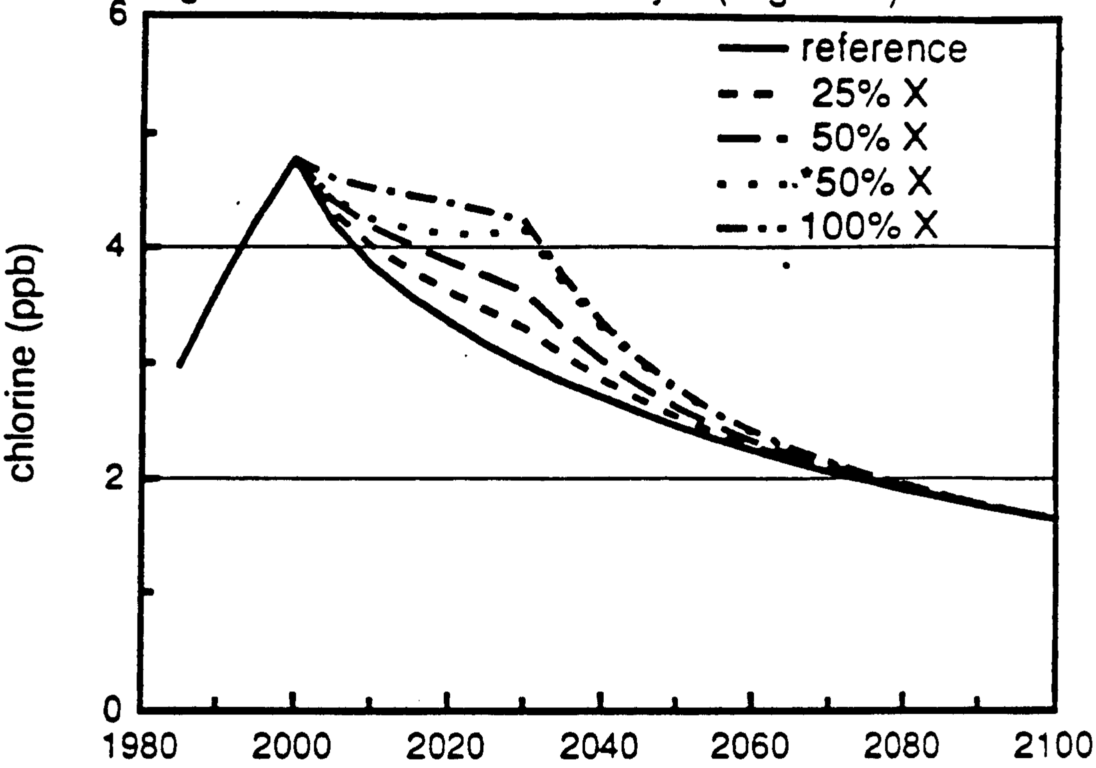

Fig. 4. Substitution for 30 yrs (*=growth)

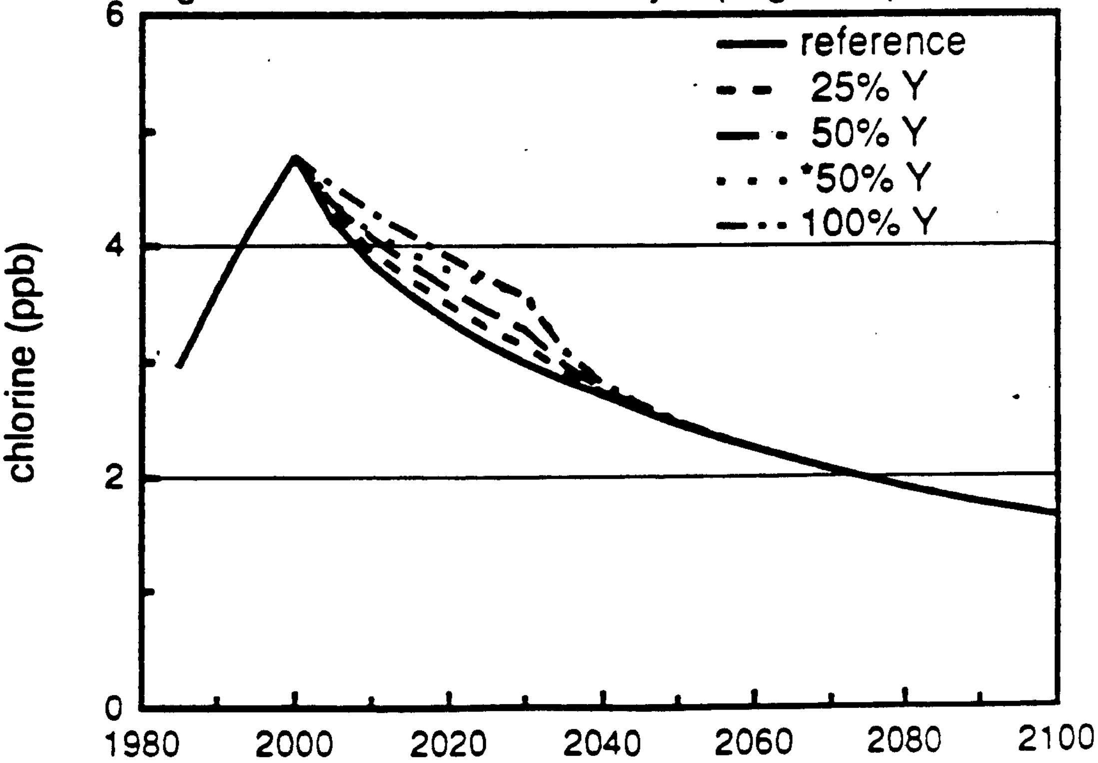

Fig. 5. Substitution for different periods

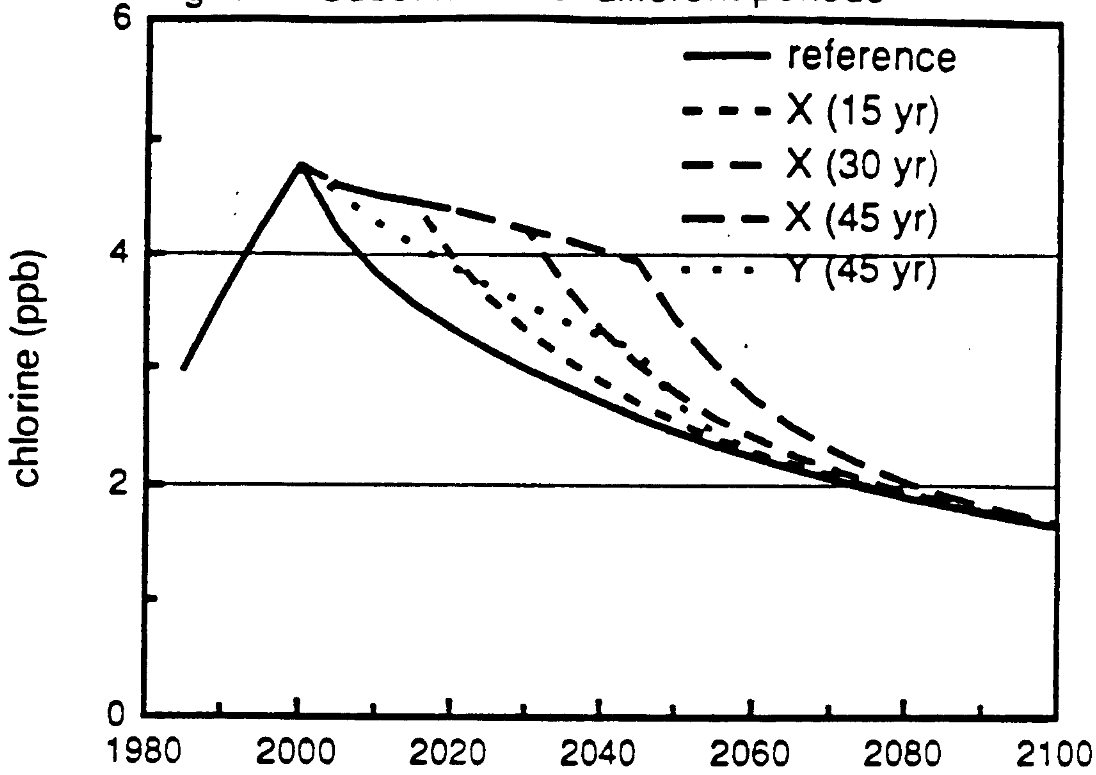

Fig. 6. Substitution until 2100

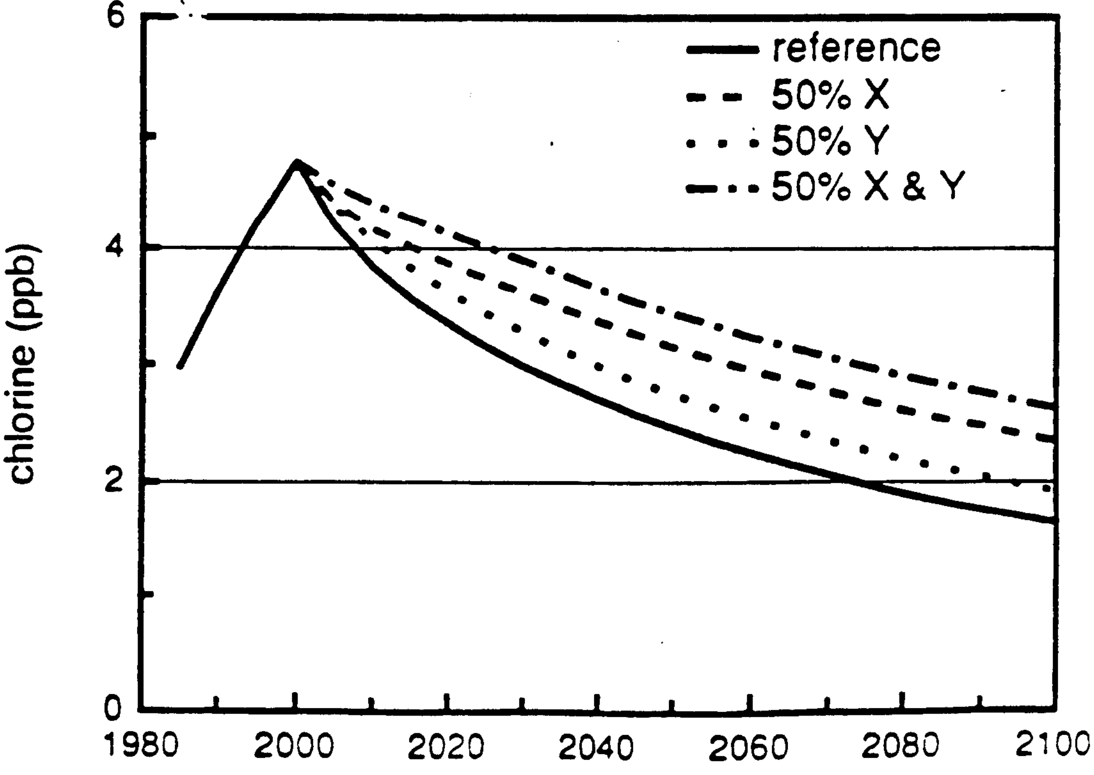

Fig. 7. 10% of CFC cuts/subs lag 15 yr

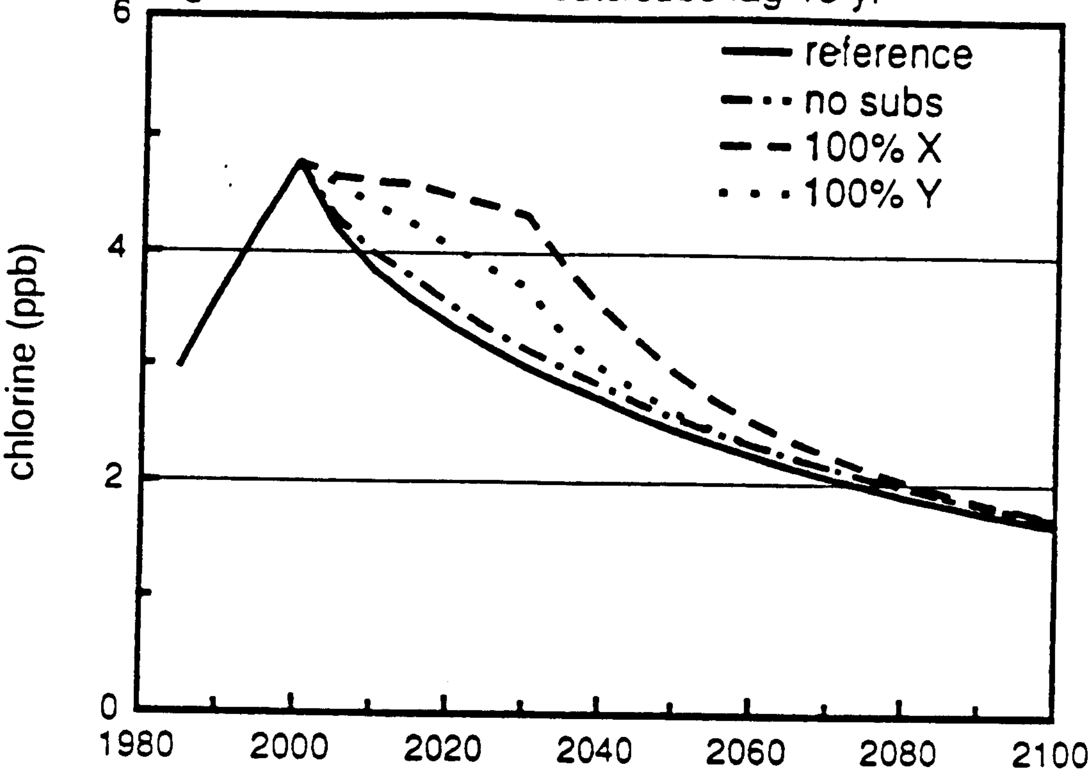

Fig. 8. 20% of CFC cuts/subs lag 15 yr

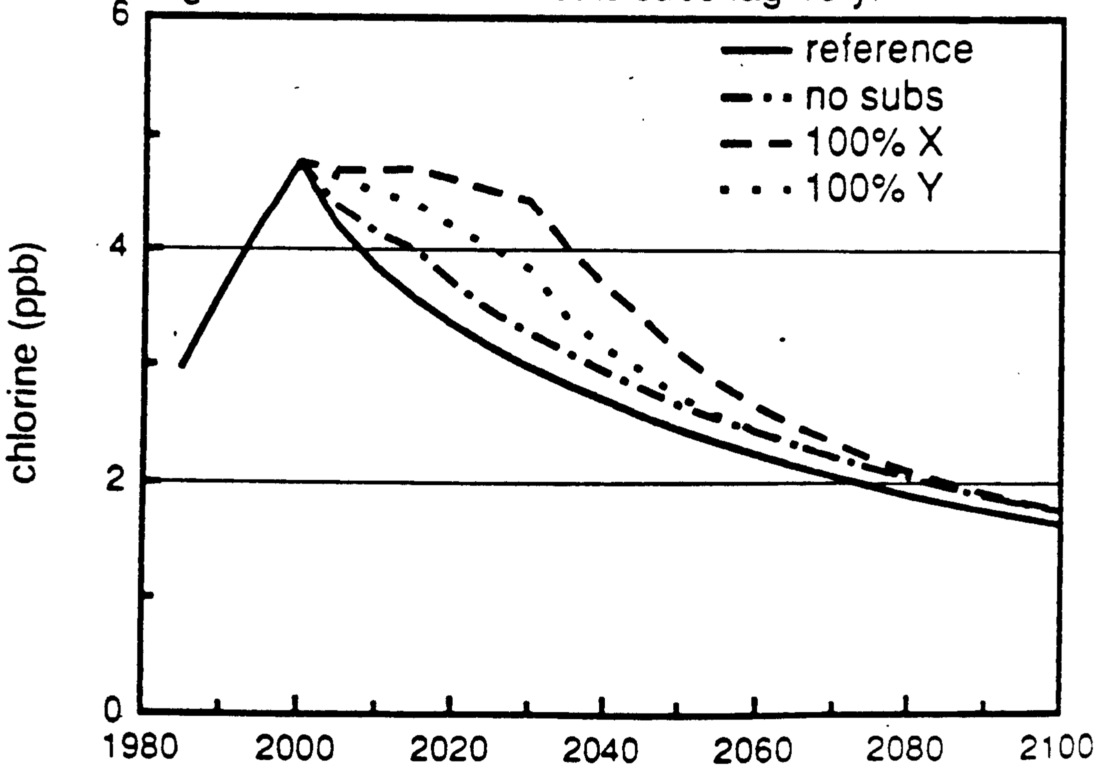

Fig. 9. 50%/50% cuts in 1995/2000 with subs

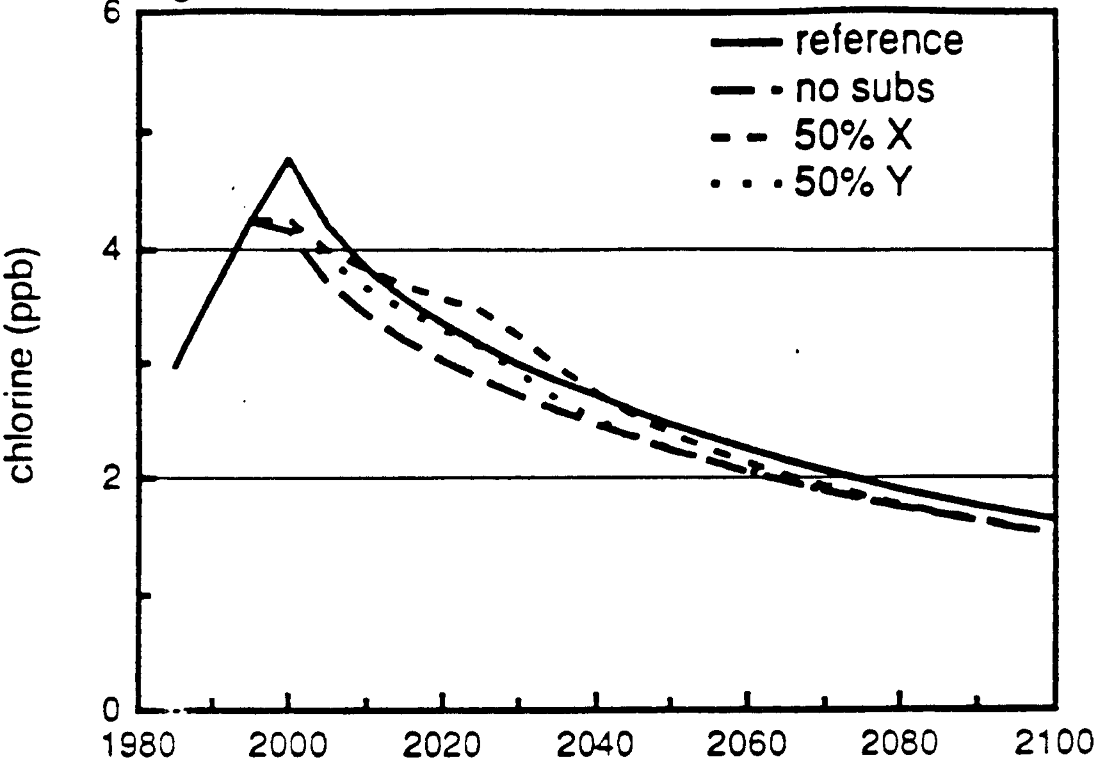

Fig. 10. CH3CCl3 to 2030, cut/sub for others

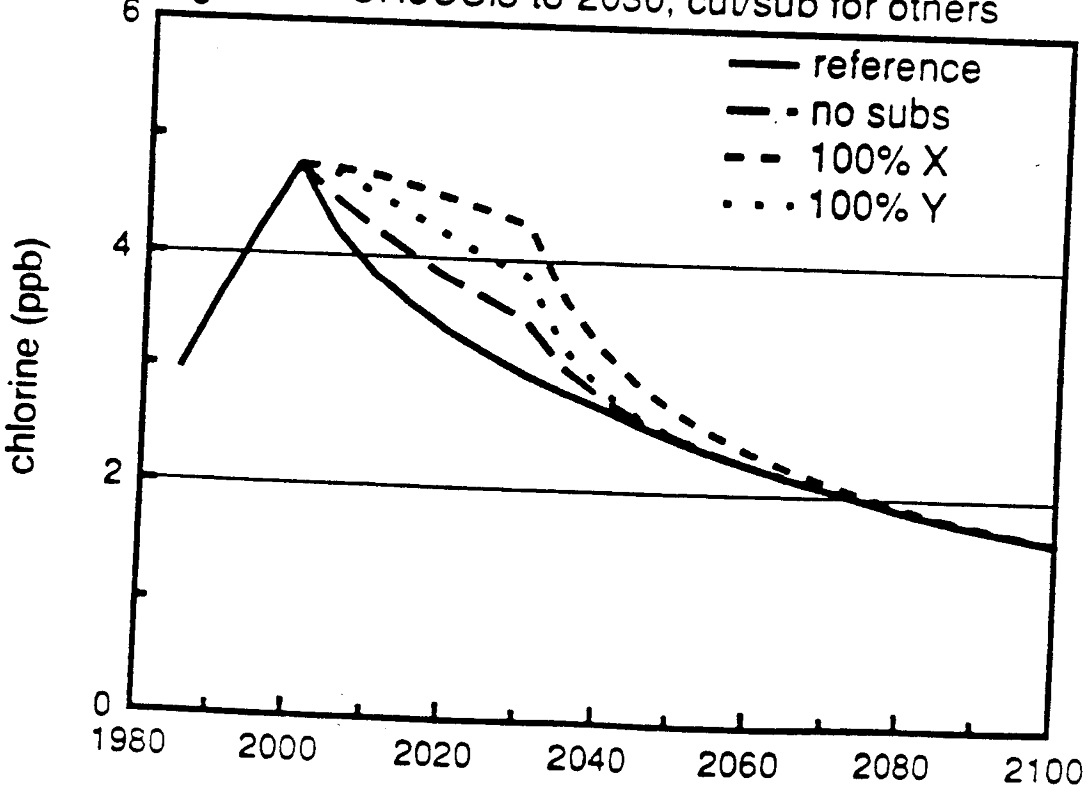

Fig. 11. Uncertainty in lifetimes

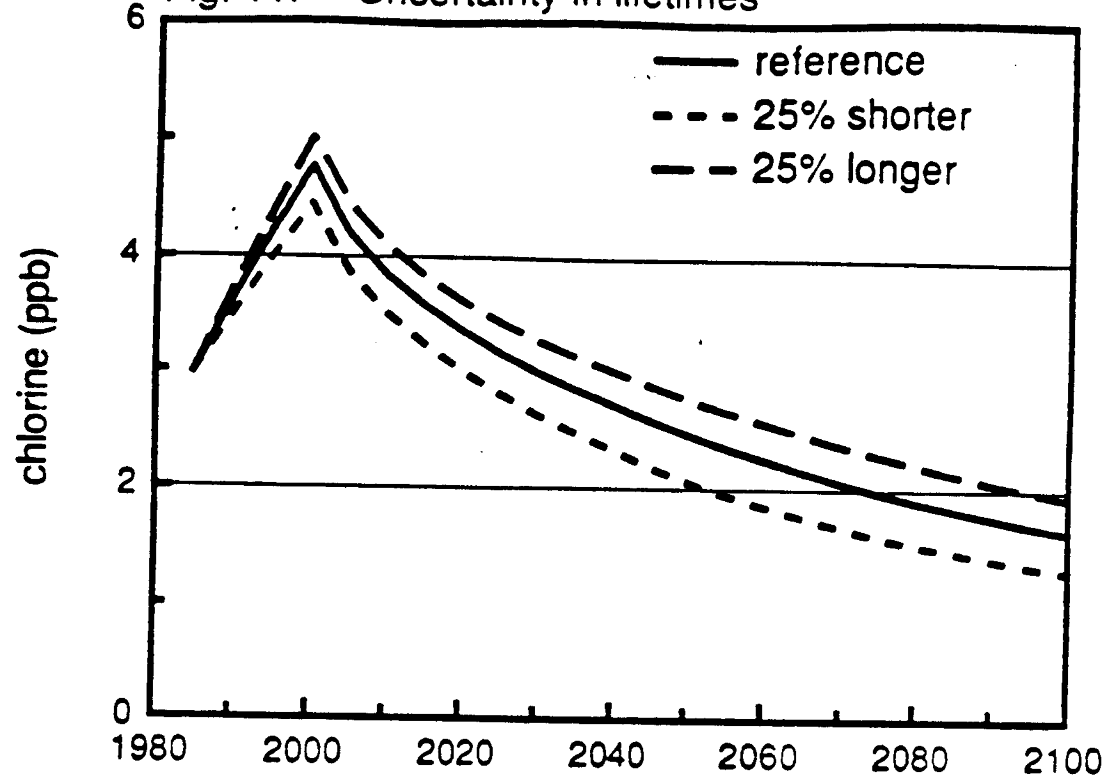

Fig. 12. Cut all halocarbons in 2000