Synthesis
of the
Reports of the Scientific, Environmental Effects, and Technology and Economic Assessment Panels of the Montreal Protocol

A Decade of Assessments for Decision Makers Regarding the Protection of the Ozone Layer: 1988-1999

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Preface

Goals. The goals of this Synthesis Report are twofold: (i) To synthesize the major 1998 findings and conclusions of the three Assessment Panels of the Montreal Protocol, and (ii) to place this information in the context of the past decade over which assessments have been provided to the Parties to the Protocol.

Origins. The genesis of the three Assessment Panels lies in the text of the Montreal Protocol under the Vienna Convention for the Protection of the Ozone Layer. Article 6, "Assessment and Review of Control Measures", defines the following assessment process:

> "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."

Assessment Panels. This decision separated the assessment process from the political (i.e., decisionmaking) process and defined the process by which the communication of information from and to the Parties occurs. At its First Meeting, held in Helsinki in May 1989, the Parties decided to endorse the establishment of, in accordance with Articles 6, the following four Assessment Panels:

Panel for Scientific Assessment

Panel for Environmental Assessment

Panel for Technical Assessment, and

Panel for Economic Assessment.

After 1990, the last two united to form the Panel for Technology and Economic Assessment.

Methods. The current three Assessment Panels periodically carry out their state-of-understanding assessment charge in the following ways:

- *Scientific Panel*. The four Cochairs, with input from an ad hoc international steering group of researchers, plan the scope, content, and Authors of a forthcoming assessment report. The Cochairs and the current set of Lead Authors meet to further plan and coordinate the contents of the chapters and the preparation of first drafts. The Authors are aided by contributed information from a large body of researchers worldwide. The resulting drafts undergo a mail peer review (with several reviewers per chapter) and a subsequent week-long panel review, at which the chapter conclusions are agreed upon and the Executive Summary is finalized.

- *Environmental Effects Panel.* The Environmental Effects Panel has 25 Panel members. They are scientists working in photobiology and photochemistry, mainly in universities and research institutes. The Panel members write the different chapters, sometimes helped by co-authors for special topics. The chapter authors review each other's chapters, and the Panel takes responsibility for the entire assessment. A draft assessment is sent out to external scientific reviewers all over the world. Between major assessments, the Panel meets at least once a year and informs the Parties about new developments.

- *Technology and Economics Panel.* The Panel had, after 1990, five Technical Option Committees: Aerosols, Sterilants, and Miscellaneous Uses; Rigid and Flexible Foams; Halons; Refrigeration, Air Conditioning, and Heat Pumps; and Solvents, Coatings, and Adhesives. The Economics Committee was added in 1991, and the Methyl Bromide Technical Options Committee was added in 1993. The periodic assessment reports are prepared by the standing Committees of industry, government, and academic experts and are, for the large part, reviewed by the broader technical communities. The Technology and Economics Panel publishes reports that include the executive summaries of the technical reports and that are reviewed internally. Furthermore, the Panel - with its 23 members from 17 countries - has become a "standing advisory group" on a large number of technical and economic issues as the Parties sought input to a growing variety of decisions. Consequently, the Panel has published annually general update reports, as well as numerous topical reports.

Appendix A lists the 60 assessment reports prepared for the Parties by the three Panels over the past decade: 1988 - 1999. The worldwide set of experts that helped prepare these state-of-understanding assessments are listed in Appendix B. Their expertise is the foundation upon which the information to the Parties rests.

The 1998 Reports. The information synthesized in the present report was drawn from the recently completed full reports of the three Assessment Panels:

"Scientific Assessment of Ozone Depletion: 1998" (~750 pp)

"Environmental Effects of Ozone Depletion: 1998 Assessment" (~200 pp)

"1998 Report of the Technology and Economics Assessment Panel" (~300 pp)

Appendix C reproduces the Table of Contents and Executive Summary of each of the three 1998 reports.

How to Use This Synthesis Report: A short guide to the format of present Synthesis Report follows:

- *Section I* provides the "historical context", illustrating how the past assessments reports were utilized by and reflected in the sequence of decisions by the Parties.

- *Section II* gives capsule summaries of the major 1998 findings of the three Assessment Panels.

- *Section III* focuses on "the future(s)" by analyzing examples of possible options for policy consideration regarding potential further measures for the protection of the ozone layer. Specifically, this section describes the predicted atmospheric responses to those options and the technical and economic feasibilities of the options. The section also describes how atmospheric changes unrelated to chlorine- and bromine-containing compounds could influence the recovery of the ozone layer.

- *Appendixes*: In addition to providing the supporting detail noted above, two sets of "Frequently Asked Questions" about the science of ozone change and its effects are included. Reprinted directly from the 1998 assessments of the Scientific Panel and the Environment Effects Panel, these questions are the ones that are most often asked by the public about the ozone layer issue. The answers given are based on the information in the assessments, but are written for non-technical readers.

The Past is Prologue to the Future. In the last section of this report, the Panels pause to describe "the world we avoided"; namely, to give a forecast of what could have occurred had there been no Montreal Protocol. The nature of "that world" underscores the high value of the efforts of so many people worldwide who wrestled with the challenging decisions and actions associated with the ozone depletion issue. The Assessment Panels are pleased to have provided, over the past decade, information to support the landmark Montreal Protocol process and remain committed to this ongoing process.

Section 1

The Past Decade: The Montreal Protocol and the Assessment Panels

A. Background: The Stage is Set

The Earth's stratospheric ozone layer is a natural feature of the planet's atmosphere. It was formed as the early atmosphere evolved. Beginning in the 1880s and extending into the early decades of the 20th century, scientists discovered that the ozone layer existed, began to explore its features, and sought to explain its existence. In the 1930s, researchers gradually clarified the chemical mechanisms whereby the ozone layer is maintained. Namely, these are a balance of (i) the production of ozone from oxygen by solar radiation and (ii) the destruction of ozone by chemical reactions with naturally occurring atmospheric chemical species (for example, hydrogen and nitrogen). The fact that this ozone loss occurred by "catalytic" reactions meant that relatively small amounts of the reacting chemicals could remove substantial ozone without themselves being consumed. It was also recognized very early that air motions distribute ozone globally to yield the observed patterns. (Indeed, global monitoring of the ozone layer was started in the 1950s to use ozone as a "tracer" partly to study large-scale atmospheric circulation.)

Parallel with this development of the understanding of the ozone layer itself grew the recognition of its importance to life on Earth. It was recognized very early (1880s) that the ozone layer absorbed most of the short-wavelength solar ultraviolet radiation, UV-B. Further, biological studies were characterizing the positive and negative impacts of UV-B radiation of various life forms. While it was noted that UV-B radiation would promote the formation of vitamin D in human skin (1937) and would kill bacteria (1929), it was also found that it had damaging effects on humans, such as sunburn (1922) and skin cancer (1928), and that it had important deleterious impacts on plants (1965).

In 1928, industrial chemistry developed a nonflammable, non-toxic compound - a chlorofluorocarbon (CFC) - to replace the hazardous compounds (such as methyl chloride and sulfur dioxide) then used in home refrigerators. During the 1950s, CFCs came into widespread use. Successful, low-cost, and sought-after CFC applications expanded in the 1970s: refrigerants, air conditioning, foam blowing agents, solvents, and medical applications, for which there were few alternatives that were recognized at the time. Similarly, halons (bromine-containing compounds) were developed and marketed aggressively as fire protection because of their effectiveness and low cost. In addition, over half of the CFC production was for "lower-value" applications, particularly aerosol-propelled personal care products, pesticides, noisemakers, dust blowers, and toys. While alternatives were available, they were not sought for several reasons, for example, for lack of substantial cost motivation and for safety considerations.

A newly developed sensitive analytical technique that could detect tiny traces of chlorine-containing chemicals was applied at various surface locations worldwide in the early 1970s. It was found that the CFCs, because of their industrial production, use, and emissions, were now a widespread part of the global atmosphere.

As a result of all of this, the "stage was set" for the ozone-layer "drama" whose scenes were to unfold over the last quarter of the 20th century. Namely, it was known by the early 1970s that natural chemical cycles - that of hydrogen and nitrogen - are a factor in maintaining the ambient ozone layer levels. It was known that the ambient ozone layer, as the shield from harmful solar UV-B, was important to the well being of humankind. It was known that we were producing and using growing amounts of new chemical compounds that were appearing in the lower atmosphere. What was *not yet* known were the facts that (i) we were overwhelming a third chemical cycle - that of chlorine, which was once a negligible factor for the ozone layer - and that (ii) our actions could lead to significant ozone reductions and UV-B increases. Namely, the picture that linked all of this information together was not there.

B. First Signs of the Gathering Issue

It was the feasibility of supersonic aviation in the stratosphere that changed atmospheric chemical catalytic reactions from being purely a scientific topic to one lying at the heart of environmental issues. Namely, in the early 1970s, atmospheric, environmental, and technical researchers began to examine the potential environmental impact of a possible worldwide fleet of supersonic aircraft. These studies highlighted the fact that the reactive nitrogen compounds in engine exhaust could enhance the stratospheric catalytic nitrogen chemistry. These emissions would increase this nitrogen-cycle component of ozone loss and thereby "unbalance" the processes that form and remove ozone, leading to a thinner ozone layer.

As noted above, the consequences of a thinner ozone layer had been recognized. The possibility that these would occur and would cause damaging effects to humans and other organisms focused public attention on the supersonic transport debate and established protection of the ozone layer as an issue.

In the mid-1970s, two discoveries opened wide the curtain on the ozone drama. First, it was hypothesized that *chlorine chemistry* could also participate in catalytic ozone destruction in the stratosphere. Second, it was proposed that break-up of CFCs in the stratosphere by solar radiation would greatly enhance the chlorine catalytic chemistry, that the growing use of CFCs would thereby lead to a thinning of the ozone layer, that harmful effects of UV-B radiation that would ensue. Further, since the CFCs were shown to have long (decades-to-centuries) residence times in the atmosphere, it implied that the ozone loss would continue long after any reductions in CFCs emissions.

Twenty years hence, the 1995 Nobel Prize in Chemistry would be awarded to three scientists for recognizing the significance of the atmospheric chemistry of ozone formation and loss, particularly the roles of nitrogen chemistry and the CFCs.

C. The Debate Years: Clarifying the Credibility of the Ozone Depletion Issue

The decade from the mid-1970s to the mid-1980s saw the initiation of comprehensive laboratory, field observations, and predictive modeling research activities in the atmospheric, biological, health sciences, as well as technological characterization, relevant to the ozone depletion issue. The accumulating results and the emerging mosaic of understanding from several assessments were producing a substantive characterization of the relation between the ozone layer and humankind. Major milestones along this road from hypothesis to predictive understanding stand out as examples.

CFCs were observed in the stratosphere in the predicted quantities. The key chlorine species in the ozone-loss chain reaction was also observed directly. Bromine was found to be many times more effective than chlorine in ozone loss. Global monitoring of CFCs and halons exhibited steady annual increases (several per cent per year) in their atmospheric abundance. An increase in ozone depletion was found to cause a larger percentage increase in the impacts (e.g., skin cancer) associated with the higher UV-B radiation. The suite of ozone-depleting compounds was identified and their production, and the quantification and inventorying of their release rates were begun, for example, the losses of CFCs from mobile air conditioning. The possibility of using hydrochlorofluorocarbons (HCFCs) as alternatives to CFCs was identified, and the refrigeration-relevant properties of some of the hydrofluorocarbons (HFCs) were characterized.

The public-policy debate was engaged. The results of a decade of focused research were being assessed and reported. In 1985, for example, while no current CFC-induced ozone depletion could yet be unequivocally distinguished from natural ozone-layer variation, it was predicted that, if CFC emissions were to continue to grow into the future, then (i) substantial ozone losses would likely occur in coming decades, (ii) ozone-layer recovery times would unavoidably be decades-to-centuries long, and (iii) the resulting elevated UV-B radiation over such extended time periods would cause significant impacts in humans, animals, and plants to be manifested in later decades. Furthermore, in 1985, a then-baffling discovery was reported; namely, the ozone layer over "the last place on Earth" - Antarctica - was behaving unexpectedly. On the other hand, it was pointed out that (i) CFCs and halons were substantial factors in current economic development, consumer welfare, and public health and that (ii) there was a current lack of available substitutes and that the expense associated with evaluating the toxicity and broad environmental acceptability of candidate substitute compounds could be considerable.

The debate was national and international. In addition to the mid-1980s status of the ozone layer, effects, and technical and economic information above, decision makers were also assimilating and weighing into the process the suite of governmental, legal, demographic, social, ethical, and political information. In 1985 and 1987, decisions were made formally.

D. 1985 Vienna Convention and 1987 Montreal Protocol

March 1985, Vienna Convention for the Protection of the Ozone Layer. Based on the current understanding of the multitude of factors noted above, this Convention signified (i) the belief that ozone depletion was a real issue,(ii) a global commitment to address it; and (iii) an agreed-upon process for doing so.

September 1987, Montreal Protocol on Substances That Deplete the Ozone Layer. The decisions became specific. A watershed had occurred: an international action on a global issue whose predicted impacts lay largely still in the future. Based on the information in hand by the mid-1980s, the nations crafted a Protocol that included the major long-lived CFCs and halons, a future-year freeze, and a subsequent 50% reduction in the production and consumption of CFCs and halons.

The Assessment Panels. In addition to its specific emission identification and amelioration steps, the Protocol recognized that research is an ongoing exercise, understanding is thereby continuously improving, and updated status reports are important input for any sequence of policy evaluation and/or re-evaluation. Specifically, Article 6 of the Montreal Protocol established the process for the Parties to gain such updated information from Assessment Panels. The Panel reports (Appendix A), which began in 1988 and has extended to the present, are the updating of ozone-layer-relevant knowledge by the world's ozone-layer, effects, and technological and economic experts. These experts, from many institutions in many countries (Appendix B), have provided the knowledge base that now has served the Parties for over a decade.

E. Post-1987: The Protocol's First Decade and the Assessment Panels

A succession of Assessment Panel reports have described the advancing status of scientific understanding and technical response. As requested by the Parties, these have preceded the periods in which the Parties have considered major decisions. In the following section, the major findings reported by the Assessment Panels are listed along side the major decisions by the Parties over the decade-plus from 1987 to the present. For reference, Appendix A lists the Panel reports by year.

How can the "progress" of the Montreal Protocol be tracked? It is a fair question, because accountability has been viewed by many as a necessary component of human endeavors. No doubt, there could be many indicators of such progress. One that lies in the early sequence of cause-to-effect in the ozone-depletion issue and one that can be evaluated very quantitatively is the abundance of ozone-depleting substances in the atmosphere. Figure 1 illustrates (i) the past observed abundances of atmospheric "equivalent" chlorine (which includes bromine, appropriately weighted) and (ii) the future abundances that would have been associated with each of the major "decision steps" of the Montreal Protocol. In any given year, the amount of human-caused ozone depletion is related to the effective chlorine abundance. Since many of the environmental effects of ozone depletion (for example, elevated incidences of skin cancer in humans) arise from long-term exposure, such impacts are related to the area under each of the curves - the larger the area, the larger the environmental effect and vice versa. Because of these associations, the summary below is linked to the figure and its messages.

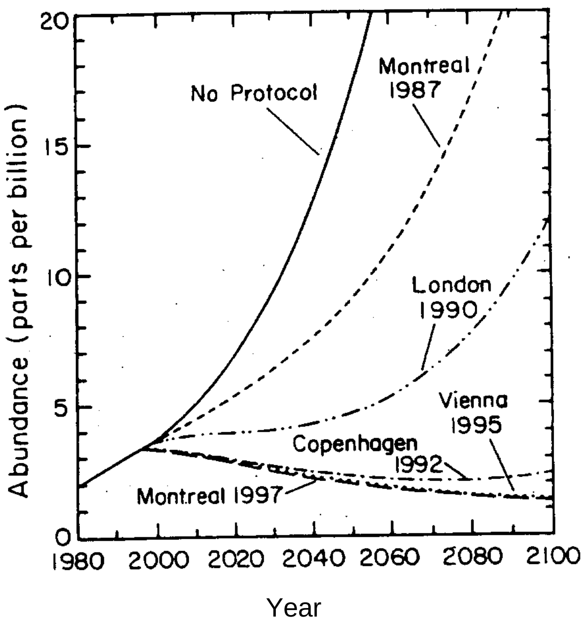

Figure 1. Effect of the international agreements on ozone-depleting stratospheric chlorine/bromine.

Figure 1 also illustrates the rationale for the time intervals used in the section below. The move beyond the 1987 Protocol "freeze" provision to introduce some "phase-outs" (London, 1990) dramatically lowered projected future effective chlorine growth rates over the period 2000 - 2040 (but still permitted a possible later return to significant growth rates). The advancement of phase-out dates and the addition of new controlled substances (Copenhagen, 1992) implied, for the first time, that a peak in effective chlorine burden would lie ahead (but still permitted a possible much later return to a positive growth. The setting of production and/or consumption caps on all controlled ozone depletors eventually for all countries (Vienna, 1995) implied (assuming full compliance) no return to positive growth rates. The advance of information as reflected in the Assessment Panel reports and the corresponding policy decisions are arranged by these "effective chlorine milestones".

1. From the Montreal Protocol (1987) to the London Amendment: (1990)

Ozone Science:

- Antarctic ozone hole is attributed to human-produced chlorine/bromine compounds whose impact is enhanced by polar stratospheric clouds.

- A global downward trend in the ozone abundances is detected during winter months at the middle and high latitudes in the Northern Hemisphere.

- "Ozone-friendly" properties (for example, ozone depleting potentials of the first set of CFC substitutes - the hydrochlorofluorocarbons (HCFCs) are characterized.

- The Science Panel of the Montreal Protocol and the newly formed Intergovernmental Panel on Climate Change (IPCC) begin a continuing interaction on the assessment of the understanding of atmospheric phenomena in common to both issues; for example, the Global Warming Potentials of ozone-related gases are jointly evaluated.

Environmental Effects: Investigations show that UV-B radiation, especially at shorter wavelengths, has a multitude of effects and that most of them are damaging: effects on eyes (cataracts and snow blindness) and suppression of the immune system; plants (half of those studied grew less and had smaller leaves under increased UV-B); effects on aquatic organisms (especially the smaller ones, like phytoplankton); and damage to materials (UV-B exposure is the primary cause of outdoor plastic degradation).

Technology and Economics:

- Industry consortia start work on environmental acceptability and toxicity of CFC and halon substitutes and methods for accommodating phase-out of chemicals in industrial processes.
- Major efforts on recovery and recycling are initiated.
- Development begins on retrofit blends of chemicals without CFCs.
- Feasibility of non-halogen propellants is demonstrated,
- Not-in-kind substitutes for the cleaning of electronics are identified for CFC-113.
- Feasibility of dropping the use of halons in the training and testing of fire extinguishing equipment is demonstrated.

Policy - London Amendments:

- Other fully halogenated CFCs, carbon tetrachloride, and methyl chloroform are added.
- Phase-outs are established for these substances for future dates.
- HCFCs are included as transitional substances and their reporting is prescribed.
- An interim financial mechanism is established for meeting the agreed incremental costs of the phase out of production and consumption of ozone-depleting substances in developing countries.

2. From the London Amendment (1990) to the Copenhagen Amendment (1992)

Ozone Science:

- Outside of the tropics, global downward trends of lower-stratospheric ozone in the lower stratosphere are detected and quantified at middle and high latitudes in both hemispheres and in winter, spring, and summer.

- The Antarctic ozone hole becomes more intense.

- Significant, but variable, ozone losses are detected in the Arctic.

- Methyl bromide is identified as a significant ozone depletor.

- UV-B increases are observed to occur with large ozone losses over Antarctica.

- A preliminary evaluation is made of the effects of aviation, shuttles, and rockets on the ozone layer.

- The loss of ozone in the lower stratosphere is found to have a cooling effect on the tropospheric climate system.

Environmental Effects:

- A sustained 10% decrease in ozone is predicted to be associated with a 26% increase in non-melanoma skin cancer.

- The induction of immunosuppression by UV-B has now been demonstrated in humans, including deeply pigmented individuals.

- Research on plant responses to UV-B radiation underscores the concern for managed and natural ecosystems.

- It is shown that aquatic ecosystems is already under UV-B stress; hence, there is concern that additional stress will cause detrimental effects.

- Chemical reactivity in the troposphere is expected to increase in response to increases in UV-B.

Technology and Economics: For all sectors, a variety of substitutes are identified that enables a virtual phase-out of CFCs by the 1995-to-1997 time frame.

- Many multinational companies phase out the use of ozone-depleting chemicals much faster than the Protocol requirements.

- Analyses are promoted that combine considerations on both ozone depletion and global warming via the direct (chemical) and indirect (energy production) factors.

- The first refrigerators with HFC-134a are introduced on the market.

- The availability of HCFC substitutes for use in different types of foam cause rapid decrease in use of CFC-11 for that purpose.

- The first mobile air conditioning units with HFC-134a are introduced on the market.

Policy - Copenhagen Amendments:

- The phase-out dates are moved forward.

- Methyl bromide is included (with exceptions), specifying a developed-country freeze in a future year.

- HCFCs are now included as controlled substances, specifying a series of caps and reductions, leading to a distant-future phase-out (namely, confirmation of these compounds as "transitional substances"). Hydrobromofluorocarbons (HBFCs) are included for immediate phase-out by developed and developing countries.

- The Multilateral Fund becomes a permanent financial mechanism.

- Mechanisms (involving the Technology and Economics Assessment Panel) are established to identify "essential uses" of controlled substances.

3. From the Copenhagen Amendment (1992) to the Vienna/Montreal Amendment/Adjustments (1995/97)

Ozone Science:

- The slowing of the atmospheric growth rate of ozone-depleting gases in the lower atmosphere is detected.

- The increasing growth rates of the CFC substitutes are documented.

- Downward global ozone trends continue.

- The role of particles is explained in the halogen-caused, temporarily enhanced ozone losses that followed the 1991 eruption of Mt. Pinatubo volcano.

- Antarctic ozone losses continue unabated.

- Non-polar UV-B increases (clear sky) are recorded for low overhead ozone in non-polar regions.

- Negative impact on the ozone layer of illegal CFC production is quantified.

Environmental Effects:

- DNA-damaging UV-B radiation in Antarctica is characterized during the period of ozone depletion.

- Increased UV-B radiation is likely to cause substantial increases in the incidence of and morbidity from eye diseases, skin cancer, and infectious diseases, with risks now quantified for some effects (for example, skin cancer).

- Researchers have measured the increase in, and penetration of, UV-B radiation in Antarctic waters and have provided conclusive evidence of direct ozone-related effects on phytoplankton.

- In terrestrial ecosystems, increased UV-B could modify production/decomposition of plant matter, with concomitant changes in atmospheric trace gases.

Technology and Economics:

- Many HFC-blends are identified and tested as replacements for HCFC-22 in refrigeration.

- Hydrocarbon-based refrigerators enter the market.

- Commercial refrigeration units are designed so that substitutes like ammonia and hydrocarbons can be used.

- Cyclopentane-based and hydrocarbon-blend-based foams are developed and/or commercialized.

- Identification of halon essential-use exemptions opens consideration of earlier phase-outs.

- Considerable increases in halon production and consumption in the Article 5(1) countries are identified.

- Except for quarantine and preshipment uses, alternatives to the uses of methyl bromide are identified.

- Metered-dose inhalers based on HFC-134a are introduced on the market.

Policy - Vienna/Montreal Adjustments:

- The reduction/phase-out of methyl bromide in developed countries is accelerated, and a phase-out schedule in developing countries is established.

- For CFCs, halons, methyl chloroform, and carbon tetrachloride, the developing country phase-out dates are fixed to the developed country schedule that was adopted in 1990, plus ten years.

- Establishment of lower caps on and limited uses of HCFCs by developed countries and a freeze and distant-future phase-out by developing countries.

- A licensing system is established for the control of methyl bromide trade. (*Therefore, as of 1997, phase-outs and/or caps exist for all listed ozone depletors and for all Parties.*)

Section

2

Our Current Ozone Layer and Its Protection: The Status of Its Understanding

At the request of the Parties, the Assessment Panels have provided a new update on the understanding of the ozone science, effects, and technology and economics associated with the ozone issue. The Table of Contents and the full texts of the Executive Summaries of the 1998 assessment reports of the three Panels are given in Appendix C. The section that follows gives a shortened summary (grouped by Panel) of those status-of-understanding reports.

A. Major Current Findings: "Scientific Assessment of Ozone Depletion: 1998"

The updating of the scientific understanding of the ozone layer involved 304 researchers from 35 countries worldwide. The assessment report was planned and prepared over a two-year period, including a mail and panel peer reviews. The major findings are summarized as follows:

1. Ozone-Depleting Gases

- *The total combined abundance of ozone-depleting compounds in the lower atmosphere peaked in about 1994 and is now slowly declining.* Total chlorine is decreasing, but total bromine is still increasing. This turn-over was forecast in the 1994 assessment. The chlorine decline is largely due to decreases in methyl chloroform. Chlorine from CFCs is still increasing slightly. The abundances of most halons continue to increase (for example, 1211 at almost 6% per year). The observed abundances of CFCs and chlorocarbons in the lower atmosphere are consistent with reported emissions.

- *The observed abundances of the substitutes for the CFCs are increasing.* In 1996, the HCFCs contributed about 5% to the tropospheric chlorine from the long-lived gases. The HCFC growth, in terms of total combined effective abundance, does not offset the decline of the other chlorine-containing gases. The atmospheric abundances of HCFC-22 and HFC-134a agree with that expected from reported emissions, but the atmospheric observations of HCFC-141b and HCFC-142b are larger.

- *The combined abundance of chlorine and bromine is expected to peak in the stratosphere before the year 2000.* The delay reflects the average time for surface emissions to reach the lower stratosphere. While observations of key chlorine compounds in the stratosphere show a decline in growth rate, they also show that the peak abundance has not yet occurred at the time of this assessment.

- *The role of methyl bromide as an ozone-depleting compound is now considered to be less than was estimated in the 1994 assessment, although significant uncertainties remain.* The best current estimate of the Ozone Depleting Potential (ODP) of methyl bromide is 0.4, compared to 0.6 estimated in 1994. The change is due primarily to an increase in estimated oceanic and terrestrial removal rates. However, the current understanding of the sources and sinks of methyl bromide is incomplete.

2. Ozone Trends

- *The observed total column ozone losses from 1979 to the period 1994-1997 are about 5%, 3%, and 5%, respectively, for the northern midlatitudes in winter/spring, northern midlatitudes in summer/fall, and all seasons in the southern midlatitudes. But, the rate of decline in stratospheric ozone at midlatitudes has slowed; hence, the projections of ozone loss made in the 1994 assessment are larger than what has actually occurred.* Since 1991, the downward linear trend observed in earlier years has not continued, but rather has been almost constant since the recovery from the additional losses caused by the enhancement associated with the 1991 Mt. Pinatubo volcanic eruption.

- *The springtime Antarctic ozone hole continues unabated.* The overall extent of ozone depletion has remained essentially unchanged since the early 1990s. This behavior is expected because of the current near-complete destruction of ozone within the Antarctic lower stratosphere during springtime. The major factors contributing to the large continuing springtime depletion over Antarctica are well understood.

- *In the Arctic, the late-winter/spring ozone values were unusually low in 6 out of the last 9 years, the 6 being characterized by unusually cold and protracted stratospheric winters.* The possibility of such depletions was predicted in the 1989 assessment (Appendix A). Minimum Arctic temperatures are near the threshold for large chlorine chemical activation, and, as a result, the year-to-year variability, which is driven mainly by meteorology, leads to large ozone loss variability for the current chlorine amounts. While it is not possible to forecast the nature of an Arctic winter for a particular year, the elevated chlorine and bromine abundances over the next decade or so imply that the Arctic will continue to be vulnerable to large ozone losses.

3. Consequences

- *The understanding of the relation between increasing UV-B radiation and decreasing column ozone has been further strengthened by observations at several locations globally.* The influences of other variables besides ozone, such as clouds, particles, and surface reflectivity are better understood. Satellite data indicate that the largest UV-B increases occur during spring at high latitudes in both hemispheres.

- *Stratospheric ozone losses have caused a cooling of the global lower stratosphere and global-average negative radiative forcing of the climate system.* Model simulations indicate that much of the observed downward trends in temperatures in the lower stratosphere (about 0.6°C per decade from 1979 to 1994) is attributed to the loss of ozone in this region. Radiative calculations, using extrapolations based on the ozone trends reported in the 1994 assessment for reference, indicate that stratospheric ozone losses since 1980 may have offset about 30% of the positive forcing due to increases in the well-mixed greenhouse gases over the same time period. The climatic impact of the slowing of midlatitude ozone trends and the enhanced loss of ozone in the Arctic has not yet been assessed.

B. Major Current Findings: "Environmental Effects Panel Report: 1998"

The updating of the scientific understanding of the environmental effects of ozone layer depletion involved 102 researchers from 31 countries worldwide. The assessment report was prepared over a 1-year period, including a review process by 70 external reviewers, mostly by mail. The major findings are summarized as follows:

1. Changes in Ultraviolet Radiation

- *Long-term predictions of future UV-B levels are difficult and uncertain.* Nevertheless, current best estimates suggest that a slow recovery to pre-ozone-depletion levels may be expected during the next half-century. The recovery phase for surface UV-B radiation will probably not be detectable until many years after an ozone layer minimum because of the variation in other factors (such as clouds) that influence UV-B, but are not directly ozone-related.

2. Effects on Human and Animal Health

- *The increases in UV-B radiation associated with ozone depletion are likely to lead to increases in the incidence and/or severity of a variety of short-term and long-term health effects, if current exposure practices are not modified by changes in behavior.* Adverse effects on the eye will affect all populations irrespective of skin color. Effects on the immune system will also affect all populations, but may be both adverse and beneficial. The adverse effects include depressed resistance to certain tumors and infectious diseases. Effects on skin could include increases in photoaging and skin cancer, with the risk increasing with fairness of skin. Increases in UV-B are likely to accelerate the rate of photaging as well.

3. Effects on Terrestrial Ecosystems

- *Increased UV-B can be damaging for terrestrial organisms including plants and microbes, but these organisms also have protective and repair processes.* The balance between damage and protection varies among species and even varieties of crop species. Research the past few years indicates that increased UV-B exerts more often through altered patterns of gene activity, rather than damage.

4. Effects on Aquatic Ecosystems

- *Recent studies continue to demonstrate that solar UV-B and UV-A have adverse effects on the growth, photosynthesis, protein and pigment control, and reproduction of phytoplankton*, thus affecting the food web. Macroalgac and sea grasses show a pronounced sensitivity to solar UV-B.

- *UV-B radiation is absorbed by and breaks down dissolved organic carbon and particulate organic carbon*. This process makes the products available for bacterial degradation and remineralization.

- *Polar marine ecosystems are in the region where ozone-related UV-B increases are the greatest*. Therefore, these ecosystems are expected to be the oceanic ecosystems most influenced by ozone depletion.

- *The potential consequences of enhanced levels of exposure of aquatic ecosystems to UV-B radiation includes reduced uptake capacity for atmospheric carbon dioxide*. This could result in the potential augmentation of global warming.

5. Effects on Biogeochemical Cycles

- *The effects of increased UV-B radiation on emissions of carbon dioxide and carbon monoxide and on mineral cycling in the terrestrial biosphere have been confirmed by recent studies of a range of species and ecosystems*. The examination of long-term UV-B effects on carbon capture and storage are underway for natural ecosystems.

6. Effects on Air Quality

- *Increased UV-B will increase the chemical activity in the lower atmosphere*. Model studies suggest that additional UV-B radiation reduces tropospheric ozone in clean environments and increases tropospheric ozone in polluted areas. Assuming other factors remain constant, additional UV-B will increase the rate at which some primary pollutants are removed from the troposphere.

7. Effects on Materials

- *Physical and mechanical properties of polymers are negatively affected by increased UV-B in sunlight*. Conventional photostabilizers are likely to be able to mitigate the effects of increased UV-B levels in sunlight.

C. Major Current Findings: "Technology and Economics Panel Report: 1998"

The updating of the technical and economic options involved 230 technical experts from 46 countries worldwide and was organized into seven Technical Options Committees and the Technology and Economic Assessment Panel. The reports of the Technical Options Committees were prepared over a two-year period, including peer review. The Panel report was prepared during the year 1998. It contains the Executive Summaries of all Technical Options Committee reports.

1. Aerosol, Sterilants, Miscellaneous Uses, and Carbon Tetrachloride

Key points from the 1998 report of the Aerosols Technical Options Committee (ATOC) are the following:

- *Aerosol Products*. The ATOC estimates that the 1997 CFC consumption in the aerosol sector was less than 15,000 tonnes in Article 5(1) Parties and some Countries with Economies In Transition, excluding metered-dose inhaler use. For aerosol products, other than metered-dose inhalers, there are no technical barriers to global transition to alternatives.

- *Metered-Dose Inhalers*. Approximately 500 million metered-dose inhalers are used annually worldwide for the treatment of asthma and chronic obstructive pulmonary disease, using approximately 10,000 tonnes of CFCs annually. It is likely that a wide range of reformulated products will be available in many developed nations and transition will be making good progress by the year 2000. Minimal need for CFCs for metered-dose inhalers is envisaged by the year 2005 in non-Article 5(1) Parties.

- *Sterilants*. By the beginning of 1997, CFC-12 use in non-Article 5(1) Parties for sterilization (in a sterilant gas mixture with ethylene oxide) had virtually disappeared. Global consumption of CFC-12 in this sector is estimated to be less that 1,500 tonnes. Estimated use of substitute HCFC replacement is thought to be less than 3,000 tonnes (some 90 tonnes weighted by Ozone Depleting Potential).

- *Miscellaneous Uses and Laboratory and Analytical Uses*. CFCs have a number of miscellaneous uses, of which tobacco expansion is the most significant. After 1998, China may be the only remaining country to use significant quantities of CFCs for this purpose. Declining use in this country is expected. It has been estimated that global consumption of controlled substances for laboratory and analytical uses does not exceed 1,500 tonnes (currently subject to essential use exception).

- *Carbon Tetrachloride*. Atmospheric emissions of carbon tetrachloride in 1996 were estimated as 41,000 tonnes, of which some 26,000 tonnes originate from carbon tetrachloride production in Article 5(1) Parties and Countries with Economies in Transition. Emissions of carbon tetrachloride can be technically and economically reduced from both feed stock and process agent uses, although in some cases, alternatives to carbon tetrachloride use may not be available.

2. Rigid and Flexible Foams

Key points from the 1998 report of the Foams Technical Options Committee are the following:

- *Global use of ozone-depleting substances in rigid foams has decreased by almost 75% since reaching a peak in 1989*. Largely all CFC use in Non-Article 5(1) countries has been eliminated.

HCFC (ODP-weighted) use is less than 20% of the total rigid foam sector, with little use in non-rigid sectors.

- *Alternatives with zero Ozone Depleting Potentials (ODP) are the substitutes of choice in many applications including packaging, cushioning (flexible), and certain rigid thermal applications.* No single solution has emerged from transition, and thus, choices must be retained to allow optimal solutions for given applications, producer-specific and country-specific circumstances.

- *The development of HFC replacements for HCFC-141b continues for thermal insulating polyurethane, polyisocyanurate, and phenolic foams.* It is anticipated that products such as HFC-245fa and HFC-356mfc will be commercially available around the beginning of 2002. No toxicity issues have been identified. However, uncertainty over costs, availability, and long-term environmental management of greenhouse gases is slowing development.

- *Pentane-based technologies for rigid polyurethane foams continue to evolve.* Technical properties have been improved with the use of blends, with improved cost competitiveness for hydrocarbon-blown products.

- *Some barriers to transition away from ozone-depleting substances exist.* CFC and HCFC users are reluctant to finalize a transition strategy until there is greater certainty concerning the long-term availability and suitability of HFCs. Further, in Article 5(1) countries, CFC-11 continues to be widely available and is generally cheaper than current alternatives. Another factor constraining a rapid phase-out is that very few alternatives are manufactured in these countries.

3. Halons

Key points from the 1998 report of the Halons Technical Options Committee (HTOC) are the following:

- *Extensive research and development into new liquid and gaseous halocarbon replacements for halons and into the use of new and existing alternative approaches has resulted in the availability of a wide range of options.* There is an almost complete cessation of use of both halon 1211 and halon 1301 in Non-Article 5(1) and in many Article 5(1) Parties for new installations, as well as many retrofitting applications. Those systems that remain are substantially non-emissive in normal circumstances.

- *Despite this success, some concerns remain.* Vastly dominant amongst these is continuing significant use of halon 1211 by Article 5(1) Parties. Technology transfer is required for several applications. Countries with Economies in Transition require implementation of effective halon recovery and recycling, a halon 2402 management program, and information dissemination.

- *Military organizations in developed countries have eliminated virtually all halon uses, with some notable and important exceptions.* The important uses for which suitable alternatives are not yet available include those on board ships, submarines, aircraft, and tactical vehicles. While research on alternatives is ongoing, these applications will likely depend on the existing halon bank for some time.

- *Two other halons, 1011 and 1202, were much less widely used.* Recently reported increases in atmospheric abundance of halon 1202 cannot be explained by use as a fire extinguishant. The Parties may wish to examine the possibility of inadvertent production and release of halon 1202 during halon 1211 production in Article 5(1) countries.

- *The needs of "Critical Users" who still require halon 1301 - presently including aviation and some defense, oil and gas, shipping - are being met by management of the existing inventory.* These are in approximate balance, which is important to be maintained. Until there is a clear surplus of halon 1301, widespread destruction cannot be recommended.

- *Efforts to minimize emissions continue to be imperative, particularly during the now-beginning period of maximum ozone layer vulnerability.* Depletion-weighted halon 1211 and 1301 emissions from Article 5(1) countries now is at a level of roughly 23,000 ODP-weighted tonnes and therefore exceeds those from Non-Article 5(1) countries, which are at a level of about 22,000 ODP-weighted tonnes. In 1992, the Non-Article 5(1) countries emitted nearly twice as much as Article 5(1) countries.

4. Methyl Bromide

Key points from the 1998 report of the Methyl Bromide Technical Options Committee (MBTOC) are the following:

- *Of the 1996 global production of methyl bromide of 71,425 tonnes, quarantine and pre-shipment use was 15,000 tonnes and equivalent to 22% of global fumigant use.* Quarantine use is exempt control and is an emissive use unregulated under the Protocol. Moreover, this use appears to be increasing for both developing and developed countries. The MBTOC noted that there is some inconsistency in the interpretation of the terms "quarantine" and "pre-shipment" that may lead to some Parties incorrectly exempting this use. Multiple applications are being used when a single application of methyl bromide just prior to shipment would meet requirements.

- *In spite of the wide spread use of methyl bromide as a soil fumigant (accounting for about 75% of its global use), the MBTOC did not identify a single crop that cannot be produced successfully without methyl bromide.* Approximately 12% of the global consumption of methyl bromide is used for treating durable commodities and about 3% for structures. The principal alternatives are phosphine, heat, cold, and contact pesticides. In many cases, integrated pest management procedures can replace methyl bromide. The MBTOC did not identify any existing alternatives for some nonquarantine and pre-shipment uses, but these are likely to consume less than 50 tonnes per annum. About 9% of global methyl bromide consumption is used for disinfestation of perishable commodities, with about half used for disinfestation of fruit for quarantine purposes. Post-entry alternative treatments are particularly problematical as they neither have been developed and approved for treating products entering via multiple air and sea ports, nor would they be easy to implement.

- *Developing countries consume 23-26% of total methyl bromide production*. Some have greatly reduced their consumption or even officially phased out methyl bromide while others have substantially increased their usage and in some cases production.

- *There has been some limited further research into the development of recovery and recycling systems for methyl bromide*, mostly directed at recovery from commodity fumigation. Only a few special examples of recovery equipment are in current commercial use.

- *The MBTOC could find no existing alternatives to methyl bromide for about 2500 tonnes of methyl bromide per annum used for non-quarantine-and-preshipment treatments*. Existing alternatives as those nonchemical or chemical treatments and/or procedures that are technically feasible for controlling pests, thus avoiding and replacing the use of methyl bromide. Based on this relatively small consumption, the MBTOC considered there are existing alternatives for more than 95% of the current tonnage of methyl bromide excluding quarantine and preshipment. Significant effort must now be undertaken to transfer these alternatives to as many locations as possible and optimize the conditions under which they can be most effective.

5. Refrigeration, Air Conditioning, and Heat Pumps

Key points from the 1998 report of the Refrigeration, Air Conditioning, and Heat Pumps Technical Options Committee are the following:

- *For the short term, the transitional HCFCs still form a valid, global option for CFCs in refrigeration and air conditioning equipment*. However, for the long term, there largely remain only five important different refrigerant options for the vapor compression cycle: HFCs and HFC blends, ammonia, hydrocarbons and blends, carbon dioxide, and water. None are perfect and all have advantages and disadvantages that need to be considered.

- *For new domestic refrigeration equipment, all manufacturers in Non-Article 5(1) countries have transitioned from CFC-12 to non-ozone-depleting substances*. Domestic refrigeration has been completely converted to the use of HFCs and hydrocarbons (i.e., HC-600a) for use in the refrigeration circuit. The conversion to these chemicals in the domestic sector is also now well underway in the Article 5(1) countries and Countries with Economies In Transition, where the transition in the former ones is faster than the Montreal Protocol requirements.

- *Commercial refrigeration includes a wide range of equipment and hence are in a variety of stages of transition away from ozone-depleting substances*. For most large stand-alone equipment, CFC-12 has been replaced by HFC-134a. Some smaller units use various hydrocarbons, mainly propane. HFC blends are often perceived as the economically preferred refrigerants, due to safety and initial costs considerations and therefore form the usual choice. Ammonia and HCFC-22 are currently common in cold storage and food processing applications. Hydrocarbons and carbon dioxide are applicable for specific applications.

- *Nearly all air-cooled air conditioners use HCFC-22.* There has been significant progress in developing HCFC-22 alternatives; e.g., hydrocarbons and the HFC-blend, R-407C, which is widely available, as well as hydrocarbons. Water chillers use a variety of refrigerants, including fluorocarbons (dominant) and ammonia. Hydrocarbon chillers have been introduced on some regional markets.

- *Most mobile air conditioning units used in 1994 have either been retrofitted or scrapped.* Since 1994, all automobile manufacturers have converted to HFC-134a, and the designs are being improved to minimize charging and to maximize energy efficiency. New vehicles are expected to be equipped with HFC-134a until an alternative has been developed and commercialized that offers comparable performance, reliability, and safety characteristics, and an economically viable global-warming advantage.

- *Next to HFCs, non-fluorocarbons and not-in-kind alternatives are more and more perceived as important candidates for future use.* The servicing aspect in the developing countries remains a very important one to be addressed in order to substantially reduce CFC emissions here.

6. Solvents, Coatings, and Adhesives

Key points from the 1998 report of the Solvents Technical Options Committee (STOC) are the following:

- *Industry in developed countries has almost two years of experience without newly produced ozone depleting solvents.* The large majority of users have been successful at implementing alternatives in a very short period. The STOC is becoming more confident that alternatives exist or can expect to be created for nearly all solvent uses. However, the STOC is not completely without concerns for developed countries.

- *Continued dependency on stockpiled solvents is evidence that interest in more economical and effective alternatives are sought.* In the near future, users who still rely on 1,1,1-trichloroethane will feel increasing pressure to find alternatives.

- *With dwindling concerns over the production phase out of ozone depleting solvents in developed countries, the focus of the STOC has shifted to developing countries.* Although the phase-out effort is going well in developed countries, many unique challenges remain for developing countries. The STOC's primary concerns are related to the overall demand for ozone-depleting substances by small and medium enterprises and to eliminating carbon tetrachloride solvent use. One of the major problems yet to be resolved is the complete phase-out of controlled solvents in the small and medium enterprises who, when taken collectively, consume a significant volume of ozone depleting solvents.

- *For almost every solvents, coatings, and adhesives use, non-ozone-depleting alternatives are available.* However, in the near term, HCFCs and the non-ozone-depleting HFCs and PFCs may be necessary in some limited and unique applications.

- *Recently, two ozone-depleting brominated solvents have been commercially introduced, chlorobromomethane and n-propyl bromide* . Because of their capability for depleting the ozone layer and high probability of extensive use, STOC has recommended that the Parties of the Montreal Protocol consider the potential danger of these substances to the ozone layer.

7. Economics

Key points from the 1998 report of the Economics Options Committee (EOC) are the following:

- *Recent studies indicate that virtually all Article 5(1) Parties will meet the "1999 freeze" on production and consumption of Annex A - Group I controlled substances.* To meet subsequent control measures for 2002 and beyond, the Article 5(1) Parties will need to improve compliance by small and medium-sized enterprises. Several case studies have highlighted increasing use of market-based instruments, but some reliance on command-and-control measures remain active.

- *The trade provisions of the Montreal Protocol have reduced international trade in controlled substances as intended.* At the regional level, there is quantitative evidence that trade flows in the relevant product groups have been impacted by the Protocol. The reasons for these impacts are (i) reduced demand for products containing ozone-depleting substances, (ii) difficulty in switching production to non-ozone-depleting substances, and (iii) differential phase-out schedules for Article 5(1) and Non-Article 5(1) Parties. These factors are re-emerging with respect to trade in more recently listed controlled substances, such as HCFCs and methyl bromide.

- *Actions to constrain illegal trade are in hand*, especially with respect to (i) the decision to require import and export licensing systems to be implemented by all Parties, (ii) proposed additional controls on the use of controlled substances in some major countries, and (iii) reductions in the supply of illegal controlled substances due to the recent decision by ten donor countries to provide additional funding to phase out specific CFC production facilities.

8. Challenges for Article 5(1) and Countries With Economies in Transition

- *Regarding Article 5(1) challenges, the experience from developing countries indicates that strong leadership and commitment from government, industry, and individuals is important to establish and maintain momentum.* A major obstacle for several Article 5(1) Parties is the inadequacy of regulatory structure necessary to support the phase-out process. Uncertainties regarding availability and costs of technologies have been mostly resolved, and there are now alternatives to replace almost all ozone-depleting substances. The greatest challenges that remain are in the implementation of Multilateral Fund projects and in addressing the large informal servicing sector.

- *Many of the 16 Non-Article 5(1) Countries with Economies In Transition are lagging behind the phase-out schedule.* The special circumstances that are hampering progress include: the lack of trade and industry association, no network of expects, no venue for reaching consensus, limited information exchange, and incomplete regulatory enforcement.

Section 3

Our Future Ozone Layer

The purpose of this section of the Synthesis Report is to look ahead. It will summarize the current knowledge about the factors that could influence the ozone layer in the 21st century. These factors include changes due to human actions and changes due to natural events and atmospheric variation. The human influenced factors will be presented and analyzed as possible options, vetted for magnitude and practicality by the 1998 Assessment Panel reports.

However, before laying out the descriptions of these quantified and assessed options, this section will pause to take a look at the future that was avoided by the Montreal Protocol and its subsequent amendments and adjustments. Such a pause seems particularly appropriate for this Synthesis Report, given the fact that the Protocol commemorated its 10th year in 1997 and that this Synthesis Report marks a decade of Assessment Panels input into that process.

A. The World We Avoided

1. The Depleted Ozone Layer

One measure of success of the 1987 Montreal Protocol, the processes that led to it, and its functioning over the subsequent years is the forecast of "the world that was avoided" by these actions and events. *In the year* 2050 (which is the approximate nominal time at which the ozone layer is now projected to recover nominally to pre-1980 levels), the abundance of ozone-depleting gases would have been about five times larger than today's value (Figure 1). Ozone depletion would have been much larger than today's. As a result, surface UV-B radiation would have doubled at midlatitudes in the Northern Hemisphere, for example. As Figure 2 shows, without any effort to protect the ozone layer, there would have been a runaway increase in the incidences of skin cancer throughout the next century.

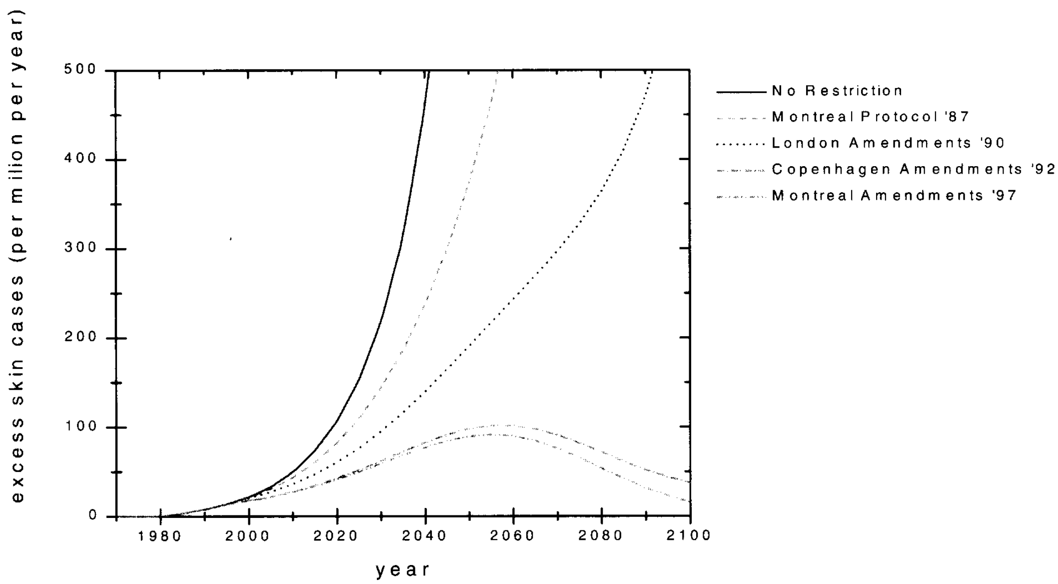

Figure 2: The excess annual incidence of future skin cancer, per million people, for five scenarios, for the current regulations (dashed, two dotted), the Copenhagen Amendment (dashed, one dotted), the London Amendment (dotted), the original 1987 Montreal Protocol (dashed), and no Protocol (solid).

Furthermore, the above impacts (and probably many others) would have continued to grow in the years beyond 2050 if there had been no Montreal Protocol. It is important to underscore that, while the provisions of the original Montreal Protocol in 1987 would have lowered the above growth rates, recovery (i.e., an improving situation) would have been impossible without the Amendments and Adjustments (London, 1990; Copenhagen, 1992, and Vienna, 1995).

2. The Technological Solutions

Even with intent by the nations to protect the ozone layer, the resulting agreements could not have been implemented without industrial commitment and innovation that led to the development and production of alternatives to the ozone-depleting substances. In this regard, it is important to note that when the Montreal Protocol was signed in 1987, there were few identified alternatives to CFC and halons. Most experts assumed that similar chemicals, primarily other fluorocarbons (HCFCs and HFCs), would be the primary substitutes for CFCs. The Montreal Protocol stimulated a global quest for substitutes and alternatives with the result that HCFCs and HFCs became a minority, albeit critical, portion of the current solution. Between 1987 and 1998, the total use of chemicals was reduced by approximately thirty percent through conservation strategies, such as containment and recycling. It was reduced by approximately 50% with non-fluorocarbon substitutes, including non-chemical options such as no-clean soldering and chemical options such as hydrocarbon propellants, cleaning agents, and blowing agents. Only 20% was reduced with HCFC and HFC alternatives. As is illustrated in Table 1, an indicator of this rapid technical progress is the evolution of the industry estimates of the expected mix of substitutes for the CFCs.

Table 1. The change over time of the mix of options that were expected to replace the CFCs.

Substitute	Estimate (%): Year			
	1989	1991	1992	1998
Non-fluorocarbon	32	47	48	50
Conservation	29	12	26	30
HCFC	30	24	11	13
HFC	9	17	15	7

B. The World That Lies Ahead: The Current Status

1. The Scientific Forecast

- *Total stratospheric abundances of ozone depleting gases is expected to maximize before the year 2000*. All other things (for example, climatic fluctuations and volcanic eruptions) being unchanged, the current ozone losses (relative to values observed in the 1970s) would be close to the maximum. These are:

  - about 6% at Northern Hemisphere midlatitudes in winter/spring,
  - about 3% at Northern Hemisphere midlatitudes in summer/fall,
  - about 5 % at Southern Hemisphere midlatitudes on a year-round basis,
  - about 50% in the Antarctic spring, and
  - about 15% in the Arctic spring.

  Such changes in ozone are predicted to be accompanied by increases in surface UV-B radiation of 7,4, 6, 130, and 22%, respectively, if other influences such as clouds remain constant.

- *The vulnerable period for ozone depletion will be extended into coming decades*. The falloff of total chlorine and bromine in the stratosphere will be much slower than the rate of increase observed in past decades. Extreme perturbations, such a natural events like volcanic eruptions during this period, could enhance the ozone loss from ozone-depleting chemicals.

- *The ozone layer will slowly recover over the next 50 yea*rs. If there is full global compliance with the current provisions of Montreal Protocol and its Amendments and Adjustments up through Montreal, 1997, the stratospheric abundance of ozone-depleting substances is expected to return to its pre-1980 (i.e., "unperturbed") level by about 2050, assuming all other things (for example, global climate) remain equal.

- *Detection of the beginning of the recovery of the ozone layer is achievable only well after the maximum stratospheric abundance of ozone-depleting gases*. Potential future increases in other gases important to ozone chemistry (such as nitrous oxide, methane, and water vapor) and climate change will influence the recovery of the ozone layer.

- *Even then, excess incidences of skin cancer will continue to long after the time that the ozone layer has recovered*. The maxima of these excess incidences may be as late as the year 2035 for cataracts and 2060 for skin cancer. This lag arises from the lag between exposure and incidence.

- *It would be very desirable to have similar quantitative predictions for the other effects associated with ozone depletion, but current knowledge is unable to do so quantitatively*. Such areas include effects on forests and food supply in agriculture, and fisheries.

2. The Technological Opportunities

- *For all sectors that used ozone-depleting substances, a range of substitutes and alternative methods has been developed*. Many new products and manufacturing equipment currently use HFCs, HCs, and other non-ozone-depleting chemicals. Exceptions can still be found, e.g., HCFC-141b is used in insulating foam, and HCFC-22 and HCFC-123 are used in stationary air conditioning and water chillers. The use of particularly HCFC-141b and HCFC-22 for new equipment are expected to halt after the year 2001, so that thereafter the main consumer of HCFCs will be the servicing sector. However, there is still substantial production and use of CFCs in the developing countries. Economic plans to come to a closure of facilities are likely to be finalized in 1999. This will be of direct influence on the availability and cost of CFCs, their resulting use, the use of alternatives, and the emissions of CFCs to the atmosphere.

- *Discussion is continuing on cost of HFC chemicals and the manufacturing of HFC products and equipment versus the cost of other chemicals and related manufacturing costs has not finished*. The issue is very related to global warming. The technical choices in the future will likely consider the provisions of both the Montreal Protocol and the Kyoto Protocol. The Technology and Economics Panel has begun to work with the Intergovernmental Panel on Climate Change (IPCC) to assess the possible consequences to the protection of the ozone layer of the control of HFCs and PFCs by the Kyoto Protocol. It could reasonably be expected that this interaction will ultimately lead to sound advice for choices or options with the best environmental properties, given the framework of both Protocols. However, the policy discussions can take considerable time, and any potential delay in the phase-out of CFCs (or any potential move back to CFCs) would slow down the recovery of the ozone layer. The future therefore will continue to ask for substantial involvement from the entire global community to address these complex issues.

C. The World That Lies Ahead: Options For Changes

- *Options to reduce the current and near-term vulnerability to ozone depletion are very limited.* The current vulnerability over the next few decades is primarily due to past use and emissions of the long-lived ozone-depleting substances, whose slow removal from the atmosphere is by natural processes beyond effective human control. Therefore, the main drivers of ozone depletion in the near term could be natural and anthropogenic processes not related to chlorine and bromine compounds (for example, greenhouse gases and climate fluctuations), but to which the ozone layer is sensitive because of the elevated abundances of ozone-depleting substances.

- *Over the longer term, few policy options are available to enhance the recovery of the ozone layer.* Relative to the current, but not yet ratified, control measures (Montreal, 1997), some options could be considered that could lower the cumulative amount of ozone depletion from now until the 1980 ozone level is re-attained. It is this cumulative ozone loss that relates to long-term UV-B exposure, and therefore serves as a relevant measure to consider for improvement. The Scientific Assessment Panel, in their 1998 Report (see Appendix C), has calculated the percentage improvements compared to Montreal (1997) for several scenarios. Furthermore, the Technology and Economic Assessment Panel has examined the feasibility, practicality, and potential costs associated with such types of scenarios. Therefore, such combined benefit/costs information can help characterize the extent to which these scientific scenarios are indeed practical options for consideration. The results are summarized as follows:

- *Scientific Scenario*: 9% future cumulative ozone loss would be avoided if global Halon-1211 emissions were to be eliminated in the year 2000.

  Technological and Economic Perspective: TEAP and its Halon Technical Options Committee (HTOC) find that the quantity of already-produced halon 1211 exceeds foreseeable needs for critical uses and that it is technically feasible to collect halon 1211 for secure storage or destruction. However, TEAP and the HTOC urge Parties to consider the likelihood that programs that mandate halon recovery at the expense of users could result in massive venting to the atmosphere at a time that the ozone layer is most vulnerable. It should be noted that total ODP-weighted emissions of halon 1211 and halon 1301 from Article 5(1) countries now exceeds those from non-Article 5(1) countries.

- *Scientific Scenario*: 7% future cumulative ozone loss would be avoided if global Halon-1301 emissions were to be eliminated in the year 2000.

  Technological and Economic Perspective: There is no excess halon 1301. Therefore, destruction cannot be recommended. Those systems that remain are substantially non-emissive in normal circumstances; emissions due to testing and training have been virtually eliminated; and recovery of agent during servicing and decommissioning is routine. Uses still requiring halon 1301 (including aviation and some defense, oil and gas, and shipping) are being met by management of the existing inventory. The halon 1301 made available as systems are decommissioned is supplying these critical uses. The market value of recycled halon 1301 created by its need for critical uses has encouraged good conservation practices. It is important to ensure that this balance is maintained and that the halon retains its asset value. Use bans and early decomissioning requirements will likely diminish the value of the halon 1301 and discourage good conservation practices.

- *Scientific Scenario*: 5% future cumulative ozone loss would be avoided if global emissions of HCFCs were to be eliminated in the year 2004.

  Technological and Economic Perspective: In most applications, zero-ODP alternatives to ozone-depleting substances are available. However, in some cases (including specific uses as insulating foam and refrigerants) HCFCs are either technically necessary or deliver higher energy efficiency. If further HCFC controls caused a shift to new equipment with lower energy-efficiency, implementation of the Kyoto Protocol would face additional challenges. In many developing countries, uncertainties on availability, suitability, and economical viability of certain non-HCFC alternatives are already barriers to transition and more stringent HCFC controls may hinder progress in the CFC phase-out. HCFC alternatives to CFCs were available for many applications long before substitutes for the non-ozone-depleting-substances were commercialized, and, at that time, users were encouraged to take early action to protect the ozone layer. Parties may wish to consider the advantages of assuring that sufficient HCFC supplies are available to allow reasonable economic recovery from early HCFC investments.

- *Scientific Scenario*: 2.5% future cumulative ozone loss would be avoided if global production of all CFCs and carbon tetrachloride were to be eliminated in the year 2004.

  Technological and Economic Perspective: It is technically feasible to virtually phase-out CFC production and use by 2004. CFC use by Countries with Economies In Transition and Article 5(1) countries is continued primarily due to limits in World Bank and Multilateral Fund financing and by the ability of implementing agencies, national authorities, and companies to manage the transition. In addition, Parties are already taking technically and economically feasible steps to limit carbon tetrachloride emissions from feed stock and process agent uses but could intensify efforts to eliminate carbon tetrachloride as a solvent and in laboratory and analytical uses (currently subject to an essential use exemption). TEAP and industry sources predict that CFC essential uses in metered-dose inhalers will be minimal in non-Article 5(1) countries by 2005. However, pharmaceutical grade CFCs will still be required for oral metered dose inhalers in Article 5(1) countries.

- *Scientific Scenario*: 1.6% future cumulative ozone loss would be avoided if the cap on HCFC production in developing countries were to be lowered from 2.8% to 2.0% in the year 2000, if the phase-out were to be advanced from the year 2030 to 2015, and if more rapid intermediate reductions were to be instituted.

  Technological and Economic Perspective: TEAP and its Technical Options Committees did not undertake detailed analysis of this option. HCFCs are now clearly identified as "transitional substitutes" under the Montreal Protocol and are generally not used where substitutes have comparable costs. Further controls on HCFCs could increase the need for additional contributions to the Multilateral Fund and World Bank. Parties may wish to consider addition efforts to support informed choices of the most environmentally acceptable technology.

- *Scientific Scenario*: About 1% future cumulative ozone loss would be avoided if the global production of methyl bromide were to be eliminated in 2004.

  Technological and Economic Perspective: TEAP and its Methyl Bromide Technical Options Committee have previously reported that a faster phase-out of methyl bromide is technically feasible. Users of methyl bromide would benefit from early notice of new controls to accelerate implementation. Current research, demonstration, and regulatory budgets are premised on the existing controls and may need to be increased if methyl bromide controls are made more stringent under the Protocol. Training is also an important element to the current phase-out schedule and would need to be intensified if controls are made more stringent.

- *Failure to comply with the international agreements of the Montreal Protocol will affect the recovery of the ozone layer*. For example, illegal production of 20-40 ktonnes per year of CFC-12 and CFC-113 for the next 10-20 years would increase the cumulative ozone losses noted above by about 1-4%.

- *The issues of ozone depletion and climate change are interconnected; hence, so are the Montreal Protocol and the Kyoto Protocol.* Changes in ozone affect the Earth's climate, and changes in climate and meteorological conditions affect the ozone layer, because the ozone depletion and climate change phenomena share a number of common chemical and physical processes. Hence, decisions taken (or not taken) under one Protocol have the potential to influence the aims of the other Protocol. For example, if emission changes were to be made related to the greenhouse gases methane, nitrous oxide, and carbon dioxide, they would affect the rate of recovery of the ozone layer. Similarly, if decisions were to be made regarding HFCs, it could affect the ability to phase out ozone depleting substances.

D. Epilogue

There is an understandable tendency in society to ask scientists, technologists, and economists to devote themselves to solving the identified problems of humanity. Recently, this was done quite explicitly in the Seoul Declaration for Environmental Ethics (1997). It is clear that these expert communities have lived up to this expectation in their contributions to addressing the issue of depletion of the ozone layer. However, perhaps the most noteworthy feature of the contribution of scientists was the prediction of ozone depletion long before it was measurable. Subsequently, the phenomena associated with anthropogenic emissions of chlorine and bromine compounds, ozone-layer depletion, and accompanying environmental effects has been and continue to be identified and characterized. Technical alternatives have been rapidly proposed, vetted for suitability, produced, and marketed worldwide. Relevant information is assessed by the experts as input to the Parties, industry, and the public. The 1998 reports of the Assessment Panels of the Montreal Protocol, upon which this Synthesis Report draws, are but the latest step in that service. The continued utility of such service is a goal of the participants.