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PREFACE

This report presents the results of studies by two committees of the National Research Council and their related panels. The Committee on Impacts of Stratospheric Change (CISC) was formed initially in 1972 (as the Climatic Impact Committee) at the request of the Department of Transportation, when it became evident that human activities could affect the earth's ozone shield with resultant significant effects on life on earth. The Committee on Alternatives for the Reduction of Chlorofluorocarbon Emissions (CARCE) was formed in February 1979 to study the alternatives, costs, feasibility, and timing of possible methods for controlling chlorofluorocarbon emissions.

The work of the two committees was conducted under a grant to the National Research Council from the U.S. Environmental Protection Agency (EPA Contract Number 68-01-4607) in response to Section 153(d) of the Clean Air Act Amendments of 1977. This section of the act directed the Administrator of EPA to "undertake to contract with the National Academy of Sciences to study the state of knowledge and the adequacy of research efforts to understand (A) the effects of all substances, practices, processes, and activities which may affect the stratosphere, especially ozone in the stratosphere; (B) the health and welfare effects of modifications of the stratosphere, especially ozone in the stratosphere; and (C) methods of control of such substances, practices, and activities, including alternatives, costs, feasibility, and timing." Parts (A) and (B) of this charge became the responsibility of CISC; CARCE became responsible for part (C).

The original Climatic Impact Committee, a multidisciplinary committee of the National Research Council, had available the results of the Climatic Impact Assessment Program, an extensive study conducted by the Department of Transportation between 1971 and 1974 in which approximately 350 scientists participated. The committee submitted its findings in a report entitled *Environmental Impact of Stratospheric Flight: Biological and Climatic Effects of Aircraft Emissions in the Stratosphere* (National Academy of Sciences, Washington, D.C., 1975). In the meantime, the potential threat to ozone in the stratosphere from the use and release of chlorofluorocarbons was beginning to receive attention. In April 1975, CISC formed a special panel to study the depletion of ozone due to chlorofluorocarbons, with emphasis on the magnitude of the effect, the uncertainties, and the critical research needed to reduce the uncertainties. Simultaneously, CISC considered the biological and climatic effects of ozone depletion and the extent to which existing knowledge and knowledge likely to become available in the future could serve as a basis for government policy.

The results of the studies by CISC during 1975 to 1977 were presented in three reports published by the National Academy of Sciences: *Halocarbons: Environmental Effects of Chlorofluoromethane Release* (September 1976); *Halocarbons: Effects on Stratospheric Ozone*, prepared by the Panel on Atmospheric Chemistry of CISC (September 1976); and *Response to the Ozone Protection Sections of the Clean Air Act Amendments of 1977: An Interim Report* (December 1977). The studies leading to these reports were supported by the National Science Foundation, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, Federal Aviation Administration, and Environmental Protection Agency. These reports presented in detail the existing knowledge, analyzed the results, and made prediction of future changes. The reports included careful analyses of uncertainties.

The present study has built upon the material in the preceding reports plus additional data and analyses that have been made available from numerous sources. The results of the study are presented in this report. A comprehensive treatment of the potential impacts of chlorofluorocarbons on stratospheric ozone, including chemistry, transport, sources, sinks, measurements, models, and projections, has been prepared by the CISC Panel on Stratospheric Chemistry and Transport, chaired by Harold I. Schiff. Their report, which supersedes the 1976 report of the CISC Panel on Atmospheric Chemistry, is being published as a separate volume entitled, *Stratospheric Ozone Depletion by Halocarbons: Chemistry and Transport*. A summary of that volume is included in this report as Chapter 1. CISC and

CARCE are deeply grateful to the members of the Panel on Stratospheric Chemistry and Transport, whose exhaustive studies during the past five years on the potential impacts of chlorofluorocarbons on stratospheric ozone constitute a crucial foundation for this report.

The Committees hope that their report can serve as a basis for deciding on specific steps to control chlorofluorocarbon release both in the United States and in the rest of the world. It must be emphasized that, although this is a final report of the current effort, it can only be considered as one of a series of analyses that will be needed as part of a continuing evaluation of the situation.

Appreciation is expressed to the various governmental agencies that have supported this effort as well as for the contributions and efforts that have been provided by many individuals from universities, industry, and government.

John W. Tukey, *Chairman*
Committee on Impacts of
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Max S. Peters, *Chairman*
Committee on Alternatives for
the Reduction of Chlorofluorocarbon Emissions

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OVERVIEW

All human life depends on satisfactory growth of plants and animals used for food. We know that release of CFCs (chlorofluorocarbons)--mainly CFMs (chlorofluoromethanes) --into the atmosphere acts to deplete ozone in the stratosphere, although we can only estimate approximately by how much. We know that stratospheric ozone depletion will increase the amount of DUV (damaging ultraviolet radiation) reaching the ground from the sun, and by how much. We know that increased DUV can have unfavorable effects on plant growth and on life near the surface of our seas, although our information is incomplete and qualitative. We do not know at what annual release of CFCs the consequences for the world's food would be intolerable, but we know that there is such a level. Thus, though the size of the danger is uncertain, it is only prudent to hold down or reduce the total release of CFCs due to human activity.

The effects of such actions cannot be immediate. Large amounts of CFCs are already in the lower atmosphere (the troposphere), and we have no way to prevent their eventual transfer into the higher atmosphere (the stratosphere), where their effects on ozone will take place. Other large amounts of CFCs are at present sealed away in rigid plastic foams, air conditioners, and refrigerators, from which they will eventually escape to the atmosphere.

The most effective way to reduce CFC releases to the atmosphere, substantially and in the short run, would be to eliminate nonessential uses of CFCs as aerosol propellants in spray cans. Should all countries decide to take action comparable with that already taken by the United States and Sweden in eliminating such uses, between one third and one half of the world's present CFC releases would be avoided.

Such a reduction would be a great step forward in decreasing the threat to the world's food supply, even though the magnitude of this threat is uncertain, and its advantage would far outweigh the relatively small costs of substituting alternative propellants and devices. It would not alone, however, cope with the long-term aspects of the problem. Other uses of CFCs are increasing, throughout the world, at such a rate that, if not restrained, they will bring nonpropellant emissions of CFCs up to today's total emissions in 7 to 10 years. Thus it will be important to consider controlling emissions from other uses.

Although the highly industrialized nations provide a major share of CFC releases, the problem is worldwide; international recognition of the problem and development of a coordinated international approach to control are vital if we are to deal effectively with this, one of the first of the worldwide environmental problems to be faced. In particular, gains from U.S. actions to further reduce emissions will rapidly be offset if emissions overseas continue to grow.

Since CFCs are not easily replaced in many of these other uses, we can hardly look toward complete elimination of the corresponding CFC releases, only to their reduction. As the largest single releaser of CFCs, the United States should take the initiative, both in beginning such reductions and in stimulating the needed international cooperation.

In the countries of Western Europe and North America and in Australia and New Zealand, the skin types of significant fractions of the population make them susceptible to skin cancer caused by overexposure to sunlight. (Light-skinned people who "never tan" seem to be at a particularly enhanced risk.) In those countries, then,

- Anticipated increases in skin cancer from ozone reduction are additional reasons for concern about CFC releases, and
- Increasing voluntary overexposure to sunlight calls for public-health measures to facilitate recognition of those individuals at higher risk and to educate those who need to reduce their overexposure concerning their special risk.

In the United States, significant ozone depletions would eventually mean

- A likely probability of thousands of new cases a year of melanoma skin cancer, which is frequently fatal, and
- A certainty of very many thousands of additional cases every year of nonfatal (nonmelanoma) skin cancer in addition to
- Even larger increases in both kinds of skin cancer associated with changing habits of exposure to the sun.

There is also an effect of CFC releases on climate. A small warming, of uncertain size, is expected, which will enhance the warming effect of CO_2 buildup due to the burning of coal, oil, methane, wood, and similar fuels (and, to an uncertain extent, to the cutting down of tropical rain forests). This can only make more severe what is recognized as a major problem of the decades ahead.

Dealing with CFC release would be much less difficult if a "wait-and-see" approach were feasible. But it is not, since

- Because of slow movement of CFCs to the stratosphere, present and past CFC releases will influence ozone depletion for decades to come;
- Moreover, even a sudden complete cutoff in CFC emissions would be followed by further increase in stratospheric CFCs, and by a corresponding increase in ozone depletion,
- Practicalities of regulation and of industrial change make either an immediate or a complete cutoff out of the question.

A reasonable projection for the "wait-and-see" policy, with decision triggered by a crucial depletion, involves exposure about 20 years later to at least twice that depletion as well as continuing exposure to at least the crucial depletion for several decades more. This is clearly not a prudent strategy.

No country can afford to adopt all the technical changes that would decrease CFC emissions. The body of this report discusses possible actions in the United States; it is hoped that this discussion can also assist in consideration of measures adapted to the situations in other countries, especially the highly industrial countries. These measures may include, for example, replacement of CFCs in certain industrial processes by substitutes that are not ozone depleters. They may also include replacement of the more ozone-depleting CFCs by a less ozone-depleting relative, F-22 (CHF_2Cl), although to be effective such a measure may require a governmental commitment to permit F-22 use over a long enough period to justify the industrial changeovers required. Finally, they may include development of new technology that bypasses the processes that today utilize CFCs.

The most important step in reducing the biological uncertainties, by far the greatest that face us, about the consequences of the release of ozone-depleting gases is the development and maintenance of a long-term program of biological research, carefully balanced between basic and applied aspects. Without this, we are likely to find ourselves in a state of similar uncertainty after 5 or 10 years. Crash programs cannot provide the answers, and spasmodic or unbalanced programs will not.

The uncertainties about how much ozone is depleted by a given release of ozone-depleting gases are still substantial. Careful stratospheric measurements and laboratory research are still needed; they can and should reduce these uncertainties, but will do this slowly.

Measurements of observed ozone amounts must continue but, of course, will not resolve our difficulties. Natural fluctuations in ozone amounts are a major complication in detecting human-caused fluctuations. Present estimates, even allowing for the increased use of satellite measurements, are that human-caused depletion by about 5 percent could be detected by such observations, so that waiting for direct observation would expose us to an eventual depletion of at least 10 percent.

The problems associated with halocarbon emissions will not become easy to handle; they will not fade away. We must strive to deal with them effectively and wisely, decade after decade, in the light of changing circumstances and increasing knowledge.

KEY FINDINGS

Our key findings fall into two groups: those concerned with the nature and extent of the danger posed by depletion of stratospheric ozone and those concerned with the available alternatives for reducing the extent of ozone depletion by chlorofluorocarbons. At the end of the Key Findings is a list that directs the reader to relevant discussions in the body of the report.

With regard to the dangers associated with ozone depletion, we find that

1. Continued release of halocarbons, particularly chlorofluorocarbons (CFCs), into the atmosphere will decrease the average concentration of stratospheric ozone.
2. The expected magnitude of this depletion is increased over earlier calculations,* mainly because of improved values for key reaction-rate constants.
3. If the worldwide release of various types of CFMs were to continue at 1977 levels, the most probable value of eventual ozone depletion would be 16 percent (a reduction of worldwide ozone to 84 percent of what it otherwise would have been). This figure remains within the 95 percent confidence limits previously stated.* The depletion would reach one quarter of its eventual value in about 15 years, and one half of it in about 35 years.
4. Estimates of the various uncertainties in the prediction indicate a roughly even chance that the eventual depletion (for continued release at 1977 rates) would lie between 10 and 23 percent. We are quite confident (19 chances in 20) that it would lie between 5 and 28 percent.

**Halocarbons: Environmental Effects of Chlorofluoromethane Release* (National Academy of Sciences, Washington, D.C., 1976).

5. Despite a temporary leveling off of global CFC emissions due to the U.S. ban on nonessential aerosol propellant use, CFC emissions will again rise and will continue to grow, unless further controls on the production and use of CFCs are initiated--in the United States as well as in the rest of the world.

6. If the release of CFCs were to increase at an annual rate of 7 percent between the years 1980 and 2000 (equivalent to doubling the release rate in each decade), it is most likely (3 chances in 4) that the ozone depletion would eventually exceed 30 percent.

7. A decrease in average ozone concentration will increase the average intensity of biologically damaging ultraviolet radiation (DUV) in natural daylight. Such an increase in DUV would provide no established benefits and would clearly be detrimental both to human health and to nonhuman biological systems. A 16 percent decrease in average ozone concentration will produce a DUV increase of about 44 percent at midlatitudes, while a 30 percent ozone depletion would increase DUV by about 100 percent.

8. Strong evidence links incidence of the more common (nonmelanoma) type of skin cancer with the lifetime-accumulated DUV exposure in susceptible individuals. These individuals constitute substantial fractions of the population of western Europe, Australasia, and North America, in particular up to one third of the U.S. population. Such cancers are rarely fatal but entail medical costs and possible disfigurement.

9. Melanoma is a less-frequent but much more life-threatening type of skin cancer than nonmelanoma. Its occurrence is correlated with DUV exposure and skin type, though in a more complex way.

10. The increasing incidence of both types of skin cancer, plausibly caused by increasing voluntary exposure to the sun, shows that whether or not we release CFCs or other halocarbons into the atmosphere, excessive exposure to the sun can be a "deadly pleasure" for those people who are highly susceptible.

11. With any specified pattern of sunlight exposure in the more susceptible part of the population, skin-cancer incidence rates would be higher under conditions of depleted ozone. In the United States, with present habits of personal exposure, a 16 percent ozone depletion would result eventually in

- Several thousand more cases of melanoma per year, of which a substantial fraction would be fatal, and
- Several hundred thousand more cases of nonmelanoma per year.

12. Crop yields from several kinds of agricultural plants are likely to be reduced as a result of a 16 percent to 30 percent ozone depletion. Present data do not permit a quantitative estimation of the expected production losses but do show differences in the ultraviolet sensitivities of different plants cultivated in the United States. Since nonagricultural plants show ultraviolet sensitivities in the same range as do agricultural plants, effects of ozone depletion on wild and cultivated plants should be similar.

13. Larval forms of several important seafood species, as well as microorganisms at the base of the marine food chain, would suffer appreciable killing as a result of a 16 to 30 percent ozone depletion. Present ignorance of ultraviolet penetration into the waters that they inhabit and of the depth distribution of the organisms precludes an estimate of actual losses.

14. Climatic effects of continued CFC release at the 1977 rate would include an average warming of the earth's surface by a few tenths of one degree Celsius before the middle of the twenty-first century, as well as changes in the stratospheric temperature patterns, which in turn affect ozone chemistry. The surface warming from such CFC release is expected to be about 10 percent of the warming that is predicted to result from increased atmospheric CO_2 (mainly from continued increase in the burning of fossil fuels).

With regard to the options available for ameliorative action, we find that

15. With the cessation of domestic nonessential aerosol use, CFC emissions in the United States dropped from half to about a third of the world total. Further unilateral U.S. action can have only limited impact in reducing the extent of global stratospheric ozone depletion --a problem that is worldwide in both its causes and its consequences. International harmonization of attitudes and actions on the control of CFC production and use, supported by international efforts to address the principal substantive scientific questions and to achieve greater understanding of the risks posed by CFC emissions, should be essential objectives of U.S. policy.

16. The greatest global gain would result from the worldwide elimination of nonessential aerosol propellant uses. The penalty for such action would be small.

17. No single approach to further U.S. regulation is optimum across the board for all the diverse sources of

CFC emissions. Adequate advance declaration of intent and/or gradual application of controls will minimize the disruptive effects of any regulatory approach adopted.

18. For any CFC control actions undertaken, most of the costs will occur now, while benefits will accrue largely in the future. The extent to which present costs are justified depends on the relative importance attached to the public welfare in future decades. This must be determined by political and ethical judgments rather than by technical or economic ones; political and ethical judgments should thus guide decisions regarding the severity of the additional regulatory actions that should (or should not) be taken now.

19. Useful alternatives to CFCs (but carrying some penalties) exist for at least the following applications:

- Blowing agents for a substantial part of flexible plastic foam production;
- Metal cleaning and drying, solder flux removal, and garment cleaning;
- Industrial sterilization of medical supplies;
- Liquid fast freezing of food.

Actions leading to implementation of these alternatives could begin immediately.

20. Options for stimulating adoption of the alternatives listed above include:

- A gradually increasing use tax on CFCs;
- Quotas for specific uses, implemented by marketable (transferable) permits;
- Bans on specific CFC uses.

The first two options appear to involve less cost to society, for a given level of effectiveness, than the third.

21. Acceptable non-CFC blowing agents for rigid polyurethane and polystyrene insulating foams are not available. Alternative insulating materials that do not require CFCs for their manufacture will be satisfactory in some applications--although not so good as present materials in others.

22. Techniques exist for containment, recovery, and recycling of CFCs in the following applications:

- Commercial air conditioning,
- Commercial refrigeration,
- Industrial sterilization of medical supplies,
- Some solvent applications,
- Factory procedures for automotive air-conditioner testing and filling,
- Liquid fast freezing of food.

23. Substitution of F-22 (CHF_2Cl) for F-11 ($CFCl_3$) or F-12 (CF_2Cl_2) in refrigeration and air-conditioning systems, including automobile air conditioners, would substantially reduce stratospheric ozone depletion, because F-22 introduces only one tenth to one fourth as much chlorine into the stratosphere as do F-11 and F-12. However, because F-22 does introduce some chlorine into the stratosphere, there may be reluctance on the part of industry, in the absence of some assurance that specific uses of F-22 will not be banned or otherwise restricted for a definite period, to undertake the redesign and conversion of manufacturing facilities that substitution of F-22 would require.

24. Improved recovery and recycling of refrigerants during servicing of automobile air conditioners could yield significant emission reductions, but the cost is likely to be high if put into operation at the existing large number of service facilities.

25. Design and construction modifications to minimize leakage from automotive air conditioners could yield significant emission reductions at relatively lower costs than improved recovery and recycling during servicing.

26. Options for stimulating containment, recovery, and recycling include

- A deposit-refund system,
- A tax on CFC use,
- Emission standards,
- Required use of best available control technology.

The first two options appear to involve less cost to society than do the last two.

27. Home refrigerators and freezers are relatively small sources of CFC emissions, and no practical methods for significantly reducing emissions from these sources are now available.

28. Materials that can be substituted for CFCs, but contain no chlorine, have been sought by many industrial groups. It is exceedingly difficult to find other refrigerant materials that can match the favorable combination of physical properties, chemical stability, and safety of currently used CFCs. The fluorocarbon F-134a (CH_2FCF_3) has physical properties similar to those of F-12 but there is, as yet, no known commercial synthesis and its toxicology has not been assessed.

29. The increasingly difficult decisions to be made in the future will require better knowledge of chemistry and circulation in both stratosphere and troposphere; better knowledge of the biological effects of increased

DUV, particularly on humans and crop plants; and better knowledge of industrial alternatives, both in manufacture and in use.

The following list is provided to guide the reader to those portions of the text that contain the bases for these key findings:

Findings 1-6: Chapter 1
Finding 7: Chapter 2; Appendix C
Findings 8-11: Chapter 3; Appendixes F, G, H
Findings 12-13: Chapter 2; Appendix B
Finding 14: Chapter 4
Findings 15-16: Part III, Introduction; Chapter 5
Findings 17-18: Chapter 7
Finding 19: Chapter 6
Finding 20: Chapter 7
Findings 21-25: Chapter 6; Appendixes I, J
Finding 26: Chapter 7
Findings 27-28: Chapter 6
Finding 29: Chapters 1, 2, 3, 4, 6

I

Introduction and Summary

INTRODUCTION AND SUMMARY

INTRODUCTION

Most of the oxygen in the atmosphere is in the form of molecular oxygen, O_2, the life-essential part of the air we breathe. Occasionally an atom of oxygen, O (produced in an electrical discharge or photochemical reaction), combines with an O_2 molecule to form ozone, O_3. This unstable, highly reactive gas does not persist in the lower atmosphere, or troposphere, for long periods of time, except in regions affected by the familiar photochemical smog of urban pollution. However, in the more rarified stratosphere (between altitudes of 10 and 50 km) a significant amount of ozone exists continuously as a natural component. This natural accumulation is sometimes referred to as the "ozone layer," although the concentration of ozone varies smoothly over the whole altitude range and never exceeds ten parts per million of all the substances present.

This ozone layer is neither constant in time nor uniformly distributed above different parts of the earth's surface. The amount directly overhead is smallest at the equator and increases toward the poles. It increases by as much as 25 percent from autumn to spring in temperate latitudes, decreasing again through the summer. Since ozone is created in photochemical reactions initiated by ultraviolet radiation from the sun, its concentration also varies with changes in solar activity. Superimposed on these variations in amounts of ozone are irregular, local shifts in concentration, many associated with the passage of weather systems in the lower atmosphere. These natural variations make it difficult to detect any man-induced change in the long-term global average, unless that change is of substantial magnitude (say 5 percent or more).

Ultraviolet radiation is a part of the electromagnetic spectrum of wavelength too short to stimulate the human eye. Its quanta, more energetic than those of the longer-wavelength visible light, are more likely to initiate photochemical changes when absorbed. At wavelengths below about 320 nm they do, in fact, produce photochemical damage to nucleic acids and proteins within cells, to the detriment of living organisms. Fortunately, solar radiation with wavelengths shorter than about 290 nm is so strongly absorbed by the ozone layer that almost none would be transmitted to earth even with large reductions in the ozone concentration in the stratosphere. However, some of that part of the spectrum lying between 320 and 290 nm reaches the earth's surface. For historical reasons this spectral region is called UV-B.

Deoxyribonucleic acid (DNA) is the nucleic acid carrying the genetic information in living cells. UV-B is effective in altering this cellular material and is largely responsible for sunburn, skin cancer, and other biological effects--although in some circumstances light of other wavelengths may be important. The total amount of UV-B reaching the earth's surface, weighted by the different relative effectiveness of its constituent wavelengths for producing damage, is called the damaging ultraviolet (DUV) intensity. DUV intensity in sunlight changes appreciably as the amount of ozone through which the sunlight has passed varies.

When the earth was formed, its atmosphere was much different than at present. It contained very little oxygen and was more like the present atmospheres of other planets: Venus, Mars, and Jupiter. Life developed first in the oceans, where organic compounds provided protective absorption of ultraviolet. As the abundance of organisms carrying out photosynthetic processes like those of modern plants increased, the previously absent oxygen was formed, and with sufficient oxygen, ozone (created by the action of ultraviolet radiation on the O_2) began to function as the ultraviolet shield. This allowed animal and plant life to emerge from the oceans and live in open daylight. The relationship between life as it has evolved on earth and the concentration of stratospheric ozone may be fragile, and any alteration of it should be viewed with concern.

Ozone is created and destroyed continuously by chemical reactions between gases in the stratosphere. The ozone-destroying reactions involve atomic oxygen, atomic chlorine, or oxides of several elements--notably hydrogen, nitrogen, and chlorine. A dynamic balance between the creative and destructive reactions determines the actual level of stratospheric-ozone concentration. This concentration may be expected to change if either rates of formation or rates of destruction are altered. There is now reason to believe that the large quantities of chlorofluorocarbon compounds (CFCs) released into the atmosphere by man in recent years are finding their way into the stratosphere, where their decomposition products, particularly Cl and ClO, enter into ozone-destroying reactions. The resultant alteration of the dynamic balance, with its likely consequences, constitutes the subject of Part II of this report.

The earliest concerns about possible destruction of stratospheric ozone centered on the oxides of nitrogen released directly into the stratosphere from the exhausts of high-flying aircraft--in particular, from the then proposed supersonic transports. Two papers, by P. J. Crutzen (1970) and H. Johnston (1971), had alerted the scientific community to this possibility. At the request of the Administrator of the National Oceanic and Atmospheric Administration, the NRC's Geophysics Research Board conducted a study that confirmed the general conclusions of Crutzen and Johnston. The results were reported to NOAA and other interested government agencies.

On the basis of this information, the Congress in 1971 authorized funds for research on the possible modification of the stratosphere by high-flying aircraft. As a result, the Climatic Impact Assessment Program (CIAP) of the Department of Transportation was formed and began the most extensive investigation of the problem undertaken to that time. The National Research Council created the Climatic Impact Committee in 1972, which conducted a study and issued a report in 1975 entitled *Environmental Impact of Stratospheric Flight*, making use of the data assembled by CIAP. This report alerted national and international regulatory authorities to the existence of potentially serious problems if large fleets of stratospheric airliners, either supersonic or subsonic, should grow in the future.

In 1974, a landmark paper by F. S. Rowland and M. J. Molina first called attention to the possibility that chlorine-containing compounds, such as CFCs, released into the atmosphere might also have a deleterious effect on stratospheric ozone. In April 1975, the NRC undertook a formal study of the CFC problem and created the Committee on Impacts of Stratospheric Change, which subsequently issued two reports: *Halocarbons: Effects on Stratospheric Ozone* (1976) and *Halocarbons: Environmental*

Effects of Chlorofluoromethane Release (1976). These reports predicted that stratospheric ozone reduction would reach 6 to 7.5 percent eventually, if the 1973 release rate of CFCs were maintained, and the latter report (page 3) concluded "In our present state of knowledge, it would be imprudent to accept increasing CFM use and release, either in the United States or worldwide."

Some aspects of the ozone-depletion problem have been studied by the NRC Environmental Studies Board in reports that dealt principally with other environmental effects. The report *Non-Fluorinated Halomethanes in the Environment* (1978) describes the effects of these chemicals on humans through their introduction into water, air, and food. The principal nonfluorinated halocarbons posing potential danger to ozone are carbon tetrachloride (CCl_4) and methyl chloroform (CH_3CCl_3), each of which has at present a lesser effect on stratospheric ozone than the CFCs. Another report *Nitrates: An Environmental Assessment* (1978) concludes that the effects on the ozone layer of N_2O released by natural degradation of nitrate fertilizers develop slowly over decades and that no immediate corrective action is required.

In response to these and other studies and to growing concern about long-term effects of continued chlorofluoromethane release, the United States in 1978 initiated steps to ban the nonessential use of CFMs as aerosol spray propellants. The ban went into final effect in April 1979, by which time compliance was complete. However, only a few other nations took comparable steps; and concern remained that, after a temporary drop, global CFC emissions would again begin to increase.

In the Clean Air Act Amendments of 1977 (Public Law 95-95), Congress directed the Environmental Protection Agency "to contract with the National Academy of Sciences to study the state of knowledge and the adequacy of research efforts to understand (A) the effects of all substances, practices, processes, and activities which may affect the stratosphere, especially ozone in the stratosphere; (B) the health and welfare effects of modifications of the stratosphere, especially ozone in the stratosphere; and (C) methods of control of such substances, practices, and activities including alternatives, costs, feasibility, and timing." The first two of these tasks were assigned to the existing Committee on Impacts of Stratospheric Change (CISC).

In response to the new charge, CISC, assisted by three subsidiary panels, addressed (i) stratospheric chemistry and transport, (ii) effects on climate, and (III) effects on health and produced late in 1977 the report, *Response to the Ozone Protection Sections of the Clean Air Act Amendments of 1977: An Interim Report*. The 1977 CISC report generally confirmed the earlier CISC results, although the estimated stratospheric ozone reduction resulting from continued chlorofluoromethane emissions was roughly double the earlier figure because of improved information on the rate constants for several key reactions. Nevertheless, the new estimate lay within the uncertainty limits of the previous report. In addition, recognition of the strong coupling between the ozone-destructive reactions involving oxides of chlorine and those involving oxides of nitrogen (which make the expected effects of either contaminant depend on the amount of the other) markedly reduced the expected effect of nitrogen oxides. The Committee concluded that the effect of nitrogen oxides --emitted in the exhausts of high-flying aircraft and by natural degradation of nitrogen fertilizers--is probably now quite small and not of immediate concern.

In 1978, CISC, aided by the creation of a fourth panel on biological effects, began a new and more thorough series of studies the results of which are described in Part II of this report.

The third task, listed as (C) in Public Law 95-95, involved economic, industrial, and social considerations and was deemed to be beyond the scope and expertise of CISC as it was constituted. To address this aspect, a new committee was created. The Committee on Alternatives for the Reduction of Chlorofluorocarbon Emissions (CARCE) began its work in February 1979, assisted by two subsidiary panels--one addressing industrial technology and one concerned with socioeconomic impacts. CARCE's charge was to "examine the costs, feasibility, and timing of various methods of controlling human sources of stratospheric ozone depletion with primary attention to chlorofluoromethanes and other substances that have effects of similar magnitude." It was to consider technological methods, including emission controls, recovery and recycling, substitution of different materials, and development of new technology. It was to identify strategies for implementing controls, including both regulatory and economic-incentive measures. It was to assess the costs of implementing these strategies, their likely effectiveness in reducing the extent of ozone depletion, their overall economic impact, and side impacts on worker health and safety and on the environment. The assessment was to be carried out in the context of a global problem wherein international agreement on control measures would ultimately be needed.

Because much of the economic and industrial information needed for this study did not exist, EPA sponsored, in parallel with the CARCE and CISC studies, several major research efforts aimed at assembling and analyzing data on the economic and technological feasibility of controls on chlorofluorocarbon emissions and the benefits likely to accrue therefrom. Progress reports from these undertakings have been made available to CARCE and its panels.

The primary issues that this report attempts to address are as follows:

In Part II, prepared by CISC:

1. What are the likely impacts of continued chlorofluorocarbon release to the atmosphere on the concentration of stratospheric ozone?
2. What are the likely impacts of changes in stratospheric ozone on health, climate, and plant and animal life?
3. What are the uncertainties in the above assessments, what further research is required to reduce these uncertainties, and how long is it likely to take to do so?

In Part III, prepared by CARCE:

4. What options or alternatives for reducing chlorofluorocarbon emissions are now technologically feasible or are likely to become so in the near future, and how long would it take to implement them?
5. What regulatory or economic-incentive measures would be required to bring these technological changes about?
6. What will these measures cost, both in the sense of immediate costs to industries and governments and in the sense of broader socioeconomic impacts?
7. How effective are they likely to be in reducing global chlorofluorocarbon emissions?
8. What are the critical uncertainties, and what futher research is necessary to resolve them?

CAUSES AND EFFECTS OF STRATOSPHERIC OZONE DEPLETION

Atmospheric Chemistry and Transport (cf. Chapter 1)

The photochemistry of stratospheric components affecting production and destruction of ozone has been advanced appreciably over the past few years by substantial improvements in the knowledge of reaction-rate constants. This advance has not qualitatively changed the predictions about ozone depletion made earlier, but it has altered the quantitative values and the sensitivity of these values to changes in various parameters. Remaining uncertainties in the rate constants contribute more than half of the uncertainty in the predicted values. Other sources of uncertainty include the possibility of tropospheric destruction sites (such as desert sands) for the most important stratospheric contaminants released by human activities, uncertainties in rates of gaseous transport, the future changes to be expected in atmospheric composition, and errors inherent in the reduction of a three-dimensional stratosphere to a one-dimensional model that is practical for calculations.

Stratospheric Contamination and Predicted Ozone Depletion (cf. Chapter 1)

Chlorofluorocarbons released into the atmosphere by human activities cause reduction of the stratospheric ozone concentration. The present reduction in average concentration is estimated to be about 2 percent--an amount that cannot be detected in the face of short-term natural fluctuations--but this will grow over the next few decades. Maintenance of the 1975-1978 annual release rates would lead to an ultimate depletion of roughly 16 percent.* Approximately one quarter of the ultimate depletion would occur in the next 15 years (bringing it near the level of detectability with existing instruments), and half of it would occur in the next 35 years.

There is a 50 percent chance that the ultimate ozone depletion would lie somewhere between 10 and 23 percent, and only a 5 percent chance that it would be either less than 5 percent or greater than 28 percent. Calculations of expected ozone depletion for more complicated patterns of CFM release over time have also been made and are outlined in Part II.

The expected ozone depletion is caused mainly by two chlorofluoromethanes, CFCl3 (F-11) and CF2CL2 (F-12),

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*This is equivalent to a reduction in worldwide ozone to 84 percent of what it would have been otherwise.

which are highly effective in ozone removal and are widely used. The less effective compounds CH_3CCl_3 (methyl chloroform) and CHF_2Cl (F-22), for which release rates are rapidly increasing, may become important in the future and need continued monitoring. Nitrogen oxides released directly into the stratosphere from exhausts of high-flying aircraft or N_2O diffusing upward from the soil after natural degradation of excess nitrogen fertilizers can also, if present in large enough quantity, increase somewhat the rate of ozone destruction, but the effects of these sources are at present too small for serious concern.

Nonhuman Biological Effects (cf. Chapter 2)

Tests of over 100 agricultural plant varieties in controlled-environment growth chambers have indicated considerable differences in UV sensitivity. About 20 percent were sensitive to daily UV-B doses similar to those that occur under cloudless conditions during Florida summers at present ozone levels, 20 percent were resistant to doses four times greater than this, and the remaining 60 percent showed intermediate sensitivity. However, 15 varieties tested in the open field with artificially supplemented UV-B radiation appeared more resistant than plants grown in the laboratory environmental growth chambers. Where comparisons of the same plants were possible, the field plants tolerated up to fourfold greater doses. The field experiments were necessarily less well controlled, and the results consequently less clear-cut, than the growth chamber studies. If the field experiments correctly indicate the solar-UV sensitivity, some species (sugar beets, tomatoes, mustard, corn) would be significantly affected by a 16 percent to 30 percent ozone depletion, but many others would not. An estimate of the overall impact on crop productivity is not possible with present information.

The existence of relatively more resistant varieties of the same plant species offers the possibility, but not certainty, of selecting and breeding agricultural plant strains better adapted to increased UV-B stress. Introduction of new varieties into the agriculture of undeveloped countries would, however, be more difficult. Increase of DUV may be too rapid to allow natural evolution of more resistant plants and animals.

Increased DUV may also affect the production and the species composition of some grazing lands and forests, since the range of sensitivity of nonagricultural plants is about the same as that of crop plants.

Experimental study of the UV sensitivity of young anchovies indicates that this commercially important species now lives near the limit of its solar-UV tolerance when at the surface of the water. The same is true of certain crab and shrimp larvae. A 16 percent reduction in ozone concentration would be distinctly harmful to them in a surface location, but insufficient information about their customary depth distribution at various times of day, their likelihood of changing the depth, and the UV penetration into the waters they usually inhabit prevents quantitative estimate of the magnitude of any losses.

At this point it can neither be demonstrated that a 16 percent reduction in ozone would cause significant losses in yield from agricultural crops and terrestrial or aquatic ecosystems, nor can it be assured that significant losses would not occur.

Human Health

The skin is the major target of DUV exposure in humans and may develop three types of skin cancer--(1) basal- and (2) squamous-cell cancers (nonmelanoma skin cancer) and (3) melanoma skin cancer. In the white population, the incidence of nonmelanoma and melanoma skin cancers increases as the latitude of residence decreases. Nonmelanoma skin cancers are concentrated on the habitually exposed anatomical sites (face and hands), and melanoma on the relatively exposed body areas (legs of females, upper backs of males and females). Nonmelanomas are strongly associated with personal exposure to sunlight, ease of sunburning and inability to tan. For melanomas these factors also apply, but melanomas have a more complex solar relationship, depending more on irregular sunlight exposure. This may explain the higher incidence of melanoma among professionals, e.g., physicians, lawyers, and administrators.

The increases in damaging ultraviolet radiation accompanying 16 percent ozone depletion would increase the incidence of nonmelanoma skin cancer in the white population of the earth. Although these cancers are rarely fatal, they require medical treatment and often lead to disfigurement. Their incidence is related to accumulated solar-ultraviolet exposure, which depends on the average intensity of the damaging wavelengths in sunlight and the personal habits of exposure to sunlight that have become customary. Numbers of the susceptible white population currently expose their bodies excessively to sunlight and, after some years of such exposure, develop cancers as a consequence. With any given exposure habits, however, a 16 percent ozone depletion would increase skin-cancer incidence.

Melanoma, the form of skin cancer that is frequently fatal, is rapidly increasing in the white populations of advanced countries, possibly because of increasing recreational sunlight exposure. Until its causes are better understood, no exact prediction of the magnitude of the effect of ozone depletion is possible, although a corresponding additional increase in incidence is expected.

Climatic Effects (cf. Chapter 4)

Chlorofluorocarbons released into the atmosphere absorb infrared radiation, both to and from the earth's surface, and therefore directly affect heat exchanges between the earth and its atmosphere. This results in surface warming due to what has been called a "greenhouse" effect. Current estimates show that continuation of the 1977 release rates of CFCs should produce, through this direct effect, a slow, average warming of the earth's surface by the mid-twenty-first century. However, this warming is expected to be only 10 percent of that owing to the predicted increase (mainly due to burning of fossil fuels) in the CO_2 content of the atmosphere.

Eventually the CFCs rise to the stratosphere, where they participate in the depletion of ozone. This process results in a cooling of the stratosphere, but the effect on surface temperature is small and its sign is in doubt. Moreover, the previously described direct or "greenhouse" effect predominates and causes a small surface warming.

ALTERNATIVES FOR THE CONTROL OF CHLOROFLUOROCARBON EMISSIONS AND OPTIONS FOR THEIR IMPLEMENTATION

Present trends suggest that global release of CFCs will continue to increase unless adequate steps are taken to control emissions or to curtail usage. The selection of such steps requires an assessment of (1) the international dimensions of the problem, which establish the context for national assessments and control measures; (2) the technological bounds on what can be done, now or in the near future, to reduce emissions; (3) the governmental actions that would induce the necessary technological measures, and their socioeconomic consequences; and (4) the constraints on timing imposed by technical, economic, social, and international considerations and influenced by current uncertainties in our knowledge.

International Aspects (cf. Chapter 5)

Because the CFC-ozone problem is global in both its causes --CFC emissions--and its consequences--impacts on health and the environment--the international dimensions of the fluorocarbon problem are of crucial importance. If the United States were to undertake all the near-term technologically feasible measures identified below, domestic CFC emissions would at most be cut in half, and global emissions would be reduced by at most 15 to 20 percent. The socioeconomic impact of such drastic measures within the United States would not be insignificant.

In contrast, elimination of nonessential aerosol propellant uses in other countries would have substantially the same effect, in terms of reducing global CFC emissions, as a complete ban on *all* remaining uses of CFCs within the United States. For these reasons, the international harmonization of attitudes and action on the control of fluorocarbon production and use should be an essential component of U.S. action on CFCs, and the U.S. should seek the most effective way to encourage international cooperation in reducing CFC emissions.

Decisions made in other countries concerning restrictions on production and use of CFCs will depend, as in the United States, on a variety of factors, including confidence in the scientific evidence of the danger, assessment of the economic and social impact of control measures, and national attitudes toward risks. Up to now, action to control CFC emissions in other countries has been modest, although some movement is under way. A few countries (Canada, Sweden, The Netherlands, and West Germany) have employed regulatory or persuasive measures, and the European Economic Community is on the verge of a limited decision on aerosols. This suggests that the availability of more extensive scientific information and the U.S. ban on aerosols have contributed to positive developments abroad; continued scientific progress and further U.S. regulatory action may encourage additional control measures in other nations.

The scientific basis for expecting significant deleterious health and environmental effects from continued CFC emissions will continue to be examined by scientists in other nations, thereby either creating a broader international consensus or bringing into sharper focus any substantive scientific questions on which opinion is divided. An international scientific effort would be desirable (a) to develop international scientific consensus on the present state of knowledge and uncertainty regarding the nature and magnitude of expected health and environmental effects of CFC emissions; and (b) to develop, by international cooperative action, such additional scientific information as is required to provide international consensus on the risk posed by continued emissions. This kind of consensus can be expected to facilitate coordinated control of CFC emissions.

At the same time, steps might be taken to seek political agreement internationally to proceed with control measures. Conventional techniques such as bilateral discussions, nationally sponsored conferences, and consideration by appropriate international organizations might be employed.

Further U.S. action to control CFCs will have relatively modest effect on U.S. international trade. The most significant, potentially adverse effect would be in the air-conditioning and refrigeration sector. This impact has been estimated to be as high as $1 billion, but would probably not be sufficient to alter significantly the desirability of further U.S. CFC regulation. For reasons of international trade law, it is important that imported products be treated no differently, in terms of market-access, than domestically produced products in the implementation of any U.S. CFC policy. On the export side, U.S. restrictions are not likely to be effective, as foreign producers would replace U.S. output with production abroad unless local action to control CFCs is pursued simultaneously.

Technological Alternatives (cf. Chapter 6)

Chlorofluorocarbon emissions arise from a variety of sources. In the United States, mobile (principally automobile) air conditioners are the largest single source today, but industrial solvents and plastic foams each emit almost as much. Other refrigerant applications (e.g., commercial and residential air conditioners, refrigerators, and freezers), sterilization of medical supplies, fast-food freezing, and many other uses give rise to smaller but significant releases to the atmosphere. Within each of these categories there is substantial variation in the facilities employed, the timing of emissions, and the ease of substitution of alternative materials and technologies.

The present pattern of emission sources is expected to change in its details over the next decade or two. Solvent and plastic-foam applications are growing at a faster rate than air-conditioning and refrigeration uses, but all three categories will remain important. New applications of CFCs continue to be introduced, and uses unforeseen today could emerge to become major sources of emissions. The appropriateness of government action to ban or restrict new uses, and thus slow down the expected growth of CFC use, is not addressed in this report but clearly is an option to be considered. There would be no immediate benefits of such a course, in the sense of a reduction in present CFC emissions, but the long-term benefits might be highly significant.

Technological alternatives that could lead to reduced CFC emissions include substitution of other chemicals for the CFCs; containment, recovery, and recycling of CFCs; development of new technology not requiring CFCs; and restricted production of the items in which CFCs are used. Each approach to reducing CFC emissions has been addressed in this report in terms of technological feasibility, the time required for implementation (and, additionally, the time required to show results), cost, and penalties in product performance and in safety and health. Although these factors are imperfectly known, it is possible to identify some significant emission sources for which there are potentially promising technological means for reducing or eliminating emissions. In most cases these technologies are not available today but could be brought to commercial readiness within the next decade and in some instances in as little as one to two years.

Air conditioners in automobiles and trucks constitute a large source of F-12 (CF_2Cl_2) emissions. Improved manufacturing, installing, and testing procedures could achieve modest reductions at small additional cost. Recovery and recycling in servicing could accomplish larger reductions, but the costs will be large and the program difficult to administer if put into operation at the existing large number of service locations, each dealing with small CFC volumes. Improved air-conditioner design could result in large emission reductions through reduced leakage and charge. Costs of these changes would be small. The principal cost might well be that of the research needed as a basis for the changes.

Emissions from commercial air conditioning and refrigeration could be reduced by improved service and disposal procedures at small cost.

Substitution of F-22 (CHF_2Cl) for the F-11 ($CFCl_3$) and F-12 (CF_2Cl_2) refrigerants used now might be possible for most or all air-conditioning and refrigeration systems. F-22 is already used in some refrigeration applications, and manufacturing plants for F-11 and F-12 are in most instances either capable of commercial F-22 manufacture now or capable of being converted to F-22 manufacture at relatively modest cost. However, the cost of redesign of the air-conditioning and refrigeration equipment in which the CFC is used would be very high, as the equipment now in use cannot be converted to accommodate F-22. Several years would be required for initial introduction and perhaps as much as a decade for full implementation. F-22 is also a source of stratospheric ozone depletion, although to a lesser extent than F-11 and F-12 (see footnote on pages 154 and 155); therefore industry may require some assurance that F-22 will not itself be banned for at least a definite period of years before undertaking the costly redesign and equipment changeovers that will be required.

Flexible polyurethane foam production gives rise to large emissions of F-11, which could be substantially or almost completely eliminated by replacing the CFC with methylene chloride (CH_2Cl_2), although some health and safety questions need to be resolved and some loss of cushioning properties may have to be accepted. Rigid polyurethane foam requires large quantities of F-11, most of which is retained within the foam cells--giving the foam its superior insulating properties--and is emitted during the lifetime of the foam and after disposal. No substitute has been found that gives equal insulation capacity. Polystyrene and polyolefin foam production result in emissions of F-12 and F-114 ($C_2F_4Cl_2$). F-142b ($C_2H_3F_2Cl$), a less-effective ozone depleter, could be employed as a substitute, but a considerable cost penalty would be incurred. Additionally, testing for toxicity and flammability of F-142b still needs to be completed. Methyl chloride or methylene chloride might be an acceptable substitute in polystyrene foam manufacture, but additional research is needed. Recovery and recycling procedures for CFCs are relatively unpromising in plastic foam manufacture.

Industrial cleaning and drying constitutes a large source of F-113 ($C_2F_3Cl_3$) emissions. Substitute solvents and processes can be introduced for some applications at small cost (or even a cost advantage), but there are significant questions about the health and safety aspects of these substitutes. However, no practical replacement for F-113 is known for many of the highly specialized critical cleaning procedures in which it is used.

Other CFC uses contribute relatively small amounts of emissions. More than 90 percent of this remainder comes from sterilization applications and liquid fast freezing of food. Improvements in containment, recovery, and recycling of CFCs in these two applications could reduce emissions substantially. There are also existing alternatives for both uses that do not involve CFCs. Sacrifices in performance, cost, and/or safety would be involved in implementation of these alternatives.

Regulatory Options and Socioeconomic Considerations (cf. Chapter 7)

CFCs have come into widespread use because of advantages in cost, performance, or safety. Implementing the technologically feasible alternatives will carry some penalty and will require either a government mandate or some economic incentives to be successful. All these alternatives have costs, and it is necessary to consider whether these costs are justified in view of the benefits to be expected. Because of the many uncertainties involved, benefits and risks must be expressed in probabilistic terms, and it is important not to be misled into thinking that average or most likely estimates are necessarily the proper determinants of governmental actions. This is particularly true when events whose likelihood is small have sufficiently severe consequences. A 5 percent likelihood of a major disaster may impel some individuals or societies to take action even though the "most likely" occurrence represents no more than a minor inconvenience; other individuals and societies will set higher or lower thresholds for action.

There are many options for control of CFC emissions, and the list of available options will change with time in response to technological innovations and a changing regulatory climate. There is today, and will continue to be, considerable uncertainty as to what course future regulatory actions will take. The resulting indecision, within both government and industry, cannot help but add to the overall cost of controls. This is perhaps a necessary consequence of the pace with which new technology and new problems continue to arise.

Control Options Seven broad regulatory options are considered for reducing CFC emissions. These are

1. Bans on CFCs in specific applications;
2. Standards for allowable emissions from specific applications either in the form of specific restrictions on emissions or in a requirement to use the best available control technology;
3. Quotas or ceilings on CFC production or purchase for specific uses*;
4. Taxes on production and/or use of CFCs, to increase cost and thereby reduce demand;
5. Deposit-refund systems to create user incentives to recycle;
6. Subsidies to promote the creation of recycling and recovery activities;
7. Education and labeling to promote public awareness and consumer concern.

Some of these approaches are only applicable to a small part of the range of CFC uses. None of the approaches appears to be clearly superior to others for the whole range. Some of the more important considerations for each approach are the following:

- A *ban* is simple, clear-cut, and direct and is probably easier to enforce than the other conventional approach--the setting of emission control standards. The simplicity of a ban is not always advantageous. Both essential and nonessential uses are affected equally, unless a system of exceptions--which may become both elaborate and costly--is devised. The adverse impact of the aerosol ban appears to have been relatively small because, in most cases, acceptable substitutes were available and few exceptions were made.
- *Emission standards* and *quotas*--if applied to the various CFC uses rather than to CFC production alone--are difficult to enforce. The cost of administration and enforcement can be high, especially if the marketplace is complex, and the process must allow for many special situations.
- *Taxes* are easier to enforce and are self-financing, although, to be most effective, a tax scheme should be

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*Quotas would be implemented by marketable (transferable) permits, i.e., by "rights" to purchase a certain amount, which could be traded among firms.

implemented gradually, with rates that increase on a scheduled basis until the desired degree of reduction in CFC use has been achieved.

- *Special incentives*, such as a refundable deposit system, may be worthy of further consideration in stimulating emission-reduction approaches such as recovery and recycling of CFCs from discarded equipment. However, the costs and effectiveness of such a policy cannot be assessed at present. Government subsidies may be required to stimulate the development of a recovery and recycling industry by assisting entrepreneurs with the construction and acquisition of facilities and equipment.
- *Education and labeling* is a "background" measure that could accompany all other approaches and could begin immediately as a precursor to further measures.

For any of these approaches, advance notice may be necessary to allow both industry and consumers to adjust practices, and consequently the time required for implementation may be longer than technological considerations alone suggest.

Each CFC use should be considered separately, and for each use the most effective and least costly means of control should be identified. An overall national policy should be based on an assortment of control measures selected to minimize the total adverse economic, social, personal, and environmental impact on society. From the point of view of economics, this means first reducing CFC use in those applications where good substitutes are available at comparable, or only slightly higher, cost, while postponing action in those areas where it would be very costly to replace present CFC-using practices. However, other judgmental factors, such as the essentiality or nonessentiality of different uses and who will bear the cost of change, should be taken into account.

Impacts of Controls In addition to the economic impacts of the various control options, there are also international impacts, health impacts, and impacts on nonrenewable resources such as energy. Moreover, administrative feasibility and political acceptability are other significant factors that differ for the different approaches. While it is difficult to quantify and compare factors of this type, a bird's-eye view of the effects is presented in Table 7.8 of this report. This table suggests that, for those CFC uses for which bans, quotas, or taxes could be effective regulatory approaches, the costs (in a broad sense) to society of reducing CFC emissions to any given level would be lowest if tax incentives were used, higher for quotas, and highest for bans.

Costs and Benefits of Controls Costs of control are more readily expressed in monetary terms than are benefits, although even the costs are not always straightforward. Some of the effects of ozone depletion, such as those that affect human health, life itself, and the biological environment, involve considerations that society does not traditionally measure in monetary terms, and it may be necessary to use indirect measures such as "willingness to pay" that are both controversial and difficult to measure accurately. A further difficulty in quantifying benefits from the reduction of CFC emissions arises from the fact that the benefits will not be received until many years or decades after the cost of making the change has been incurred.

Examination of three benefit-cost studies carried out prior to the U.S. aerosol ban indicates the dependence of the results of such analyses on assumptions and postulates adopted by the analyst. Such studies can be of great help to the regulatory decision maker if they are turned to for guidance but should not be used as absolute determinants of the economic aspects of a regulatory decision.

In this study no benefit-cost analysis was attempted. Rather, the expected effectiveness of each control strategy was expressed in terms of the reduction in CFC emissions likely to result from it; the costs and other effects of the strategies were estimated independently. Cost and effectiveness together were then used to assess the "desirability" of each strategy.

Timing and Uncertainty in Regulatory Decision Making

The regulatory decision maker faces a host of uncertainties, including uncertainty about the economic consequences of a particular regulatory action, uncertainty about the future growth in global CFC use, and uncertainty about the likelihood of regulatory actions in other nations. It would be wise to adopt a regulatory stance sufficiently flexible to be changed as new understandings remove some of those uncertainties. At the same time, it is important to industry to have a clear understanding of what actions are and are not acceptable, so that investment and planning can proceed in an orderly and rational way. Periodic reassessment of regulatory strategies, with some assurance that the "rules of the game" will not be changed unexpectedly, may be a satisfactory compromise.

It takes many years before CFCs emitted today cause diminution of stratospheric ozone. Likewise, it will be many years before the effects of control measures adopted now make themselves felt. A compromise must be sought among (a) the need to take action now, emphasized by the knowledge that a delay of a few years means increased damages in the next century; (b) the need to avoid precipitous action that could have disastrous impact on some sectors of our economy; and (c) the need to allow time for feedback and iterative readjustments as both the costs and the effects of various control measures become known.

Assessment of the desirability of various alternatives for control of CFC emissions requires decision making in the presence of uncertainties of several kinds. Hard sets of facts are not available for most aspects of CFC emissions control. The variety of compounds to be considered, their many potential uses, and the scope of possible control methods constitute further parts of the problem. An inability to predict and measure effects of future developments in control technology contributes another group of unknowns.

RESOLVING AREAS OF UNCERTAINTY

Major Areas of Uncertainty

It is important to begin now to take steps to reduce existing gaps in our knowledge, thereby diminishing uncertainties and setting the stage for choosing most desirable alternatives with confidence and credibility. This does not imply that no actions should be taken until all uncertainties are removed, but rather that there should be a continuing enlargement of the knowledge base.

The uncertainties can be placed in at least seven categories:

1. *The magnitude of ozone depletion.* Although we have stated that continued release of CFCs will reduce the total amount of stratospheric ozone, the amount of such depletion is at present uncertain. The degree of uncertainty is decreasing, and, with continued study of the chemical reactions involved and the atmospheric models used, it should decrease further. As previously noted, we also need better

measurements of tropospheric and stratospheric trace constituents and better altitude profiles of their concentrations. Improvements should be made in modeling so as to obtain better correlation between one-, two-, and three-dimensional models. Finally, improvements in the direct measurement of stratospheric ozone, particularly from satellites, will hasten the day when experimental proof of ozone depletion is available.

2. *Nature and magnitude of effects of CFC emissions on life and the environment.* Uncertainties associated with the nature and magnitude of the effects of ozone depletion on life remain great. At one extreme, there is the possibility that such effects are so small that costly control measures are unwarranted. At the other extreme, catastrophic environmental and health effects cannot be excluded. These uncertainties will become smaller with the passage of time if we learn more about the effects of damaging ultraviolet radiation (DUV) on plants and animals, including human beings. There is strong evidence for a relationship between sunlight exposure and nonmelanoma skin cancer; the relationship to melanoma is more complex and less clear. A significant increase in the number of cases of nonmelanoma and deaths from melanoma has occurred in recent years and, to the extent that this is due to increasing overexposure to sunlight, can be expected to continue. The deoxyribonucleic acid (DNA), which contains the genetic material in living cells, is altered by exposure to solar-ultraviolet radiation, thus affecting the growth and reproduction of plants and animals. Hence, we can expect the yields of farms and fisheries to be affected by any increase in DUV, but the magnitude of this effect cannot be ascertained at this time. A great deal of study needs to be devoted to the causes and incidence of skin cancer and also to the effects of DUV on living cells.

3. *Anticipated future CFC production and release rates worldwide,* taking into account the delayed release rates from products such as rigid plastic foams. Reliable data may be near at hand on current production of the most important compounds, with the possible exception of Eastern Europe and the Soviet Union. Information is also becoming available on the amounts of CFCs locked up or "banked" in equipment and materials already in use, although a breakdown by nation and product around the world is not available. Predicting bank size and emission rates in the future cannot be done easily, but the effectiveness of present decisions on control requirements will be aided by more accurate forecasts of future production and release rates.

4. *The identity and properties of chemicals that may be suitable as substitutes for CFCs in various uses.* Consumers and their suppliers will bear the cost of a phaseout of one CFC in favor of another, or of still another substance. The uncertainties about CFCs in use, however, are probably much less than those about the hoped-for substitutes. Research into the properties and effects of proposed alternative products and technologies can reduce the risk of unwise or unworkable mandates to change.

5. *Actual costs of reducing CFC emissions and of foregone benefits.* Each alternative proposed for the reduction of a specific CFC emission results in new net economic costs, to the government, to the manufacturer, and to the consumer, the sum of which can be termed "actual economic costs." In addition to these costs, each proposed alternative may result in products having poorer performance in terms of energy conservation, a shorter product lifetime, reduced comfort and convenience, and other foregone benefits. The "actual economic costs" are probably amenable to quantitative analysis to the extent that pertinent data are available, but much uncertainty exists regarding the costs that are to be ascribed to the foregone benefits. This may require that regulatory decisions will have to be made even though the imponderables of foregone benefits cannot yet be quantified.

6. *Relationship between CFC demand and price structure.* A critical unknown at this time is how demand for CFCs will decrease as CFC prices rise. Without a measure of this factor, it is difficult to estimate the effectiveness of substitution or the reduction in demand that might take place. This is a key element of the overall effectiveness of market-based strategies such as taxes and quotas. Changes in demand will vary from use to use, depending on the cost of the next most desirable substitute. Thus, demand for rigid foams may continue despite a substantial tax on CFCs because the available substitutes (fiberglass, cellulose, rock wool) are considerably less cost-effective, particularly where space is important. Flexible foams, however, are more easily replaced (as in packing material) and some might simply be eliminated (for example, supersoft foams as fabric backings in clothing.

7. *Responses by governments worldwide to U.S. initiatives and to the scientific evidence.* The CFC-ozone problem is different in nature from many of the other pollution problems that the nations of the world have recently begun to face. While unwise use of pesticides, pollution of rivers, and oil spills at sea are problems that exist the

world over, may have consequences to many countries, and often require agreement between nations for effective control, the problems themselves are relatively local. Damage is done in the vicinity of the polluting activity, and the damage is felt--and the costs borne--by the affected parties shortly after the event. The ozone problem is different: regardless of where in the world CFCs are released, the ultimate effect is on ozone globally. All nations, whether they are responsible for the problem or not, will share in the damage, much of which will not occur until many decades later. There is, at this time, no precedent to turn to for guidance in this matter. Yet the ozone problem is a forerunner of another very serious global problem--that of increased global concentrations of carbon dioxide as a result of a continued increase in the burning of fossil fuels. The nations of the world collectively need to devise mechanisms for dealing with problems of this sort, assessing the scientific evidence as it develops and finding ways to agree on effective control actions, since these are not problems that can be adequately dealt with by the actions of only a few nations.

Future Needs in the Applicable Science

The magnitude of ozone depletion and the magnitudes of the effects of such depletion can be better known if certain measurements and analyses are undertaken in the near future. These are as follows:

(a) For atmospheric chemistry and transport

1. We need better simultaneous measurements of related chemical species in order to test photochemical theory. In most cases, isolated measurements of a single such species are no longer useful, because the natural variability makes these measurements difficult to interpret. We also need measurements of the photolysis of species such as O_3, $ClONO_2$, $HOCl$, and NO_3. In addition, some critical species are as yet unmeasured or only poorly measured; these include HO_2NO_2, N_2O_5, NO_3, HO_2, H_2O_2, and OH.

2. Much of the natural variability of stratospheric species is due to dynamic and meteorological influences rather than to photochemical reactions. Time series of measurements of individual compounds are important in order to understand diurnal, seasonal, and solar-cycle variations.

3. Because of the strong interactions between tropospheric and stratospheric processes, it has become

clear that the complex chemistry of the troposphere is in need of further study. In this connection the role of OH as an agent in reducing the lifetimes of certain CFCs, such as F-22, needs to be determined more precisely.

4. Tropospheric altitude profiles of certain species, e.g., NO, NO_2, and O_3, with solar flux measured simultaneously, are needed to improve our understanding of the tropospheric ozone cycle, which is important, because of coupling between the two cycles, to an understanding of the stratospheric ozone cycle.

5. Further measurements of stratospheric Cl, ClO, and HCl are needed to clear up the uncertainties associated with their concentrations and their variations in concentration.

6. Laboratory studies of the decomposition of CFMs on desert sand should be done in order to provide data from which to assess the role of this possible mechanism for reducing the amount of CFC in the atmosphere.

(b) For climatic effects

1. We need more realistic 3-D models (general circulation models) of the atmosphere with better spatial resolution in the troposphere.

2. We need measurements of the radiative properties of the other halocarbons, e.g., methyl chloroform and F-22, for which release rates are increasing.

(c) For human health effects

1. We need more detailed studies involving personal dosimetry of untraviolet-radiation exposure in relation to behavior patterns.

2. We need case-control studies to define the skin types of persons who develop melanoma skin cancer.

3. The collection and analysis of carefully recorded data on a large number of melanoma cases is required to better understand the roles of patterns of sunlight exposure as well as the roles, cooperative or competitive, of other agents.

4. We need well-planned and continuing surveys of the incidence of nonmelanoma skin cancer.

(d) For nonhuman biological effects

1. A major effort should be undertaken to establish the relative effectiveness of different solar wavelengths for producing the different biological effects of concern.

2. Effects of ultraviolet radiation on plants and marine life should be determined, in a few carefully selected instances, using sources that reasonably simulate the intensity and wavelength distribution of the sun itself.

Future Needs Relating to Options for Control

The need to minimize CFC emissions will be with us for some time, and continued effort will be needed (1) to develop new chemicals to replace CFCs and new processes that do not require CFCs and (2) to bring the most promising of these to the stage of commercial feasibility as rapidly as possible. A crucial step involves determining the acceptability of existing and proposed substitutes for CFCs from the point of view of the hazard they present to health and safety and to the environment.

Development of effective technology for in-plant recovery of CFC vapor, and adoption of appropriate incentives to industry to commit itself heavily to containment, recovery, and recycling within the factory, will do much to permit continuation of efficient and highly valued processes that are dependent on CFC availability and that might otherwise be banned or restricted.

In addition, the possibility of developing alternate systems for air conditioning and refrigeration, as well as additional alternatives for the production of insulation for buildings and household appliances, and for the production of cushioning and packaging materials should be explored. These are long-range research and development efforts that should be undertaken but not with hopes for a quick payoff.

For the more immediate future, it is important to develop adequate data on the production and use of CFCs worldwide and on the amount emitted currently and the amount "stored" in refrigerators, air conditioners, and plastic foams. These data should be used to set bounds on the magnitude of the problem and also to assess the effectiveness of the control measures that are put into effect. This will permit periodic reassessment by those countries taking control actions and provide guidance to those considering such actions.

II

Causes and Effects of Stratospheric Ozone Depletion

INTRODUCTION

This report from the Committee on Impacts of Stratospheric Change (CISC) covers four areas:

1. *Stratospheric chemistry*, outlining the changes in stratospheric ozone concentration expected from continued chlorofluorocarbon (CFC) releases;
2. *Nonhuman biological systems* and their response to the expected ozone changes, which in turn increase the solar-ultraviolet radiation at the earth's surface;
3. *Human health* effects stemming directly from the expected ultraviolet radiation increase; and
4. *Climatic effects* of CFC releases.

The studies of stratospheric chemistry have led to a large and complex report describing the conclusions. Since the findings of this panel are fundamental to the rest of the report, a detailed description of the stratospheric chemistry, and of the assumptions regarding atmospheric gas transport, as well as a careful analysis of possible errors, seem needed. Consequently, the report of this panel is issued as a separate report entitled *Stratospheric Ozone Depletion by Halocarbons: Chemistry and Transport* to facilitate critical evaluation of the conclusions. The corresponding account here (Chapter 1) is simply a summary of the larger report, outlining the major points, without presenting their details. The chapters that follow on nonhuman biological systems, human health, and climatic effects are intended to stand alone, representing the full contributions of the panels involved.

Predicting the eventual magnitude of CFC effects requires assumptions about the future releases of these substances. We cannot, of course, foresee the future industrial appetite for CFCs in either the United States or the world, nor can we anticipate worldwide patterns of regulatory activity and their effectiveness. Consequently the Panel on Stratospheric Transport and Chemistry has calculated ozone depletions for several patterns of CFC release rates (several scenarios). It simplifies discussion, however, to have one general release figure for reference in relating different effects. The roughly constant world release rates from 1975 (when a recession slowed production) through 1976-1978 (when decreasing U.S. use of CFC aerosol propellants approximately balanced increasing uses elsewhere) provides a convenient reference plateau. This does not mean that continuation of the 1975-1978 release rates is necessarily the most likely scenario: with future regulation the release rates could be smaller than those for 1975-1978, while without some regulation release rates will almost surely increase. The constant rates simply represent a basis for convenient figures that are easy to understand and that have already been used in several published studies.

As outlined in the Summary, this is the third report of the full CISC. While agreeing generally with the earlier reports, it is able to draw further conclusions on some points and does not depend on, or require, reference to the earlier publications.

1 PROJECTED CHANGES IN STRATOSPHERIC OZONE

This chapter confirms previous findings of the National Research Council and others that continued release of chlorofluorocarbons into the atmosphere will result in a decrease in the average concentration of stratospheric ozone. The most probable value *of the depletion that will accrue eventually is 16.5 percent, if the 1977 rate of CFC emission continues.*

Although this subject has been studied extensively, it is not possible to state exactly *how much the ozone will decrease. The reasons for the uncertainty and the limits of that uncertainty are delineated in this chapter on atmospheric chemistry and transport.**

REITERATION OF THE PROBLEM

The importance of the relatively small amount of ozone in the earth's atmosphere lies mainly in its ability to absorb the biologically harmful ultraviolet radiation from the sun and to prevent most of it from reaching the surface. In addition, ozone plays an important role in determining the climate of this planet.

Most of the ozone is located in the stratosphere, a region of the atmosphere located between 10 and 50 km above the surface. Its concentration is determined by a balance between chemical processes that produce it and others that destroy it and never reaches more than a few ten-thousandths of a percent (a few parts per million).

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*A more complete exposition of this subject is found in the companion report, *Stratospheric Ozone Depletion by Halocarbons: Chemistry and Transport* (National Academy of Sciences, Washington, D.C., 1979).

The natural processes that destroy ozone are believed to involve substances that are normally present in trace amounts, thousands of times less than that of ozone itself. These include chemical compounds that contain hydrogen (HO_x), nitrogen (NO_x), and chlorine (ClO_x). These compounds enter into catalytic chain reactions in which one molecule can destroy many ozone molecules before being removed by some competing process. The concern is that human activities can appreciably alter the amounts of these catalytic substances in the stratosphere.

A number of such activities have been identified, including the use of high-flying aircraft, halocarbons, nuclear weapons, and nitrogen fertilizers. There may be others not yet identified. The "Clean Air Amendment of 1977" requires that all possibilities be evaluated. However, since the release of halocarbons appears to be the greatest and most immediate threat, the present report confines itself to evaluating the possible effects on stratospheric ozone of continued release of halocarbons.

PREVIOUS EVALUATIONS

The NAS released a report in September 1976 entitled *Halocarbons: Effects on Stratospheric Ozone.** The study focused attention on chlorofluoromethanes (CFMs). Two of these, $CFCl_3$ (F-11) and CF_2Cl_2 (F-12), were of greatest concern. They were being produced and released in large and increasing quantities. They are not removed, to our knowledge, in the troposphere (the region between the surface and the stratosphere), and so the same large quantities could enter the stratosphere. Here they could be dissociated by ultraviolet radiation into ClO_x fragments capable of destroying ozone. The main conclusion of the report was that "their continued release at the 1973 production rates would cause the ozone to decrease steadily until a probable reduction of about 6 to 7.5 percent is reached, with an uncertainty range of at least 2 to 20 percent using what are believed to be roughly 95 percent confidence limits. The time required for the reduction to attain half of this steady state value (3 to 3.75 percent) would be 40 to 50 years."

The uncertainty range is determined by uncertainties in the rates at which these substances are released into the atmosphere, uncertainties in the rate constants that deter-

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*Subsequently referred to as the "NAS, 1976 report."

mine the speeds of seven of the most important chemical reactions, and by the use of one-dimensional computer models to represent the distribution and transport of chemical species. Uncertainties in the rate constants made the largest contributions to the overall uncertainty. The 6 to 7.5 percent range for the most probable reduction allowed for the possibility of some CFM removal in the troposphere.

In August 1977, NASA released a report entitled *Chlorofluoromethanes and the Stratosphere.** Eight modeling groups evaluated the ultimate ozone reduction resulting from continued release of these two substances at the 1975 rates. Their predictions of the most likely value ranged from 10.8 to 16.5 percent. This spread in most likely values is due to differences between the eight models and should not be confused with the uncertainty range given above for the NAS, 1976 report. It will be noted that the most probable values predicted for ozone reduction in the NASA, 1977 report are close to a factor of 2 larger than, although still within the uncertainty range of, that of the NAS, 1976 report. The reason is that, in the period between these two reports, the rate constant for an important chemical reaction (NO + HO_2) had been remeasured, using improved techniques, and found to be substantially different from the value used in the earlier report.

PRESENT FINDINGS

Chlorofluoromethanes

Since the release of the two earlier reports there have been continuing improvements in the computer models and in the measurements used as inputs to these models. There has also been a considerable increase in the number and the quality of atmospheric measurements that can be used to check the validity of the models. These activities have not altered the principal conclusion reached in the previous reports that continued release of halocarbons into the atmosphere will result in a significant decrease in the amount of stratospheric ozone. For comparison purposes with the previous reports, the present study estimates an eventual decrease of 18.6 percent in the total

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*Subsequently referred to as the "NASA, 1977 report."

amount of ozone for continued release of F-11 and F-12 at the 1977* rates, which we will call Case A.

Other considerations, to be discussed below, but not included in the previous reports, have led us to reduce the "best estimate" for the eventual ozone decrease to a value of 16.5 percent. Our estimate of uncertainty is such that there is a 95 percent probability that the true value of the ozone reduction lies between 5 percent and 28 percent, i.e., a range of a factor of 6. Ozone reduction to half of the eventual value, i.e., to 8 percent if the eventual value were 16.5 percent, would occur in about 30 years.

Although several countries (Canada, The Netherlands, Sweden, and West Germany) have taken action to reduce the amount of CFMs that they are releasing into the atmosphere, release rates in other countries are increasing. It is therefore not possible to anticipate future, global release rates with any high degree of confidence. We have therefore chosen three additional scenarios to span the likely range. In Case B, we assume the 1977 release rate until 1983, followed by a 25 percent reduction at that time, and then continuation at that reduced level. Case C is similar to Case B, except that an additional reduction of 25 percent is assumed to occur in 1988, with constant release thereafter at half of the 1977 level. Both Cases B and C tacitly presume considerable further regulation to limit release. Case D has been suggested to us by the Committee on Alternatives for the Reduction of CFC Emissions to reflect the increasing release rates in other industrial countries and for nonaerosol purposes in the United States. It assumes a constant release rate at the 1977 level until 1980, a 7 percent per annum growth rate until 2000, and a constant release rate at the year 2000 level beyond that date.

The projected steady-state values for Cases B and C are 13.2 percent and 9.4 percent, respectively, with the same sixfold uncertainty range at the 95 percent confidence level. Case D leads to an ozone reduction of 25 percent in the year 2025 and an eventual steady-state

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*The NAS, 1976 report used 1973 release rates; the NASA, 1977 report used 1975 release rates. These, and the 1977 release rates, are all within 5 percent of each other (cf. Chapter 2 of the companion report *Stratospheric Ozone Depletion by Halocarbons: Chemistry and Transport* (National Academy of Sciences, Washington, D.C., 1979).

reduction of 56.7 percent. High reliance cannot be placed on the steady-state value, since, at large levels of ozone reduction, changes in the dynamics and the temperature structure of the stratosphere are expected that would invalidate the model's treatment of transport. It is highly probable that the steady-state reduction for Case D would be at least 30 percent.

It is interesting to note that the model and error analysis also show that a (2.1 ± 1.5) percent reduction in O_3 has already occurred and that by the year 2000 the reduction will be (5 ± 3.5) percent, almost independent of which of the four cases is considered. Although there is no likelihood of it happening, immediately stopping all release worldwide would still produce roughly one and a half times the present reduction in about 15 years, after which the ozone level could gradually recover.

Other Halocarbons

Although the production of F-11 and F-12 has not been increasing significantly during the past four years, there has been a dramatic increase in the production of two other halocarbons capable of affecting stratospheric ozone. The use of F-22, largely in refrigeration, has increased 25 percent in the past two years, and the production of methyl chloroform is now doubling every five years. Atmospheric measurements indicate that methyl chloroform is contributing between a quarter and half as many chlorine atoms to the stratosphere as are F-11 and F-12. If it gains increased usage, as a substitute for other solvents in degreasing and coating operations, it may well become the largest source of stratospheric chlorine.*

ESTIMATES OF UNCERTAINTIES

Uncertainties Due to Chemistry

To estimate the effect on stratospheric ozone of any scenario of halocarbon release rate, it is necessary to

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*Once methyl chloroform reaches the *stratosphere*, its effectiveness in destroying ozone is not identical to that of CFMs because of differences in the chemistry of these compounds. But, to a first approximation, these differences may be ignored.

know the detailed chemistry of all substances that may be involved and the rates at which chemical species are transported into and out of the stratosphere.

In the model calculations it is assumed that there are no processes that remove F-11 and F-12 in the troposphere and thereby prevent them from affecting stratospheric ozone. In our previous report (NAS, 1976) we considered all such inactive removal processes that had been suggested and put upper limits on the degree to which each of them might reduce the predicted ozone depletion. Only three of these had upper limits that could have reduced the predictions by as much as 10 percent of the most probable value. The limits of two of these, removal by chemical reaction by gaseous ions and photodecomposition in the troposphere by sunlight, were based on the failure to observe these processes in laboratory experiments and an estimate of the detection limits in these experiments. Subsequent consideration has indicated that these processes are unlikely to be of any significance. The limit of the third process, removal by oceans, was based on sparse measurements of the concentrations of F-11 in surface waters. Subsequent measurements have suggested that this process is also unimportant. One new removal process has been suggested, photodecomposition of the halocarbons when in contact with desert sand. This suggestion is based on laboratory studies that reveal that halocarbons, when in contact with sandlike materials, can be decomposed by light of wavelengths that do not otherwise decompose them. These studies are at present not definitive enough to permit a reliable estimate of how much change, if any, is likely to result from this process. Nevertheless, we have reduced our estimate from 18.6 percent to 17.4 percent for the most likely ozone reduction for Case A to take into account this and other possible inactive removal processes.

A more direct way to determine whether such processes do, in fact, exist would be to compare the amount of fluorocarbons released into the atmosphere minus the amount that has been calculated to have been dissociated in the stratosphere with the amount still remaining in the entire atmosphere. Any difference between these two quantities could then be ascribed to inactive removal in the troposphere. Our previous study indicated that the uncertainties in the calculations based on the total amount now present in the atmosphere were too large to reach meaningful conclusions. Despite considerable improvement in the number and quality of the measurements, that situation still obtains. It has been suggested that a more definitive answer to the problem may be achieved by measuring the rate at which the amount of fluorocarbons in the atmosphere increases with time. An experiment to make such measurements has been initiated.

All other halocarbons that are being released into the atmosphere in appreciable quantities contain either hydrogen atoms or double bonds and therefore are removed, to some extent, in the troposphere by reaction with HO radicals. This removal is virtually complete for most of these substances, so that they do not pose a threat to stratospheric ozone. Tropospheric removal by reaction with HO is, however, not complete for three of these halocarbons, methyl chloride, methylchloroform, and F-22, so that appreciable fractions of these substances do reach the stratosphere and contribute to ozone destruction. Methyl chloride is mainly produced by natural processes and is therefore present in the natural atmosphere in an essentially unchanging amount. By contrast, F-22, and, to a large extent, methyl chloroform, are man-made chemicals that are being produced in rapidly accelerating amounts. The fraction of these chemicals that reaches the stratosphere depends on the HO concentrations in the troposphere, which are only poorly known.

For these reasons we have not undertaken an estimate of the magnitude of the threat to stratospheric ozone posed by the increasing use of these chemicals, although there are sufficient grounds for concern. There is a need for increased measurements, in the troposphere, particularly of HO concentration. There is also a need for increased research efforts to improve our understanding of tropospheric chemistry.

Our understanding of stratospheric chemistry has improved considerably since our last report. Stratospheric measurements have supported the basic chemical postulates. Halocarbons do reach the stratosphere; they do photodissociate into fragments that can catalyze the destruction of ozone, and these fragments do, in fact, react with ozone. But there are still limitations to our knowledge of stratospheric chemistry that introduce uncertainties in our estimate of the magnitude of the expected ozone reduction.

There has been considerable improvement in the accuracy with which the rate constants are known for the chemical reactions that are believed to occur in the stratosphere. But since the number of these reactions is large, at least

125, the cumulative uncertainty is also large and is unlikely to show rapid improvement in the near future. Measurements of several reactions have been made by more reliable, direct methods and have led to large changes in their rate constants compared with the values (deduced by indirect methods) that were used in our earlier report. These new values, particularly that for the reaction of HO_2 with NO, have resulted in an increase in the predicted ozone impact by halocarbons. In addition, they have forced us to recognize a much greater interaction among the various chemical families that affect stratospheric ozone; e.g., a change in the amount of NO_x or HO_x in the stratosphere has a marked affect on the ozone reduction caused by halocarbons. It is felt that large changes in the adopted values of rate constants are unlikely to occur in the future because direct methods are now generally used to measure these quantities. There is, however, a need to measure rate constants over the range of pressures that exist in the stratosphere, since there is reason to believe that some of them may be pressure-dependent. Moreover, many of the measurements have been made without confirming that the products of the reactions are the ones assumed. Efforts should be made to define all the products of each chemical reaction.

In any description of a chemical system there is always the possibility that an important process has been overlooked or dismissed as being unimportant. An example of this was recognized just before the completion of the NAS, 1976 report, when it was learned that chlorine nitrate ($ClONO_2$) was more stable than previously believed. The inclusion of the new information caused a reduction of the predicted ozone depletion by a factor of about 1.85. More recently, it has been suggested that hypochlorous acid, HOCl, might play a similar role. However, most of the laboratory studies on this compound indicate that it will be broken up relatively rapidly by sunlight and therefore will not provide a significant hiding place for stratospheric chlorine.

Two additional reactions that may affect the impact of halocarbons on stratospheric ozone have come to our attention too late to be incorporated into our model calculations. One of these, the reaction of Cl atoms with formaldehyde (CH_2O), has the effect of decreasing the ozone depletion by roughly 7 percent of the calculated value. The other reaction, between ClO and BrO, increases the impact of halocarbons on stratospheric ozone by approximately the same factor. Since the effects of these two reactions operate in opposite directions, are somewhat speculative, and are not large, we do not believe that their omission in our model produces significant errors in our projections.

In assessing *the uncertainty in our prediction caused by the uncertainties in rate constants* we have used an error analysis similar to that used in the NASA, 1977 report, which we consider to be an improvement over the method used in the NAS, 1976 report. This analysis gives a cumulative uncertainty for the predicted ozone change of a range *of a factor of 4 at the 95 percent confidence limit.** This can be compared with the fivefold range of uncertainty in the NAS, 1976 report, in which only seven key reactions were considered. The lower range we obtain using all (~125) reactions in the analysis is a measure of the improvement that has been achieved in the laboratory measurements.

Uncertainty Due to Transport

The predictions of this and previous reports have been made using the so-called one-dimensional (1-D) model. This type of model considers only vertical motions of chemical substances. But air, of course, moves in three dimensions. The justification for this approximation is that, when all the motions are summed over all latitudes and longitudes, the effects of horizontal motions of substances largely cancel and the vertical movements dominate. These models therefore represent forms of global average over both distance and time. The speed with which all substances enter or leave the stratosphere as a result of these vertical movements is characterized by an "eddy-diffusion" coefficient $K(z)$, the value of which depends on altitude. The values of $K(z)$ are usually determined by measuring the change with height of the concentration of some trace substances whose chemistry is believed to be

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*More specifically, for the most probable value of 16.5 percent for steady-state ozone reduction in Case A, there is one chance in 40 that, because of this particular error, it could be lower than 6.3 percent and one chance in 40 that it could be higher than 26 percent. The uncertainty range of a factor of 4 is equivalent to a ±60 percent uncertainty in the predicted value, i.e., $(1 + 0.6)/(1 - 0.6) = 4$.

well understood. Methane (CH_4) and nitrous oxide (N_2O) have often been used for this purpose.

The analysis of these data by the method used in the NAS, 1976 report indicates a somewhat wider possible variability than that given in our earlier report.

However, a second approach (described in Chapter 4 of our panel report*) has, in fact, resulted in a decrease in our uncertainty estimate. This approach involves fitting simple analytic expressions to the vertical distributions of the concentrations of trace species. Data on three species were used, the measured N_2O data, global ozone data, and the distribution of an inert tracer generated by a three-dimensional model. This method showed remarkable self-consistency among the three tracers used and agreed with the results for N_2O in the first method. It is felt that the uncertainty in the eddy-diffusion coefficient at a given altitude is about a factor of 2, although it is admitted that this uncertainty estimate is somewhat subjective. Fortunately, the prediction of ozone depletion from halocarbon injection is not too sensitive to the choice of eddy-diffusion coefficient. Slower transport would permit a greater buildup of the chlorine compounds (ClO_x) that destroy ozone but would also increase the concentration of nitrogen compounds (NO_x). Because of chemical coupling processes, the increased NO_x would, in turn, decrease the effect of the chlorine compounds.

We estimate an uncertainty in the projections due to the use of the 1-D method of characterizing transport to be a range of a factor of 2 within the 95 percent confidence level. This can be compared with the threefold range of our earlier report.

Other Uncertainties Inherent in the 1-D Model

We have seen that the 1-D model represents the vertical distribution of different chemicals averaged over the entire globe and over all seasons. Thus chemical reactions are represented as occurring between the average concentrations of each chemical species at a given altitude. In the real world the reactions occur between

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**Stratospheric Ozone Depletion by Halocarbons: Chemistry and Transport* (National Academy of Sciences, Washington, D.C., 1979).

chemicals having their instantaneous, local concentration. The global average of the products of these concentrations, which determine the chemical rates, is not necessarily the same as the product of their averages, which is used in 1-D models.

Moreover, there are feedback effects involving temperature changes resulting from ozone changes. A decrease in ozone due to halocarbons would result in a decrease in the stratospheric temperature that affects the rates of many of the chemical reactions. This temperature feedback is calculated to lower the predicted ozone reduction by 1.8 percent, for Case A at steady state.

The amount of water vapor in the stratosphere is believed to be governed mainly by the temperature of the tropical tropopause, the boundary between the tropical troposphere and the tropical stratosphere, and by stratospheric methane. Stratospheric temperature will probably decrease as a result of halocarbon injection. Tropospheric temperature, in contrast, will increase because of enhanced greenhouse effect caused by the halocarbons. The net effect is believed to be an increase in tropopause temperature that would permit more water to enter the stratosphere. Increased water content results in ozone decrease. This feedback effect is estimated to increase ozone depletion for Case A at steady state by 0.9 percent. Temperature changes will also affect the transport to some extent.

All these effects, the use of the 1-D approximation in treating the chemistry and the temperature feedback effects just mentioned, have their own uncertainties. We estimate that together they introduce an uncertainty in our projections of a range of a factor of 2.3 at the 95 percent confidence level.

VALIDATION OF THE 1-D MODELS

There has been considerable refinement in the 1-D models. All models include methods for treating the diurnal (day and night) changes in solar intensity. Some are also capable of calculating the temperature changes that occur if the composition of the atmosphere changes. The quality of the data used as inputs to the models has also improved as a result of more and better atmospheric measurements.

The validity of the models can be checked by comparing calculated concentrations of minor constituents against measurements, particularly the way these concentrations change with height. There are, however, severe limitations to these comparisons. The 1-D models can, of course, only provide globally averaged values of these height profiles for long-lived trace species. Although the number of measurements and their geographic coverage have both increased considerably, they are still far from providing true global averages. However, the comparison can be considered satisfactory for most substances within these limitations and the uncertainties of the measurements. There are, however, some notable exceptions. A number of the ClO measurements have given high values for the concentrations, which are totally inconsistent with the models and our understanding of the chlorine budget. There are also some other disturbing inconsistencies between models and measurements, such as the shapes of the vertical profiles of ClO, HCl, and HF. Some of these may be the result of horizontal transport, which is excluded in the concept of 1-D models. Some early calculations made with two-dimensional (2-D) models do appear to account for some of the discrepancies. Two-dimensional models are under active development by several groups and may well provide us with improved projections in the near future. One of the interesting results already achieved with these models is an indication that the ozone changes resulting from halocarbon releases will be greater at mid and high latitudes than in the tropics and that, at these higher latitudes, the changes are largest in late winter and smallest in late summer. Three-dimensional (3-D) models would, in principle, be the most realistic for making predictions, and attempts are being made to incorporate chemistry in existing 3-D, general-circulation models. But the cost and complexity make it unlikely that 3-D models will provide useful projections of ozone depletion in the near future. They are, however, making useful contributions in examining some of the feedback processes, and their continued development should be encouraged.

In summary, 1-D models have probably reached their maximum potential. Despite their limitations, we believe that they provide projections for ozone depletion that have validity within the stated uncertainty ranges.

OTHER EFFECTS

We have become increasingly aware of the fact that the atmosphere is a closely coupled system. Changes in the tropospheric chemistry cause changes in the stratospheric chemistry. Changes in the amounts of HO_x and NO_x in the stratosphere will affect the impact of changing the amount of ClO_x. It is therefore difficult to project accurately the effect of increased halocarbon release when the release of other man-made pollutants may also be increasing in an undetermined way.

A moderate increase in stratospheric NO_x resulting, for example, from increased use of nitrogen fertilizers, would reduce the effect of halocarbons on ozone due to the coupling between ClO_x and NO_x chemistry and would increase the ozone amount at lower altitudes.

The amount of carbon dioxide (CO_2) in our atmosphere is increasing rapidly as a result of the increased use of fossil fuels. It is probably also increasing because of the continuing removal of tropical rain forests, which are believed to play an important role in determining the CO_2 balance. An increase in CO_2 would warm the troposphere but cool the stratosphere. A decrease in stratospheric temperature would result in an increase in stratospheric ozone, thus offsetting to a small degree (less than 10 percent) the decrease caused by halocarbon release.

An even more complex set of reactions can occur as a result of increased anthropogenic release of carbon monoxide (CO). Increased CO decreases the amount of HO in the troposphere. A decrease in HO concentration would permit a larger fraction of certain halocarbons such as methyl chloride (from natural sources) and methyl chloroform and F-22 (from human sources) to reach the stratosphere and thereby decrease stratospheric ozone. At the same time, through a set of complex reactions, involving HO_x and NO_x, there is likely to be an increase in the amount of ozone in the troposphere so that the net change in total ozone due to changes in CO in uncertain.

Even if we had reasonable scenarios for the increase in these other pollutants our knowledge of tropospheric chemistry is still too incomplete to allow meaningful predictions to be made on the net ozone change they would produce. This is an additional reason for increased research efforts in tropospheric chemistry.

OZONE MONITORING AS AN EARLY WARNING SYSTEM

The uncertainties inherent in the use of atmospheric models have prompted the suggestion that monitoring the total amount of global ozone might provide a direct way of detecting whether ozone depletion due to human activity is indeed occurring and, if such change were detected, could provide the basis for implementing regulation against that activity.

We have seen that stopping halocarbon releases will not immediately result in ozone returning to its former level. There is a time delay between halocarbon release and ozone destruction; the maximum ozone decrease actually occurs some 15 years after all release has stopped. Therefore, to be effective, an "early warning system" must be capable of detecting changes due to human activity in time to prevent the eventual maximum ozone decrease being greater than acceptable levels.

Most of the ozone measurements are now made with Dobson instruments located at a number of ground-based stations. There are a number of problems involved in using the data from this Dobson network to provide total global ozone amounts and trends. There are short- and long-term natural variations in the amount of ozone above any given station due to seasonal and other factors, many of which are unknown. Our study shows that there is an inherent statistical error due to these variations that would limit the detection of a trend caused by human activity to at least 1.5 percent almost independent of the number of stations used for the analysis. In addition to these statistical errors, other long-term (5- to 100-year) changes may occur that could lead to misinterpretation. Moreover, Dobson instruments have long-term calibration and drift errors. Most of the Dobson stations are located on land; changes in meteorological patterns could move relatively high ozone amounts from sea to land or vice versa. Long-term changes in atmospheric aerosols, clouds, and temperature could also lead to incorrect interpretation as ozone trends. Finally, there could be long-term changes in ozone due, for example, to changes in solar flux and changes in atmospheric substances resulting from natural or human causes not directly related to CFM releases. We therefore conclude that it is unlikely that a Dobson network would, within the next decade, be able to identify a reduction in global ozone attributable to CFM releases of less than 4 to 5 percent. The model predicts that such an ozone change will occur by about 1995. Total cessation of CFM release at that point would result in a decrease in ozone of about 7 percent some 15 years later.

Model calculations have shown that the decrease in ozone concentration due to CFM release is twice as great at 40 km than is the decrease in total ozone. There are also reasons for believing that natural variability is smaller at that altitude. Monitoring ozone concentrations at this altitude should therefore provide a more sensitive "early warning system." This region of the stratosphere is best monitored by satellite. A number of satellites are currently measuring ozone by several techniques. The time period for which data are available is short, and some of the data still require verification. At the time of writing, the satellites do not provide a superior system for trend analysis to the Dobson network but should be able to do so in the near future.

CONCLUSIONS

Effects of CFM Releases

We find ourselves in agreement with the principal conclusion reached in our earlier report, viz., that it is inevitable that CFMs released into the atmosphere do destroy ozone. In fact the laboratory and atmospheric measurements, made in the interim between these two reports, have tended to strengthen this conclusion. *The value of the ozone depletion caused by continuing release of F-11 and F-12 at the 1977 (similar to 1973) rates obtained by our 1-D model calculations is 18.6 percent.* This can be compared with the most probable value of 7.5 percent of our previous report. The difference between these values is mainly the result of new, more reliable, measurements of the rate constants of several key chemical reactions.

Destruction of ozone by halocarbons also changes the temperature profile in the stratosphere, which, in turn, changes the rates at which a number of chemical reactions occur. The temperature change in the stratosphere and the temperature change in the troposphere resulting from the increased greenhouse effect due to the halocarbons also alter the amount of water vapor that reaches the stratosphere. This, in turn, changes the amount of ozone destruction. *These feedbacks were not considered quantitatively in our previous report but are evaluated in the present report. They result in a reduction of the most probable value of ozone reduction to 17.7 percent.* Although there is no compelling reason to believe that a "sink" exists that removes a significant portion of CFMs in the troposphere, we recognize that such a possibility exists. Removal by photodestruction in the presence of desert sand is one such possibility. *To make provision for possible tropospheric sinks, we have, somewhat arbitrarily, reduced the most probable value to 16.5 percent.*

An improved error analysis has been used to estimate the uncertainty range due to uncertainties in all the rate constants. At the 95 percent confidence level, this source of uncertainty amounts to a range of a factor of 4 and remains the largest source of uncertainty.

Somewhat more subjectively, we estimate the uncertainty due to the approximation used to represent transport to be a range of a factor of 1.9.

The combination of these two sources of error gives a total uncertainty of a range of a factor of 5, which can be compared with the range of a factor of 10 estimated for these two sources of errors in the previous report. This improvement of the uncertainty range reflects the improvements in both laboratory and atmospheric measurements.

We have also estimated the error due to the feedback effects mentioned above and made an even more subjective estimate of the uncertainty resulting from the approximation inherent in treating rates of chemical reactions by the average concentrations of the 1-D models. These sources of uncertainties are estimated to amount to a range of a factor of 2.3.

Combination of all these sources of error amounts to a range of a factor of 6. Thus our best estimate is that for continued CFM release at 1977 levels there is 1 chance in 40 that ozone depletion will be less than 5 percent and 1 chance in 40 that it will be greater than 28 percent.

There are two possible sources of errors, which, inherently, cannot be quantified. One is that some important chemical reaction has been overlooked. The other is that some systematic error exists in the chemistry, such as the existence of pressure dependence on the reaction rates, or that other product channels exist for some of the reactions. It is obviously impossible to estimate the unknown with any precision. Nevertheless our experience of the past has prompted us to hazard a rough estimate of the probability. Inclusion of this subjective estimate obviously broadens the uncertainty limits. For example, with steady CFM release at the 1977 level, there is a three out of four chance that the ozone depletion will reach a steady-state value between 10 to 23 percent without including the uncertainty estimate due to these unknown effects; inclusion of this estimate extends the range to 9 to 24 percent.

Release of Other Halocarbons

We have not attempted to evaluate the ozone depletion due to halocarbons that contain hydrogen, largely because our lack of knowledge of tropospheric chemistry introduces a large uncertainty in the fraction of these compounds that reach the stratosphere. However, if current trends in the rapidly increasing use of F-22 and methyl chloroform continue unabated, the release rates and atmospheric behavior of these compounds will require careful attention. However, the substitution of F-22 for F-11 and F-12 is beneficial, because, per molecule, F-22 releases four to ten times less chlorine to the stratosphere than do either F-11 or F-12.

2 NONHUMAN BIOLOGICAL EFFECTS

The studies of atmospheric chemistry outlined in earlier parts of this report find that several human activities indirectly diminish the amount of ozone in the stratosphere. Under particular assumptions about the future continuation of these activities, it is estimated that the ozone would ultimately be reduced by about 16 percent. Such a reduction would increase the amount of biologically damaging solar ultraviolet that reaches the surface of the earth by known amounts at each affected wavelength. (See Appendix D.) Our problem is to estimate the biological consequences of this increased UV radiation in terms that could guide decisions about the conduct of ozone-reducing activities.

The basic effects on nonhuman biological systems are not qualitatively different from those on human beings but lend themselves to a different kind of analysis. With people, where each individual is precious, injury to even small numbers over a long period of time may be intolerable. But most effects on the nonhuman biological world can be viewed as possible costs of lost agricultural production, diminished fishing yields, and disturbed nonagricultural ecosystems, to be weighed against the costs attending restriction of ozone-reducing activities. While the information required to make such estimates accurately is not yet available, such an approach can establish goals for investigative efforts. Less-tangible effects of possible ozone depletion on the environment, affecting the general quality of life, also have to be considered.

BIOLOGICAL RESPONSES TO ULTRAVIOLET RADIATION

The most critical part of a cell from the standpoint of damage by ultraviolet (UV) radiation is its genetic material: deoxyribonucleic acid, or DNA. The shortest wavelengths of solar radiation penetrating the earth's atmosphere, even at normal ozone levels, will produce photochemical damage in this genetic material, thus affecting its function (Setlow, 1966). Since it is DNA that carries the basic information for constructing a cell and controlling its growth and reproduction, such a malfunction is a serious matter.

All cells are inherently vulnerable to this type of UV-induced damage. However, the long history of organic evolution in cells exposed to solar radiation has led to a number of cellular mechanisms for the repair of such damage (Hanawalt and Setlow, 1975, for reviews with reference to other literature; Hanawalt *et al.*, 1978, for more recent findings). These mechanisms can be so effective that DNA damage may not predominate after exposure to normal solar UV intensities. However, at sufficiently high UV radiation levels repair systems do not keep pace with the damage created. It is not necessary to understand repair mechanisms in detail here, only to recognize their existence and effectiveness and some of their general characteristics.

The simplest mechanism, *photoreactivation*, or *photorepair*, is a precise photochemical reversal of the major UV damage to DNA through a light-dependent enzymatic reaction driven by longer solar wavelengths. The extent of this repair (and the accompanying decrease in cell injury and death) depends on general illumination levels during and after the primary solar UV exposure. Even subdued daylight can be effective. This mechanism acts against only one kind of DNA damage. A more intricate process, *excision repair,* removes damaged regions from a DNA strand by a kind of molecular surgery and rebuilds them using equivalent genetic information from corresponding undamaged regions on their companion strands in the double helix. This light-independent mechanism can correct a number of kinds of chemical and radiation injuries. Other mechanisms can patch together undamaged segments of partly replicated, damaged DNA to give an undamaged copy (much as a military unit in the field may use parts from several damaged vehicles to give a single functioning machine). Still another process permits the blockage of DNA replication caused by unrepaired damage to be bypassed. The latter mechanism may be "error prone" and thus lead to mistakes in the genetic information of viable progeny cells. Such genetic alterations, which are passed on to any descendants of the original cell, may constitute part of the mechanism of UV-induced carcinogenesis.

Because only absorbed energy can lead to photochemical changes, the effectiveness of UV radiation at different wavelengths in causing damage to cells (the *action spectrum*) depends on the absorption at these wavelengths by the material involved in the damaging photoreaction. [It further depends on the photochemical efficiency (or *quantum yield*) of the adsorbed energy, but the latter usually changes more slowly with wavelength than does the absorption.] This effectiveness pattern may further be modified by differential absorption in photochemically inactive substances in the organism, which filter the primary radiation before it reaches the critical site. Such filtering does not, however, change the general wavelength range in which the effective radiation lies.

The UV absorption per unit of DNA is small at wavelengths where stratospheric ozone does not influence solar-radiation intensity. In moving to shorter wavelengths, where ozone begins to cut off sunlight (i.e., below 320 nm), DNA absorption increases sharply. Although the greatest absorption occurs at wavelengths below ~290 nm, where sunlight at the earth's surface is extremely attenuated at present, it is appreciable at those wavelengths (290-320 nm, the so-called UV-B range) the intensities of which would change with stratospheric ozone thickness. Therefore, the amounts of DNA damage generated by sunlight would increase as ozone decreases.

Other, less-critical cellular materials may also undergo detrimental photochemical changes. Ribonucleic acid, or RNA, has an absorption spectrum similar to that of DNA, and photochemical injury to it usually shows a similar action spectrum [although damage to some transfer RNA species, containing the unusual base 4-thiouracil, is produced at longer wavelengths around 340 nm (Ramabhadran *et al.*, 1976)]. In the case of photoreactive proteins, the absorption of different active wavelengths, over the range where sunlight has appreciable intensity at the earth's surface, also roughly resembles that of DNA. Consequently, the damage stemming from photochemical changes in any of these three major cellular materials would have a similar action spectrum in the wavelength region of concern, and its incidence in sunlight would be increased by a decrease in stratospheric ozone. However, this would not necessarily be true for other photosensitive materials; the effectiveness of sunlight for causing the alteration of some of them might be essentially unchanged by ozone depletion. Also in the case of "sensitized" photoreactions (in which light absorbed by a natural or artificial small molecule in the cell causes it to carry out a damaging photoreaction with a major molecule, like a nucleic acid or protein) the action spectrum determined by the absorber could differ considerably from the DNA/protein type.

In general, the action spectra for cellular effects of UV radiation cannot be predicted with assurance but must be determined by explicit investigation. Where only a single photochemical process is involved, it is possible in principle to make this determination experimentally, one wavelength at a time, and thus to know accurately the relative biological effectiveness of radiation at each wavelength. The radiation intensity in each small wavelength region from a broadband source can be weighted by its effectiveness in inducing biological damage and then summed to yield a damaging ultraviolet (DUV) dose rate. This figure, multiplied by the exposure duration, then yields the DUV dose. However, if matters are more complicated, and more than one photochemical reaction is involved in the effect observed, the effectiveness of one wavelength might be altered by the intensity of illumination at others. The proper weighting function could then differ somewhat from an action spectrum determined one wavelength at a time. It is not easy to be sure when this situation might occur. Even though a DNA-like action spectrum is often a plausible possibility, demonstration of the correct weighting function is usually a laborious process. (See Appendix D for further details.)

UV-B injury to whole organisms stems from its damage to their constituent cells. Such damage is particularly harmful in plant buds and larval or embryonic structures, since cell death or injury at this stage of life can affect the subsequent development of an entire part of the organism. The production of altered somatic cells, with abnormal properties, like poorly controlled growth and division, contributes other problems, such as cancer in animals. Leftover unrepaired DNA damage is a plausible though not a certain cause of such effects, and where there is no other information, a DNA-like action spectrum might reasonably be surmised as a first guess.

Plant photosynthesis is partially inhibited by UV-B in a variety of species. Although the mechanism of this inhibition is not clear, it is unlikely that it results directly from absorption of UV-B radiation by nucleic acids, and a DNA-like action spectrum is less likely there. However, the action spectrum has not yet been adequately determined in intact plants.

Certain plant hormones controlling growth processes are also rendered ineffectual in their normal functions by sufficient UV-B absorption (Curry *et al.*, 1956; Lindoo *et al.*, 1979).

While most of the biological responses to UV-B radiation are considered harmful, an apparently beneficial effect occurs in the formation of vitamin D from 7-dehydrocholesterol in human skin. Since moderate sunlight exposure is normally sufficient for all vitamin D needs, there is no reason to believe that ozone depletion would provide any advantage here. There is also evidence to suggest that a key photosynthetic enzyme in plants might be activated by UV radiation (Daley *et al.*, 1978), but unequivocal evidence that UV can stimulate photosynthesis is wanting.

While there is no doubt that depletion of the ozone layer would lead to an increase in the short-wavelength ultraviolet radiation at the surface of the earth, or that high doses of this radiation are biologically harmful, the effects of a moderate increase in the natural doses delivered over a considerable period of time are much less clear. Moreover, all quantitative predictions are powerfully affected by the choice of weighting function for evaluating the relative effectiveness of different UV-B wavelengths. Inadequate knowledge of this function is one of the major reasons for uncertainty about the effects of ozone depletion.

Recognizing all the above uncertainties, Figure 2.1 indicates the increases in the annual DNA-damaging UV at 40° N latitude expected from possible ozone-layer reductions over the next century (assuming continued release of chlorofluorocarbons at the 1977 rates). A 7.5 percent ozone-layer reduction would, for example, lead to about a 19 percent increase in DNA-damaging UV, and a 16 percent reduction to about a 44 percent increase. (These values will be somewhat less at latitudes toward the equator and greater at higher latitudes.) The increase in DUV for a given decrease in ozone concentration is larger than the figure estimated in earlier reports, but this is hardly a significant change in the light of remaining uncertainties about the proper weighting function. The change arises from more recent knowledge of the solar intensity distribution at the shorter wavelengths, coupled with a presumably better action spectrum (Appendix C).

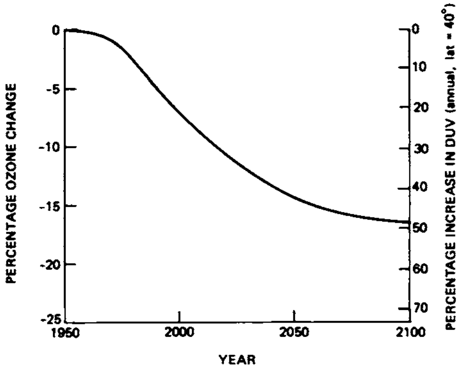

FIGURE 2.1 Percentage ozone change and corresponding percentage increase in DNA-damaging UV between 1950 and 2100. These are annual averages at 40° N latitude. These estimates are based on the analysis in this report, which assumes that the 1977 release rate of CFCs will continue indefinitely.

EXPERIMENTAL STUDIES

The existence and general nature of biological damage from solar UV-B is known from basic studies conducted first on simple microorganisms and later extended to higher forms of life. For the quantitative estimates desired here, further specific experiments are required to delineate both the magnitudes of the effects accompanying known UV-B exposures and the relevant action spectra. Only beginnings have been made in this direction.

Use of Natural Ozone Variations

One rather direct, epidemiological approach, which has proven useful in studies of human skin cancer, seems unworkable for estimating effects of ozone depletion on plants and animals. Both the average path length of solar radiation through the atmosphere and the ozone concentration decrease systematically with decreasing latitude. By observing skin-cancer incidence in human populations of similar racial makeup and life styles, but living at different latitudes, a useful estimate of one effect of ozone depletion is obtained rather directly. However, man is unique in the degree to which he controls his own intimate environment. Physiological stresses and nutrition are, for example, not very different for the modern populations of Norway and Australia, or of Minnesota and Texas. The lack of similar control capabilities in plants and animals means that other significant factors also change systematically with latitude. The latter will obscure whatever changes in productivity or competitive success within ecosystems might accompany solar UV-B variation. Even in agricultural systems, where optimal water and fertilizer are supplied, so many other uncontrolled factors still influence crop yields that comparisons between latitudes are vitiated. Matters are further complicated by the use of different genetic varieties of crop plants at different latitudes.

Another type of natural ozone variation offers an opportunity to set limits on the magnitude of ozone-depletion effects. These are cyclic variations, amounting to approximately 5 percent total amplitude at temperate latitudes, over a period of about a decade (Angell and Korshover, 1973). Weighted for DNA-damaging effectiveness, such ozone variations would produce roughly a 13 percent change in DUV. The common experience of temperate areas of the world (which have repeatedly been through such cycles) shows that changes of this magnitude do not produce any spectacular effects on plants or animals over the relatively few years of their duration. (Small effects would, of course, tend to be blurred by the ordinary variations in weather and other factors.) While there seems to have been no concerted effort at detecting effects due to these changes, it would seem safe to say that most organisms can reasonably accommodate decade-long oscillations in ozone concentration, of the order of one third of the 16 percent change expected from continued CFC release at current rates.

Long-term decrease in the average stratospheric ozone level would, of course, be superimposed on the existing natural fluctuations, and the lowest ozone concentrations in the course of these fluctuations would result in exposure of ecosystems to UV-B flux levels greater than any currently experienced.

Supplementation of UV-B with Lamps

Since ozone depletion could affect only a small portion of the total solar-UV spectrum at ground level, inquiries into the consequences of continued CFC release must involve those particular UV wavelengths. Little biological work was done in this part of the UV spectrum before the ozone concerns arose because it is less convenient for experimental work than shorter, more-effective wavelengths.

In the past few years, however, radiation in the critical spectral region has been applied to plants and animals, using special fluorescent "sunlamps" equipped with filters in both laboratory and open-field environments. These experiments have been useful in gaining qualitative information about the biological consequences of reduced ozone, even though several sources of possible error limit their value for quantitative prediction.

Experimental Limitations and Sources of Error

The measured spectral composition of radiation from the lamp sources is not the same as that of sunlight over the biologically effective wavelengths (Figure E.1, Appendix E). Consequently, in comparing its effects on plants and animals with those of natural sunlight, a weighting function based on the proper action spectrum must be applied to the spectral distributions of both sources. If the biological action spectra for UV radiation damage to plants and animals were known precisely, one might make an accurate comparison by this means and be able to predict the consequences of ozone depletion from the lamp experiments. However (as explained above and in Appendix D), the action spectra for most biological effects of UV-B radiation are not well known, and one must usually surmise their form approximately. This can introduce an uncertainty of as much as twofold in predicting the increased biological damage accompanying a 16 percent reduction in the ozone layer.

A second limitation is that it is both difficult and costly to irradiate large areas with these UV lamps, and the experiments have therefore usually been confined to small numbers of plants or animals, with a resultant increase in statistical uncertainty. Also they have usually been of limited duration, and although some have encompassed the life span of particular crop plants, the work generally does not permit prediction of longer-term effects on long-lived plants and animals. Nor can the effect of increased UV-B radiation on the competitive balance or population dynamics of wild species over considerable periods of time be taken into account.

The study of aquatic organisms is further complicated by the degree to which the UV radiation penetrates natural waters. In most such experiments it is feasible to measure only the radiation incident at the water surface. Transmission into the aquatic environment depends on many factors: water surface conditions, the angle of the sun, and the impurities (many of a biological origin) contained in the water, as well as depth below the surface. An accurate determination of how much radiation actually strikes the aquatic organisms in their natural locale is quite difficult, although recent calculations (Smith and Baker, 1979) provide a much better basis for analysis than was formerly available.

Measurement of the UV radiation itself introduces additional complications, which were especially troublesome in earlier experiments. While spectroradiometric measurements (that is, absolute measurements of the radiation per unit area and unit spectral bandpass at a sufficient number of representative wavelengths) have been made recently by most investigators, this was not done in most of the earlier studies. Instead, simpler dosimeters were utilized, such as the Robertson-Berger meter, which charterizes a broad waveband with respect to a weighting function that may not be biologically correct. The uncertainty introduced by meters of this kind is discussed in Appendix E.

Finally, the environmental conditions under which many of the experiments have been performed may in some cases have altered the sensitivity of plants and animals to UV-B radiation. For example, the UV sensitivity of plants appears to be as much as fourfold greater in the artificial illumination of plant environment growth chambers, or in greenhouses, than in the open-field environment, possibly because of the different level of photosynthetic illumination. Unfortunately, this means that the experiments providing the most completely controlled conditions (which should therefore allow more refined testing) are not by themselves able to evaluate the consequences of increased solar UV on plants. Also, in most experiments, plants and animals have been subjected to environmental conditions free from other stresses besides the UV radiation. Thus, the interaction of such other stresses with the UV-B has not yet been evaluated.

Although there are many potential sources of error that limit the conclusions that might be drawn, experiments with supplementary UV lamp irradiation provide the main source of information available to assess the potential effects of a reduced ozone layer on the nonhuman biological world.

SUMMARY OF FINDINGS

The major information available on UV sensitivity of organisms, which is helpful for evaluating the possible effects of ozone depletion, is reviewed in Appendix B. This information covers agricultural crops and land vegetation, domestic and wild animals, nonagricultural land ecosystems, and aquatic organisms and ecosystems. The information is summarized briefly here for reference.

With Regard to Agricultural Plants

1. Tests of more than 100 species or varieties of species in controlled environment growth chambers indicate that approximately 20 percent are sensitive to daily UV-B doses of the order of those delivered by Florida sunshine at present ozone levels, while 20 percent were resistant to doses four times greater than this, and the remaining 60 percent showed some intermediate sensitivity. These tests would indicate that a significant fraction of the present agricultural varieties are at present under UV stress and would suffer decreased production with a 16 percent ozone reduction.

2. However, 15 species and varieties tested in the open field appeared more UV resistant than plants grown in laboratory environmental growth chambers. Where it is possible to make comparisons of the same plants, the differences in resistance are on the order of fourfold. If this result turns out to be general, the higher sensitivity indicated in the growth chambers does not represent open-field behavior, and the expected consequences of ozone depletion become considerably less than those tests would indicate. Nevertheless, some species (sugar beets, tomatoes, mustard, corn) still appear to be affected--although the field experiments were necessarily less well controlled, and the results less clear-cut, than were the chamber studies.

3. The existence of relatively more resistant varieties of the same species offers the possibility of selecting plants better adapted to UV-B stress. Efforts could be made to combine the UV resistance trait with the other characteristics desired in these plants (high crop yields and resistance to certain diseases, for example) through systematic breeding. However, in much of the agriculture of undeveloped countries, introduction of new varieties would be difficult, and any emergence of more UV-resistant

varieties might have to depend on the slower process of natural selection after the ozone decrease had occurred.

With Regard to Domestic and Wild Animals

4. The very incomplete information suggests that the impact of ozone depletion on domestic and wild animals would not be large. An increase in conjunctival carcinoma (cancer eye) affecting some cattle breeds could be expected, but the fraction of cattle affected would be small.

With Regard to Nonagricultural Land Ecosystems

5. Perturbations of nonagricultural ecosystems could ultimately be as important as more direct effects on human health or human food supplies, but there is almost no information with which to assess the consequences of increased solar-UV radiation on such ecosystems. Because nonagricultural plants show about the same range of sensitivity as crop plants, reduced productivity of some forest and grazing-land plants might occur. However, change in the species composition of these systems seems a more likely response. Such a change would alter the character of the vegetation and might qualitatively change the products provided. However, UV sensitivities and their range of variation in wild species are known in so few cases, and the theoretical modeling of ecosystems is at present so primitive, that such changes cannot be predicted confidently.

The fact that ozone depletion would be a worldwide perturbation makes its consequences more worrisome than effects on simply a local environment. The presumed effectiveness of past evolutionary adaptation, which developed over millennia, and the human need for a stable framework in which to operate, argue that widespread changes, occurring rapidly compared with the usual evolutionary time scale, would be more likely to be harmful than helpful. Consequently, where a prospective man-made change cannot be proven unequivocally beneficial, it should be viewed with some suspicion.

With Regard to Aquatic Ecosystems

6. Experimental studies on over 60 aquatic microorganisms, protozoa, algae, and small invertebrates

indicate that most of them are sensitive to current water-surface levels of DUV radiation. Because they currently thrive in nature, attenuation of DUV by natural waters, especially in productive areas, may play an important role in their survival. (The degree of penetration of DUV into such waters is not well characterized.)

7. UV-B irradiation of young anchovies by means of lamps indicates that in surface waters this commercially important species lives normally near its UV tolerance limit. UV increases similar to those expected with a 16 percent ozone-layer reduction would, as a "*worst case*," kill over 50 percent of the anchovies in the top 10 m of the clearest ocean water or else would require them to substantially readjust their usual water depth to diminish UV exposure. Such avoidance, if it were to occur, would result in a substantial shift in ecological relationships.

Similar studies show that mackerel are more UV resistant than anchovies. The "worst case," corresponding to organisms exposed near the water surface, indicates essentially no losses.

Analogous studies of crab and shrimp larvae indicate that they too are near their DUV tolerance limit, considering their location in the water column (near surface) and their reproduction/development season (late winter, early spring). A 16 percent ozone-layer reduction might substantially shorten their reproductive/development season with unknown, but probably detrimental, consequences to productivity.

This very limited sampling gives little perspective on the UV sensitivity range of commercially important aquatic organisms. If we presume that such a small sample is roughly representative, an appreciable fraction of fishery species young would be vulnerable to the DUV levels expected with a 16 percent ozone reduction. They would either be injured or would have to seek deeper water, with unknown consequences on their subsequent prosperity.

8. The final conclusion depends on where the burden of proof is presumed to lie: one cannot convincingly demonstrate that a 16 percent ozone reduction would cause significant decrease in yields from agricultural crops or from nonagricultural land or aquatic ecosystems. Neither is it clear that a 16 percent ozone reduction would not entail important losses in these yields. The uncertainty stems partly from ignorance of the proper weighting function for different wavelengths (i.e., action spectrum) to be used in comparing solar and artificial source

irradiations but mostly from the limited scope, and in some cases incomplete design, of experiments and the lack of corroboration by independent investigators. These lacks, in turn, stem from the haste with which the research efforts have been put together and the absence of a systematic longer-range program to answer well-defined questions.

MAJOR RESEARCH ISSUES

Progress has been made on several questions since the last full CISC report was published in 1976, although less than could have been made, considering the need for information to evaluate the biological effects of DUV.

The recent advances are:

1. Larger numbers of agricultural plant varieties have been experimentally tested by radiation supplement for their sensitivity to UV-B. These tests have confirmed the wide variation in sensitivity among different plant varieties that was suspected earlier and have also indicated that the sensitivity depends on conditions of testing, but the tests leave the true sensitivity profile of the most important agricultural plants in doubt.
2. Tests with larval forms of several fishery species also indicate that wide variation in sensitivity occurs from one to the other and that some species have significant sensitivity. The very small numbers tested, and uncertainty about the likelihood of UV adaption or UV avoidance by the animals under natural conditions, as discussed in Appendix B, leaves the significance of these results still unclear.

The points stated above need further investigation by a sufficient number of independent investigators and need to be pursued over a sufficient time to overcome the spotty sampling, the possible statistical fluctuations in small experiments, and, in some cases, the deficiencies of experimental design that now limit interpretation of the results. The effect of environmental conditions on the UV sensitivity of plants needs to be explored.

Because the action spectra for different UV effects on most higher plant and animal species are at present not known, emphasis should be directed to their determination. The results are needed to establish the weighting functions for predicting consequences of ozone depletion.

For organisms of appreciable size this may require the establishment of several special facilities to deliver and measure controlled doses of monochromatic UV-B as a service to visiting experimenters.

Coupled with such action-spectrum determinations is a need for further study on the physiological and photobiological mechanisms by which UV-B radiation affects the growth and success of organisms. Such studies of mechanisms can help to reduce substantially the amount of purely empirical study (such as the blind screening of UV sensitivity in large numbers of species) that would otherwise be needed.

Direct solar UV-B simulation offers a possible means of reducing the errors associated with UV lamps of the type currently employed (see Experimental Studies section). Efforts should be directed toward the establishment and utilization of two further kinds of special facilities.

First, special high-intensity solar-simulating lamp systems, such as are currently used in aspects of the U.S. space program, could be adapted and employed for some studies on the effects of UV-B radiation on organisms. The expense of operating these facilities for considerable periods of time would limit their use to a few carefully selected projects. However, they offer the possibility of combining the stable environmental control in growth chambers with light intensities and wavelength distributions approaching those of natural sunlight and of settling the questions raised above for a few key cases.

Second, a special UV-B transmitting greenhouse facility should be established in a low-latitude location, at high elevation above sea level. Such a facility, of modest proportions, would be useful in validating the predictions based on results of experiments using normal UV lamps. Using filters, like sheets of cellulose acetate, to simulate the ozone absorption currently found at temperate latitudes, experimental variations in natural sunlight equivalent to those produced by specified ozone changes could be provided. Although such a facility would not in itself be practical for screening large numbers of plants or animals, it would be useful in relating the biological response to solar radiation, as it would occur in the event of ozone depletion, with the response to the UV lamp systems normally used for experimental tests. It would also be useful in testing the reliability of biological action spectra.

A study should be undertaken to evaluate the feasibility of crop breeding to develop more UV-resistant varieties.

Facilities and financial support as suggested here will, however, be fruitful only if they form part of a consistent and sustained research program. Time is required for the development and dissemination of good research procedures, where they involve complex methods like radiation dosimetry. Time is also required for wide review and criticism of published experiments and their interpretation, and to allow independent investigators to repeat or extend the studies. Whatever the level of funding decided on, it is important that the effort be continued steadily for the order of a decade. It is also important to provide a rigorous and broadly based system of peer review to evaluate both individual research projects before and after funding, as well as the state of knowledge and the research priorities that govern the overall effort. This system should be based on a suitable council and, where necessary, auxiliary committees, with rotating membership. They should be charged with reviewing and recommending research proposals, digesting the results of projects and other published literature, and formulating conclusions about the predictability of ozone-depletion consequences and the further research needs for improving such predictions. Short-term, hastily conceived and administered programs, even if endowed with ample funding, are of limited utility, and, however earnest the effort, represent inefficient expenditures of public funds.

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3 HUMAN HEALTH EFFECTS

The deleterious effect of UV-B on human beings is related to prolonged, deliberate, as well as inadvertent sunlight exposure, which leads to the development of nonmelanoma skin cancer and malignant melanoma of the skin.

The epidemiologic evidence for the causative role of damaging ultraviolet radiation (DUV) in the development of nonmelanoma skin cancer of the exposed areas (the face and neck) is indisputable and is based on (1) latitude dependence and (2) high incidence in a susceptible population. The susceptible population includes white, fair-skinned persons who sunburn easily and who receive prolonged occupational or recreational exposure. Furthermore, preliminary data suggest that there is a subset of this white population who have been shown to have a deficient DNA repair mechanism.

Although the causative role of DUV in the pathogenesis of malignant melanoma of the skin *is less firmly established, recent evidence supports the previous conclusions of CISC that the development of malignant melanoma of the skin in man is related to DUV exposure. Previous evidence established an inverse relation of latitude and melanoma incidence, a low incidence in more pigmented peoples, and an increased number of primary melanomas on the habitually exposed areas (face) and relatively exposed areas (trunk and legs of females), with infrequent numbers of primary melanomas on the rarely exposed areas. More recent evidence substantiates, with a larger number of patients (761), this same body distribution.*

It is now known that there is a strong cohort effect (persons who are age 30 now have a higher incidence of melanoma than persons the same age born 10 years earlier). This would suggest either a new causative agent (virus or chemical) or, more likely, a change in behavioral pattern *regarding recreational exposure (increased leisure time, less concealment, more vacations in sunny areas).*

Some current studies show that age-specific incidences are higher in persons who have resided longer in sunny areas. Those persons born in Israel had a higher incidence than persons residing in Israel but born in northern Europe.

There is a well-documented, recently reported dramatic increase in the incidence of primary melanoma in Norway and Sweden, presumably related to increased recreational exposure.

Recent analysis of British occupational mortality data shows that, for both employed males and their wives, there is a strong relationship between mortality and the socioeconomic class, with the highest incidence in teachers, businessmen, professionals, and higher-level administrators.

Expected increases in melanoma mortality based on current cohort data, without regard to changes in the ozone layer, show a rise from the currnt (1971-1975) rate of 26.3 per million for U.S. whites to 28.7 in 1976-1980 and 33.5 in 1981-1985. The effect of ozone depletion and increased UV-B would be added to this expected incidence.

GENERAL ASPECTS OF SUNLIGHT EXPOSURE

A few decades ago, the western world began to believe that exposure to the sun promotes health and the more exposure, the better. The dangers of general exposure came more clearly into view as sun-seeking habits became more and more widespread. Unfavorable effects range from transient sunburn through wrinkling and keratoses to skin cancer. We shall briefly describe these different effects below.

A single 15- to 20-min exposure of white skin to the sun in middle latitudes during summer can produce sunburn. This is an exposure to about 1.2×10^6 J/m^2. In perhaps more than two thirds of the white population, careful, repeated exposures will develop a protective tan. In the remainder, little or no protective tanning occurs, and the sensitivity continues, leading to repeated sunburn on exposure.

The longer-term effects of exposure to the sun involve the accumulated dose of exposure, usually over a period of years. Most wrinkling of the skin of the face and hands and all the warty thickenings of the skin called solar keratoses are associated with prolonged or intensive exposure to sunlight. While these effects are far from desirable, their seriousness is limited.

Against unfavorable effects of UV-B, ranging from sunburn to skin cancer, we must place in the balance one favorable effect of widespread importance:

- Conversion, in the skin, of 7-dehydrocholesterol to vitamin D_3, thus preventing rickets.

This action is important to all of us in the world but fortunately does not require large doses of UV-B.

Attention is often directed to sunlight-caused cataracts. Animal studies show that the action spectrum for single-exposure induction of lenticular cataract peaks at 290 to 370 nm, and the threshold dose is above the dose that causes symptomatic photokeratitis.[1,2] There is concern that prolonged and frequent exposures may cause gradual cumulative photochemical alterations in the lens leading to cataracts in the absence of corneal changes. The action spectrum for this effect may be at longer wavelengths,[3] and tryptophan may act as one chromophore. Epidemiologic data[4-7] suggest that solar ultraviolet may be causally related to some forms of senile cataracts, but much more information is needed to know the size and action spectrum of this threat. Ultraviolet-radiation effects on the lens have been summarized recently.[8]

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SKIN CANCER CAUSED BY EXPOSURE TO SUNLIGHT

The serious effects of exposure to the sun involve the development in some individuals of skin cancers of three major kinds:

- Basal-cell cancers (nonmelanoma) (Urbach *et al.*, 1972)
- Squamous-cell cancers (nonmelanoma) (Urbach *et al.*, 1972)
- Melanomas

Together the first two types of skin cancer add up to the most frequently detected cancer in man and have an increased incidence over the past decade (J. Scotto, NCI, personal communication).* They are also the most easily and most successfully treated human cancers. The quantitative extent to which agents other than UV exposure cause nonmelanoma skin cancer in the white population has not been established. It is, however, believed to be small. Some nonmelanoma skin cancer is caused by exposure to arsenic, pitch, and x rays, often in the course of work, sometimes following treatment of skin disorders. This latter group of tumors is found among patients of all degrees of skin pigmentation who happen to be exposed to these agents. In some less-developed countries, most nonmelanomas seem to arise in neglected wounds (Camien *et al.*, 1972; Fleming, 1975).

The report of the Climatic Impact Committee (1975, page 40) stated that "The available evidence indicates that the spectral sensitivity for skin cancer is similar to either the action spectrum for erythema production or the spectrum for damaging DNA. The two spectra are similar but not quite identical." (See Figure 3.1.) Nothing has been learned since to weaken this conclusion.

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*Status report on research programs at the National Cancer Institute relevant to the health effects of UV-B radiation.

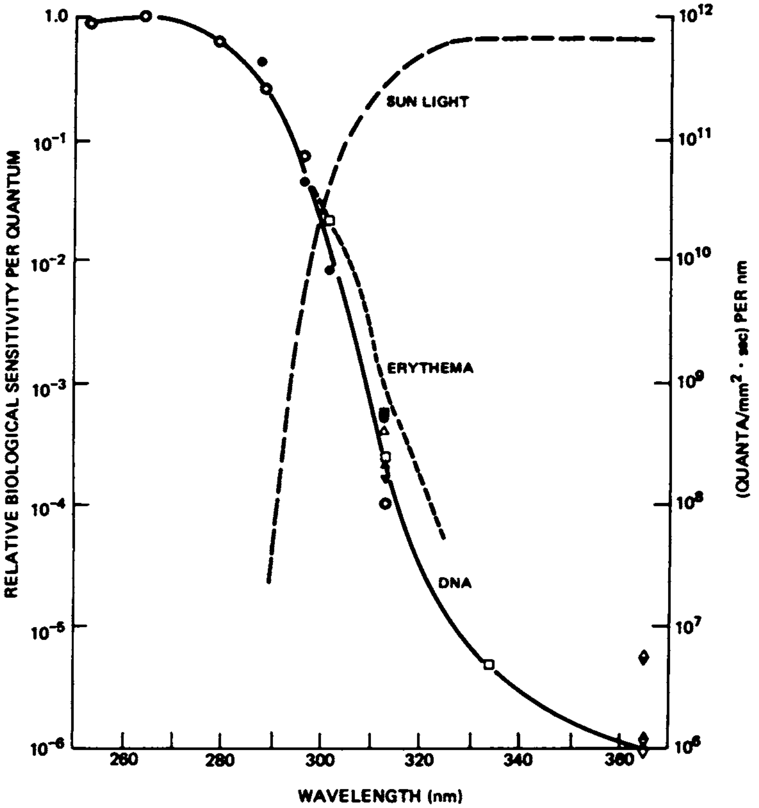

FIGURE 3.1 The solid curve represents the average action spectrum for affecting DNA (left ordinate). The dotted curve is the long-wavelength portion of a recent erythemal action spectrum normalized to the DNA spectrum at 297 nm. The sun's spectrum at the earth's surface (right ordinate) was calculated by Green for Gainesville, Florida, for 2.3 mm O_3 and a zenith angle of 25°.

Nonmelanoma skin cancer (which rarely leads to death) is at present a serious problem because of disfigurement (frequently minor and infrequently severe) and the significant economic burdens associated with its treatment.

Melanomas, the third mentioned cancer, are a serious life-threatening hazard and are more common than primary malignant brain tumors and twice as common as Hodgkin's lymphoma (Silverberg, 1979). The most recent figures, for the years 1965-1969 (Cutler *et al.*, 1975), show that only two thirds of new melanoma patients survived for five years, about the same fraction as for breast cancer.

The Climatic Impact Committee Report, 1975, page 41, stated that "Although the evidence associating uv-B with malignant melanomas is not so strong as for nonmelanoma, we believe that the only action spectra that we can prudently use for any quantitative estimate of the potential hazard arising from an increase in uv-B are those given in Figure 4 [repeated here as Figure 3.1]." The evidence collected since that report serves only to strengthen that conclusion, as we shall see below. Nevertheless, in developed countries, a fraction of malignant melanomas must come from other causes than ultraviolet radiation.

In terms of human health, then, our concern with the consequences of exposure to the sun

- Must be heavily concentrated on the production of melanomas (because they threaten life),
- Has to give rather serious attention to the production of other skin cancers (because they are very common and disfiguring),
- Should take other lesser and less well-known effects into account.

Skin cancers associated with solar-ultraviolet (UV) radiation, as diseases of the less-pigmented peoples, are thus a major concern in the United States, Europe, and Australia, and to emigrants from these regions to other parts of the world. (The as yet uncertain effects on plants, animals, and climate will be the main consequences of CFC release for the more pigmented peoples.)

GENERAL MECHANISM OF SOLAR SKIN-CANCER CAUSATION

It is generally accepted that changes in individual molecules of the body's DNA (deoxyribonucleic acid) are most often the initial key step in cell mutagenesis and cancer production. Accordingly, we expect that sunlight-induced cancers probably arise by the action of sunlight on DNA or compounds of analogous sensitivity to different wavelengths. This hypothesis is strongly supported by the increased skin cancer, including melanoma, observed in people who have DNA repair defects (xeroderma pigmentosum). Essentially no UV radiation of wavelengths less than 290 nm currently reaches the ground, and UV radiation of wavelengths above 320 nm (UV-A--320 to 400 nm) does not attack DNA seriously.

Accordingly, whenever sunlight stimulates skin cancer, DUV (defined as UV-B in the wavelength range 290-320 nm, weighted in accordance with its effectiveness in altering DNA) should be the portion of the UV that is effective. UV-B is generally believed to be the action spectrum for nonmelanoma; this has been confirmed in animals. Because the divisions between UV-C, UV-B, and UV-A are neither phenomenologically exact nor agreed on, for critical work one should define UV radiation in more rigorous spectroradiometric terms.

EVIDENCE FOR SUN-INDUCED SKIN CANCER

Beyond these general considerations, evidence for sunlight as a major or contributing cause of skin cancers takes five forms (see Appendix F):

- Differences in incidence or mortality with latitude, corresponding generally to differences in exposure;
- Locations of skin cancer on the body with regard to different degrees of exposure:
- Differences in the incidence or mortality between occupations corresponding to differences in amount or character of exposure;
- Changes in incidence or mortality over time, as plausibly related to changes in exposure behavior;
- Experimental confirmation in animals (so far only for nonmelanomas).

What patterns ought we to see in the first four of these forms of evidence if

1. Solar radiation alone causes skin cancer--operating through total accumulated dose--modulated mainly by individual differences in sensitivity and in total exposure?
2. The effect of solar radiation is not solely determined by total accumulated exposure, so that an individual's exposure experience may be important in other ways than total exposure? (Solar radiation may be one of several preconditions for skin cancer, and individual sensitivity will still be involved.)

Where total accumulated dose matters:

- We ought to see a general increase of incidence as the total DUV received increases. The geographic pattern of incidence can be expected to be modulated by differences in ethnic composition (northern Europeans, for example, appear to be more sensitive than southern Europeans) and by geographic differences in behavior patterns, so that an exact determination of incidence by the total amount of DUV reaching the ground is not to be expected (see Figure 3.2).

- The skin cancers should be heavily concentrated on the parts of the body most exposed to the sun (see Figure 3.4).
- Occupations such as farming and street repair, which involve greater accumulated exposures, should show higher incidences.
- Changes with time in incidence or mortality in a given locality will be slow, since the total exposure of those most exposed is only slowly changing, unless they start to take deliberate protective measures.

These are, of course, the characteristics shown by non-melanoma skin cancers (see Climatic Impact Committee, 1975, pages 36-40).

In the second case, where dependence on exposure is more complex:

- We should expect an increase of incidence and mortality similar to that in the first case, as latitude decreases, but somewhat more perturbed by other factors.
- The pattern of distribution of skin cancers over the body would have to have some sensible relation to exposure, not necessarily being greatest in the most-exposed regions but certainly avoiding the least-exposed regions.
- The dependence on occupation could be quite complex (since patterns of exposure could matter) so that certain occupations with lower total doses might show higher incidences or mortalities. (Occupation-related exposure to other preconditions might have a similar effect.)
- Substantial changes in incidence or mortality over time could occur, especially if there are large changes in exposure pattern, for example.

We shall see, in the remainder of this chapter, that what limited information we have about melanoma incidence and mortality is quite consistent with the second case, where dependence on exposure is more complex and other contributing factors may be involved.

With the foregoing factors in mind, what can we say about the overall strength of the evidence implicating

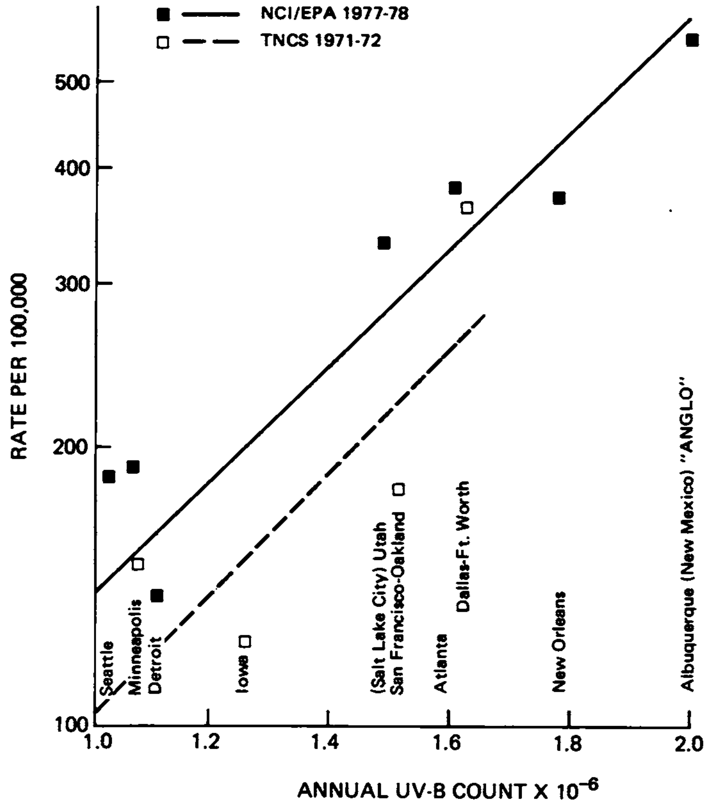

FIGURE 3.2 Nonmelanoma skin-cancer incidence in the United States by UV-B exposure. Adjusted for New Mexico "Anglos." Source: Scotto, J. and T. Fears, National Cancer Institute, preliminary data.

solar UV radiation in the causation of skin cancer and thus leading us to expect increased skin cancer when the amount of DUV reaching the ground increases?

For nonmelanomas, three kinds of evidence--latitude dependence (Figure 3.3), body location (Figure 3.4), and occupational differences--all combine to point closely to exposure to the sun as a prime cause and to increased incidence as a quite certain consequence of increased DUV.

The situation for melanomas is somewhat different. The latitude dependence appears well established (Figure 3.3). While melanomas are not heavily concentrated on the most-exposed regions of the body, they do appear to avoid the least-exposed regions, and differences in

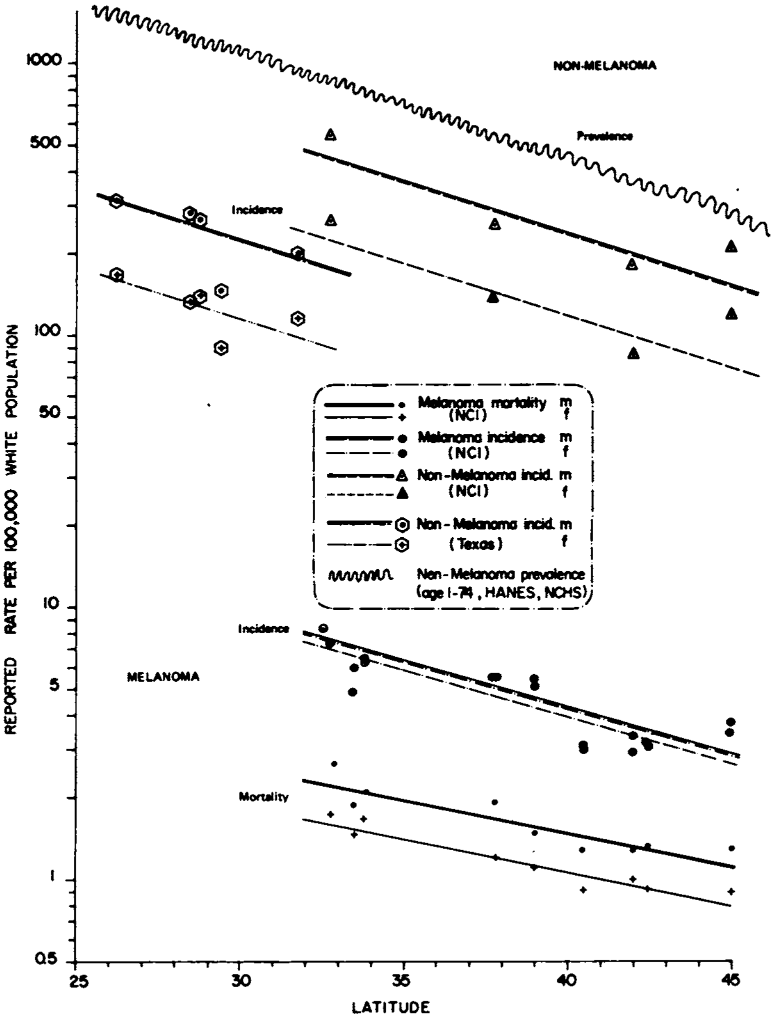

FIGURE 3.3 Reported skin-cancer rates among whites as a function of latitude. [Sources: melanoma mortality from Mason and McKay (1974), melanoma incidence from National Cancer Institute (1974), nonmelanoma skin-cancer incidence (NCI) from Scotto *et al.* (1974), nonmelanoma skin-cancer incidence (Texas) from Macdonald (1974), and prevalence of nonmelanoma skin cancer based on preliminary data from the Health and Nutrition Examination Survey of the National Center for Health Statistics (McDowell, 1974).]

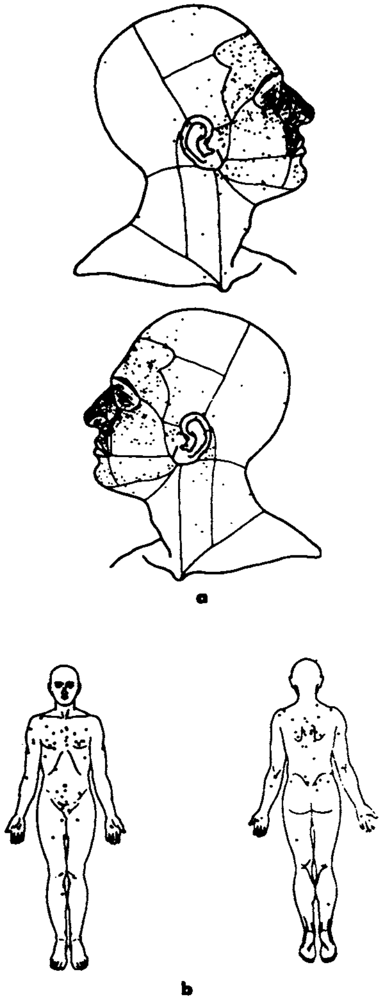

FIGURE 3.4 (a) Location of basal-cell skin cancers of the head and neck from Brodkin *et al.* (1969). Of 840 basal-cell skin cancers in the study, all but 74, or 8.8 percent, occurred on the head and neck. (b) Location of the 74 basal-cell skin cancers of the torso and extremities from Brodkin *et al.* (1969)

patterns of locations between sexes correspond to the differences in exposure to sunlight, for example, more melanomas on the legs of females and more melanomas on the scalps and ears of males (see Appendix G, Figure G.1). Occupational differences are fairly large, and, while they do not correspond to differences in total exposure they do seem to correspond to differences in patterns of exposure. Changes in mortality and incidence with time are large and can reasonably be associated with changes in exposure behavior.

This leaves us with a qualitatively well-established relation of solar UV radiation to nonmelanomas and a well-founded anticipation of increased nonmelanoma incidence if the DUV reaching the ground were to increase. The contribution of solar-UV radiation to the production of nonmelanoma skin cancers is thus a well-established health hazard of some magnitude and ought to be responded to accordingly.

Less firmly, but we believe persuasively, there is a large likelihood that solar-UV radiation contributes to the induction and/or development of melanomas and that an increase in the DUV reaching the ground will induce an increase in melanoma incidence and mortality. (Such an increase may be small compared with the increases now going on, presumably as a result of changes in patterns of exposure.)

If melanoma is induced by UV light, then increased exposure would be expected to result in earlier (on average) appearance of tumors. Just such a situation has been occurring with melanoma especially of the superficial spreading type for which a falling mean age of occurrence is being observed. This corresponds to higher rates found for younger individuals born in successively more recent decades (cohort effect).

If, as we believe, DUV plays an important role in many melanomas, the dose-response relation is complicated and is likely to involve many other variables.

To summarize, we believe that the relation of solar-UV radiation to melanoma ought to be taken as a likely health hazard of significant size and responded to accordingly.

Latitude Dependence

The dependence of both incidence and mortality on latitude has been clearly documented for melanoma skin cancer, as had dependence of incidence on latitude for nonmelanoma skin cancer (Climatic Impact Committee, 1975, pages 36-41, from which Figure 3.3 is reproduced). Higher exposure to DUV is reflected in more skin cancer.

Worldwide plots of latitude data support a latitude effect on both incidence and death rate, but some deviations exist in certain countries and at some locations within countries. These deviations may result from the effects of microclimate, difference in fraction of susceptible population, or differences in completeness of registry data collection. These factors make comparisons between countries difficult.

As we move toward the equator, the sun is more nearly overhead, and the total amount of sunlight increases at all wavelengths. This increase is significant for solar UV-B, whereas UV-A and visible light vary to a lesser degree. In the UV-B region, the controlling factor is absorption by ozone, which increases sharply toward the poles, both as we move under higher ozone amounts and as the sun departs from the zenith. Thus, the accumulated dose of UV-B--or, more particularly, of DUV--is likely to be greater for those living in lower latitudes.

The effect of more sun may well be partly compensated for by changes in living habits that lead to a smaller fraction of time spent in the strongest open sun or somewhat enhanced by a life style that increases the period of time spent in sunlight exposure. Measures of the extent of this compensating (or enhancing) effect do not seem to exist.

Body Location

Nonmelanoma Skin Cancer Most nonmelanoma skin cancers occur

- On light-skinned persons, particularly those who repeatedly burn with little or no tanning; albinos are especially susceptible (Okone, 1975);
- On exposed areas, especilaly on head, neck, arms, and hands (Figure 3.4).

While, as noted above, a small fraction of nonmelanoma skin cancers are clearly due to other causes, what we know about nonmelanoma skin cancer suggests that the accumulated DUV dose built up over years is the crucial factor.

Melanoma Skin Cancer Until recently, the relation of sunlight exposure to the development of melanoma has been difficult to interpret because the pattern of melanomas over the different parts of the body is different from the pattern of nonmelanoma skin cancer.

Incidence rates per unit area of skin, from Queensland, show significant excess melanomas on the generally or occasionally exposed sites of face, leg, neck, and arm in women and face, ear, neck, and back in men. They also show proportionally fewer tumors in parts of the body that are virtually never exposed (Elwood and Lee, 1975).

According to U.S. population-based incidence figures (Third National Cancer Survey, 1975), U.S. white men also have most melanomas on the face and head and trunk. Women have rates similar to men on the face and head and trunk but have higher rates on arm and leg. Limitation of available data, for example, to face and head combined, limits the extent to which these observations can be interpreted.

There are clear variations in incidence as latitude changes within the United States. Melanomas on totally exposed sites show the most, and those on rarely exposed sites the least, latitude dependence (Scotto *et al.*, 1976b). Melanomas of the partially exposed (relatively exposed) sites are increasing in incidence over time at a faster rate than those on sites that have always been totally exposed (Lee and Strickland, 1976).

Most melanomas seen in the Malignant Melanoma Group Cooperative Study involving four U.S. clinical centers (761 cases to date) occur on lightly covered or occasionally uncovered regions of the body (Sober *et al.*, in press). (See Appendix G, Figure G.1.) A similar pattern of location of primary melanoma has been reported by Braun Falco (1974). Very few have been seen (either in males or females) on the regions ordinarily covered by bathing suits. The difference between sites of occurrence on males and females is believed by these investigators to reflect different covering practices. Thus, women who usually wear dresses have many more melanomas on the potentially exposed part of the legs than do men who usually wear trousers. Men, who expose their trunks to the sun during recreation, have more melanomas on their chests than do women. It is highly probable that the few melanomas seen in areas virtually always covered by relatively heavy clothing are due to causes other than UV light.

Part of the argument about the role of UV radiation (presumably UV-B) in causing malignant melanoma has been the idea that basal- and squamous-cell tumors of the skin occur in exposed areas, while melanomas occur also in skin areas covered by clothing. To evaluate the UV penetration of different fabrics, Infante (R. Infante and F. Daniels, Jr., Cornell University, manuscript in preparation) measured the spectral transmittance of a number of different fabrics, some with a series of different moisture contents. A recording spectrophotometer with an integrating sphere was used so that forward-scattered and fluorescent light are included in the measurements.

At 300 nm a white handkerchief showed 32 percent transmittance in a single layer, 15 percent in a double layer, about 8 percent in three layers, and about 5 percent, 3 percent, and 2 percent transmittance with four, five, and six layers, respectively. A nurse's white nylon uniform transmitted about 4 percent at 300 nm, a white dress shirt about 21 percent, a white T-shirt about 21 percent, and a white sheet about 12 percent.

Women's modern nylon stockings transmit about 70 percent over a wide range of wavelengths since the transmittance measurement is essentially a measurement of an open network. For contrast, Infante obtained some silk stockings ca. 1904 from a costume agency and found in the calf region around 30 percent transmittance at 300 nm and in the thigh region about 10 percent transmittance. Thus UV effects could be expected to occur on regions covered by present-day clothing, especially the upper trunk.

There is a clinical impression that a majority of cases of melanoma are seen in younger middle- and upper-class males and females who pursue active outdoor recreational activities but spend their working hours indoors. A direct correlation has been demonstrated between death rate and socioeconomic level. As income and degree of education rise, melanoma death rate rises (J. A. H. Lee, University of Washington, preliminary data).

In current urbanized U.S. society, a general picture of most melanomas occurring on lightly clothed or "on-and-off" clothed body areas on persons not in outdoor occupations is quite compatible with some mechanism assocaited with the DNA sensitivity and with the observed latitude dependence of melanomas on these particular sites.

Magnus (1977) of Oslo reported on the analysis of 2541 melanoma patients observed in Norway during the period 1955-1974. The analysis supports an exogenic cause of melanoma in this series; Magnus concludes that exposure to sunlight is the important factor. Both the tripling of the incidence during this period and a steep increase during adolescence are attributed to increased recreational sunlight exposure as a result of (1) increasing leisure coincident with economic progress, industrialization, and urbanization and (2) change in clothing habits with a trend away from total concealment. Northern Norway (72° N latitude) has only one half the incidence rate of southern Norway (58° N latitude). This is attributed to greater exposure associated with the warmer climate and a higher DUV intensity in southern Norway. As in other reported series, there were striking differences in the anatomical site of the primary cancer in males and females --males showing higher incidence in the neck and trunk sites, and females showing a three times higher incidence on the lower limbs. It is to be noted that there was no change in incidence on face or feet during the entire observation period (1955-1974), supporting the hypothesis that change in behavioral pattern is an important factor in the striking increase in incidence of malignant melanoma since World War II.

Occupational Differences

Large-scale analyses of mortality from malignant melanoma were made by the Registrar General in England and Wales for the years 1949 to 1953 and 1959 to 1963 (Lee and Strickland, 1976). As might have been expected (because of higher total exposures to the sun), the rate of non-melanoma skin cancer was higher among unskilled and skilled than among professional and managerial-type workers. It was quite the opposite with malignant melanomas, for which the higher mortality was concentrated in younger professional and managerial workers, confirming the clinical impression mentioned above and quite consistent with a high efficacy of recreational exposure. The most recent British incidence figures confirm higher rates of melanoma in the middle class (*Registrar General's Statistical Review*, 1975).

For both employed males and their wives, there is a strong relationship between mortality* and socioeconomic class, defined in terms of occupation (Figures 3.5 and 3.6). Number V on the abscissa scales refers to unskilled workers, IV to semiskilled (including miners), IIIM to skilled manual workers (skilled craftsmen of all types), IIIN to skilled nonmanual workers, including clerks and salesmen, II to teachers and businessmen, for example, and I to professionals such as physicians, lawyers, and administrators. The classification lumps together some rather disparate groups, but in practice it is useful. The mortality gradient indicated in the figures is

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*The standardized mortality ratio simply compares the observed numbers of deaths with those expected for the age distribution of the occupation under study if the death rates from the particular disease in the whole population applied.

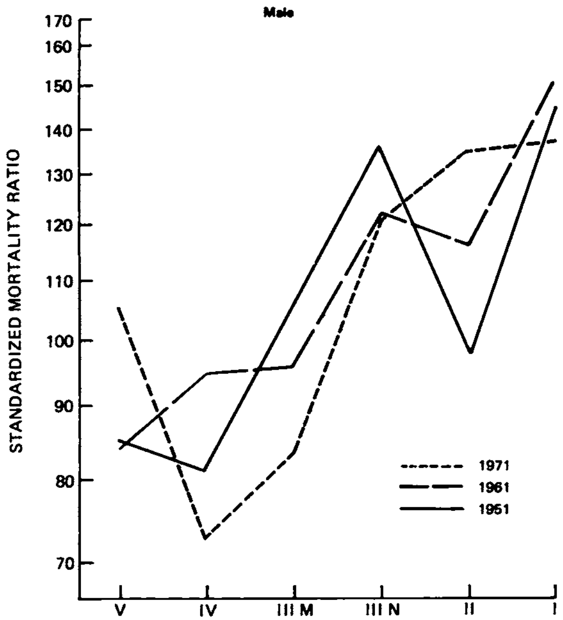

FIGURE 3.5 Standardized mortality ratios of mortality from malignant melanoma in three separate time periods by the Registrar General's socioeconomic classes: V, unskilled; IV, semiskilled; IIIM, skilled manual; IIIN, skilled nonmanual; II, intermediate; I, professional. Males, England and Wales.

particularly interesting, because the more sophisticated groups are most likely to get better medical services, i.e., they would be expected to seek treatment with smaller and early melanomas. Outdoor activity on a professional basis does little to disturb the controlling effect of prosperity or lack of it on the melanoma mortality (Table 3.1).

Changes with Time, Plausibly Related to Changes in Exposure Behavior

Some estimate of the marked impact of changes in lifestyle leading to increased exposure can be derived from careful studies of the experiences of young white women before and after the Second World War, a time when widespread changes in dress and behavior began to occur. From 1911 to 1940, approximately four out of each million United Kingdom

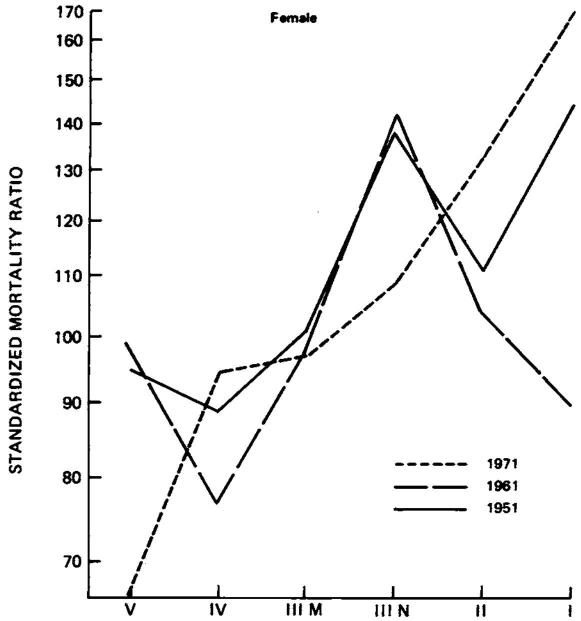

FIGURE 3.6 Standardized mortality ratios of mortality from malignant melanoma in three separate time periods by the Registrar General's socioeconomic classes: V, unskilled; IV, semiskilled; IIIM, skilled manual; IIIN, skilled nonmanual; II, intermediate; I, professional. Married women by social class of husband. England and Wales.

women aged 15-44 died each year from skin cancer. Since at these ages deaths from squamous-cell cancers are virtually unknown, and skin carcinomas are confined to males, these deaths can be assigned confidently to melanoma. In other words, in a country with limited sunlight, there was a background rate of almost four melanoma deaths per million among young women who did not deliberately expose themselves to sunlight.

In Connecticut, women of the same ages had a melanoma incidence rate of 12 per million between 1935 and 1939. Given low survival, this incidence rate compared well with the pre-1940 U.K. mortality. In both countries, there was a rapid post-1940 increase: to a mortality rate of 7.8 in the United Kingdom in 1966-1970 and an incidence rate of 48 in Connecticut in 1970-1972. The difference between twofold and fourfold increases, in the United Kingdom and Connecticut (see Table 3.2) is consistent with

TABLE 3.1 Standardized Mortality Ratios and (Numbers of Deaths) Malignant Melanoma 1959-1963 and 1970-1972, England and Wales by Selected Occupation Orders

Occupation Order	1961	1971
Farmers etc.[a]	90 (26)	103 (20)
Construction workers	95 (19)	67 (12)
Engineering trades	87 (68)	87 (64)
Warehousemen etc.	85 (17)	120 (21)
Clerical workers	122 (49)	112 (38)
Sales workers	123 (58)	127 (49)
Administrators etc.	115 (30)	121 (39)
Professional and technical	117 (49)	142 (72)

[a] Occupation Order I, farmers, foresters, fisherman (includes agricultural workers as well as employers): XV, Construction Workers; VII, engineering and allied trades workers not elsewhere classified; XX, warehousemen, storekeepers, packers, bottlers; XXI, clerical workers; XXII, sales workers; XXIV, administrators and managers: professional, technical workers, artists. Age range for all orders, 15-64.

TABLE 3.2 Skin Cancer in Females 15-44 Years of Age

United Kingdom[a]		Connecticut[b]	
Year	Mortality Rate (per Million)	Year	Melanoma Incidence Rate (per Million)
1931-1935	3.7	1935-1939	12
1936-1940	3.7	1965-1966	48
1966-1970	7.8	1976-1977	72

[a] Deaths from skin cancer are essentially all melanomas.
[b] Data from Connecticut Tumor Registry.

TABLE 3.3 Increases in Incidence and Mortality from Malignant Melanoma from Different Countries or States

			First Period of Observation		Second Period of Observation				
	Country or State	Sex	Time	Rate per 10^6	Time	Rate per 10^6	Total % Increase	No. of Years	Annual % Increase
Incidence	New York State	M	1941-1943	12.2	1967	33.7	176	25	7.0
		F	1941-1943	17.7	1967	29.3	65	25	2.6
Incidence	Norway	M	1955	17.9	1970	63.0	264	15	17.6
		F	1955	25.5	1970	68.4	195	15	13.0
Mortality	Norway	M	1956-1960	15.9	1966-1970	26.8	69	10	6.9
		F	1956-1960	13.3	1966-1970	18.1	36	10	3.6
Mortality	Canada	M	1951-1955	7.1	1966-1970	13.7	93	15	6.2
		F	1951-1955	5.9	1966-1970	12.2	107	15	7.1
Mortality	U.S.A.	Both	1950	9.3	1967	16.0	72	16	4.5
Mortality	U.K.	Both	1950	5.1	1967	10.2	100	16	6.3
Mortality	Australia	M	1931-1940	9.8	1961-1970	36.0	267	30	8.9
		F	1931-1940	7.6	1961-1970	24.9	227	30	7.8
Mortality	Denmark	M	1956-1960	15.9	1966-1969	23.7	49	10	4.9
		F	1956-1960	16.1	1966-1969	21.3	32	10	3.2
Mortality	Sweden	M	1956-1960	16.5	1966-1968	21.4	30	9	3.3
		F	1956-1960	10.6	1966-1968	14.8	40	9	4.4
Incidence	Connecticut	M	1935-1939	13.7	1965-1969	48.1	250	30	8.3
		F	1935-1939	10.5	1965-1969	47.7	354	30	11.8

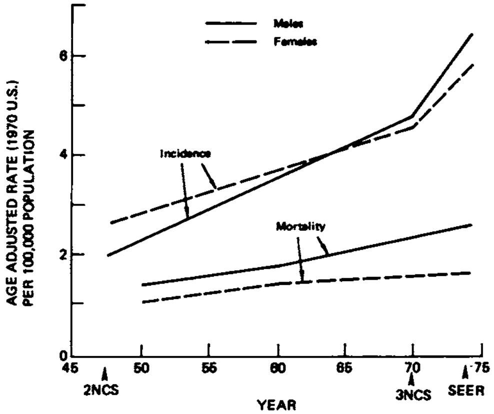

FIGURE 3.7 Trends in skin melanoma among whites in the United States. Source: J. Scotto and T. Fears, National Cancer Institute, preliminary data.

the different increases of sun exposure associated with different lifestyles.

Table 3.3 summarizes annual increases in melanoma incidence and mortality in different countries and compares two periods of observation, 1941 to 1960 and 1965 to 1970. Figure 3.7 depicts the trends in skin melanoma among whites in the United States.

Are Melanoma Incidence and Mortality Reasonably Consistent with a Major Role for Solar-Ultraviolet Radiation?

Earlier we set down the general outlines of the pattern of evidence to be expected if total UV dose were not the sole critical factor in solar-related cancers, i.e., UV-B might be a contributing but not sole cause, and pointed out that melanoma behavior fitted that pattern. We have now reviewed the details of the evidence concerning melanoma and ought to inquire further as to the reasonableness of a major role for solar-UV radiation in melanoma.

Ozone depletion will result not only in an increase in UV-B flux but also in a shift to shorter wavelengths that reach the earth. If the action spectrum of human skin cancers is similar to the action spectrum for DNA damage, a nonlinear and disproportionately higher increase of these tumors would be anticipated. *That is, a given percentage increase in solar UV-B should yield a higher* *percentage increase in melanoma. If the action spectrum for either form of human skin cancer is not sensitive in the shorter wavelengths, then a lesser effect of ozone depletion might occur.*

We do not intend to propose specific mechanisms--to do this would be inappropriate at this time. We do try to point out some classes of mechanisms that would allow varying degrees of covering (sometimes total, sometimes none or partial, the latter from semitransparent clothing) of some part of the body or intermittent recreational exposures to increase the incidence of melanoma.

We know that persons of intermediate sensitivity to sunburn develop sunburn after initial exposures, but eventually tan. On a generally exposed portion of the body, or when occupational exposure occurs daily throughout the year, the annual re-enhancement of protective tan would often take place in the spring when total daily doses are low. Thus no sunburn would be produced by the heavy doses of summer DUV--and it is possible that any melanoma-inducing effect of these doses would be greatly reduced. On a partially exposed portion of the body, or when recreational exposures are both intermittent and seasonably concentrated, the annual re-enhancement of tan would be likely to wait until summer, would result from much more intensive doses, and would involve considerable sunburn. Under such conditions, any melanoma-inducing effect would probably be stronger, although the total accumulated dose is less. Similar behavior could arise when clothing is sometimes completely UV-absorbing and sometimes not.

Experience with persons who sunburn and actual measurements of transmission of UV-B through clothing show that significant amounts of UV radiation do penetrate clothing. Other possibilities for development of melanoma underneath clothing would include combinations of UV exposure with other unknown factors, such as the presence of a susceptible melanocytic target or even mechanical friction. If photorepair occurs in man (it has not been demonstrated in mammals), it might provide an additional explanation for more response on incompletely covered regions.

What about the effects of changes in habits? What if people, particularly those most likely to be affected, those who sunburn easily and never tan, were to expose themselves less to the sun? How would we expect such changes to be reflected in melanoma rates and incidences? Suppose, for example, that total exposure (or total exposure in a given pattern) is the critical factor, and that incidence is proportional to total dose. Then, if all susceptibles reduce their accumulated exposure time (allowing for hour-to-hour and season-to-season changes in DUV) by 20 percent, thus receiving 80 percent of what might have been the dose, and if, at the same time, the ground-level DUV increases by perhaps 25 percent, the two changes could compensate, and the incidence of, and mortality from, melanomas would be the same. This might at first seem to say that the habit change took care of the increased DUV. Much more realistic, however, is the comment that if we could have kept the habit change, but not increased the DUV, we would have had perhaps 20 percent fewer melanomas.

Desirable habit changes, especially by susceptibles, can be very worthwhile, affecting general levels of incidence and mortality. But the losses from more DUV at ground level are likely to involve increases in skin cancern, by a fixed fraction, whatever base level we may be able to reach by habit change.

FORECASTING THE EFFECTS OF DUV INCREASE

If UV-B, which varies with latitude, is responsible for most melanomas diagnosed in the United States, the observed relationship between UV-B and the incidence or mortality of melanoma in the United States can be used to forecast the effects of change in DUV intensity on both melanoma incidence and mortality.

Statistical studies by the National Research Council's Panel to Review Statistics on Skin Cancer were given in the report of the Climatic Impact Committee (1975, pages 177-221). More recent studies include those by Scotto *et al.* (1976a) and Green *et al.* (1976). These studies have a number of characteristics in common, namely:

- The dependence of both number of cases (incidences) of either nonmelanoma or melanoma and number of melanoma deaths (mortality) on geographic location shows, generally, more cases and more deaths when the accumulated DUV at ground level is higher, which is roughly the same as being nearer to the equator.
- This effect cannot account for all the observed differences in incidence and mortality, something that is only to be expected in view of differences in susceptibility and habits of exposure.
- These analyses do not--and could not be expected to--provide independent and conclusive evidence that

increased DUV, rather than other variables that increase smoothly toward the equator, is the sole causative factor for either melanomas or nonmelanomas.

Scotto *et al.* (1976a) and Green *et al.* (1976) differ in their chosen dose-response relations, the one using logarithmic rates proportional to dose and the other rates proportional to dose to a power. Neither study makes allowance for varying behavior of cohorts, which may or may not be important to this aspect of their studies. Both studies, if taken at face value, would give percentage increases in nonmelanomas up to twice the percentage increase in DUV. These statistical studies serve as a basis for estimating the increased effect that results from more DUV but not as an aid in establishing cause and effect.

As noted earlier, it is our general understanding of agent-caused cancers and the direction rather than the amount or the detailed behavior of changes in incidence and mortality (as we move from poles to equator) that points to UV-B exposure as a cause of skin cancer. To say this does not deny the probable importance of other factors, acting either alone or in conjunction with DUV. The localization of melanoma in lightly or irregularly covered portions of the body may illustrate the importance of at least one factor that combines with DUV. Differences in melanoma mortality between places with similar accumulated DUV doses show the importance of other factors, some of which may act independently of DUV, although others seem likely to act concurrently with it.

Given our general information about human behavior as it depends on latitude, some will anticipate that the residents of lower latitudes accept a smaller fraction of the available DUV dose than do the residents in higher latitudes. Because of the greater amount of DUV available in lower latitudes, lower-latitude residents would otherwise receive much greater total doses. The difference in melanoma mortality--or in either nonmelanoma or melanoma incidence--between the two latitudes would then be less than that corresponding to the difference in the DUV availability, since behavior differences will partially compensate for the enhanced amount in lower latitudes. Others would expect residents in lower latitudes to accept a higher fraction of the available DUV, thus enhancing, rather than partially compensating for, the latitude difference in DUV intensity. There will also be some compensation owing to differences in the proportion of residents of higher sensitivity, reflecting ethnic composition.

What if the DUV reaching the ground increases, so that current intensities at higher latitudes now equal previous intensities at the lower latitudes? The accumulated intensities reaching the ground at the higher latitudes will build up, somewhat slowly, toward those previously occurring at the lower latitudes. The behavior patterns may also change slowly, but probably not to match previous patterns at the lower latitudes, since if only DUV is increased, the only cue for greater avoidance to the sun will be unchanged. The change in behavior will probably be slower than the change in accumulated intensity. Any changes in ethnic composition will be, relatively, still smaller and still slower.

As a result, the accumulated doses for individuals at the higher latitudes will rise toward values that may be slightly above those originally found at the lower latitudes. This will occur if behavioral compensation and ethnic composition compensation are less effective than they are now. Thus, if we use today's differences, found in statistical studies, between latitudes, both in DUV and skin-cancer rates, to forecast the eventual changes after 1, 2, or 3 decades in skin-cancer rates on the basis of an increase in DUV at one latitude, we will somewhat, but probably not greatly, underestimate the effects of the increased DUV. We may, also, if present behavior enhances latitude differences rather than partially compensating for them, somewhat overestimate these effects.

Melanoma incidence and death rates are rising rapidly in advance of any man-made disturbance of the ozone layer that has been measured. The increase in the death rate in the United States is somewhat over 3 percent per year (Lee *et al.*, 1979). The increase in the incidence rate will probably be higher, since prognosis is improving, and earlier diagnosis of tumors is being achieved. A reasonable estimate would be for an increase in the current rate of increase from 3 percent per year to 4 percent or 4.5 percent per year for perhaps five years, followed by a reversion to the current rate of 3 percent annual increase. Recent epidemiologic studies of the National Cancer Institute have concluded that the Biological Amplification Factor (fractional change in skin cancer incidence rates per fractional change in UV-B radiation) is $2\times$, rather than $1\times$ as previously presented.

$$\text{Biological Amplification Factor} = \frac{\text{Rate 2/Rate 1}}{\text{Flux 2/Flux 1}} = \frac{600/150}{2.0/1.0} = 2$$

Since the Physical Amplification Factor (fractional change in UV-B radiation per fractional change in ozone concentration) is -2, the overall amplification factor (fractional change in skin-cancer incidence rate per fractional change in ozone concentration) is -4, rather than -2 as previously presented.

An increase in melanoma deaths is likely, but not certain, to occur as a consequence of a continuing increase in the rate at which DUV is received at the ground. Such a melanoma increase, if it occurred, would be delayed, well beyond the onset of a DUV increase, while the accumulated dose builds up on individuals. A 16 percent ultimate reduction in ozone, with a consequent 44 percent ultimate increase in DUV accumulation rate, might be expected to cause a 64 percent increase in melanoma deaths, if most melanoma deaths are solar-UV radiation related.

Esimates of percentage increases in skin cancer for various amounts of ozone reduction were given in the report of the Climatic Impact Committee (1975) (Table 3.4). Table 3.5 is a summary of more recent results compiled by Scott and Straf (1977).

CURRENT PROGRAMS OF THE NCI TO RELATE UV-B TO THE INCIDENCE OF MELANOMA AND NONMELANOMA SKIN CANCER

New information is being accumulated by the Biometry Branch of the National Cancer Institute to reduce the degree of uncertainty in the estimates of the dose-response relationships with UV-B. There are new surveys to determine the incidence of melanoma and nonmelanoma, to estimate the effects of UV-B, other environmental factors, and host (genetic) susceptibility from a geographic and demographic cross section of the country. In addition to these environmental epidemologic surveys, the NCI in collaboration with other agencies (e.g., EPA, NOAA, and NASA) is monitoring UV-B measurements being collected at locations where population-based cancer registers are in effect. The preliminary results from NCI's earlier studies were consistent with the hypothesis that increased amount of UV-B may lead to increased incidence of skin cancer. Some of the preliminary results from the current (1978-1979) surveys are as follows:

1. Caucasians residing in areas of high insolation are at greater risk of developing skin cancer than those residing in areas of low insolation. The dose-response

TABLE 3.4 Estimated Percentage Increase in Skin Cancer Corresponding to a 10 Percent Ozone Reduction (about 20 Percent Increase in UV Flux) According to Several Assumptions of Cause of Cancer

Disease	Rate	Data Source	No. of Areas	Percentage Increase[b] in Skin Cancer Corresponsing to Ozone Reduction of			
				5%	10%	20%	50%
Minneapolis-St. Paul							
Skin cancer	Incidence	SNCS 1947-48	10	20 15 to 25	48 36 to 60	147 106 to 200	4453 2135 to 11321
Nonmelanoma skin cancer	Incidence	TNCS 1971-72	4	8 2 to 15	19 4 to 36	50 11 to 107	512 68 to 3661
Nonmelanoma and actinic keratosis (severe or moderate)	Prevalence	HANES 1971-72	35	15 6 to 24	34 13 to 60	94 34 to 198	1196 251 to 10936
Malignant melanoma	Incidence	TNCS 1969-71	9	10 8 to 11	22 18 to 26	61 48 to 75	947 609 to 1535
Malignant melanoma	Mortality	M & M	9 in TNCS	6 5 to 8	14 11 to 18	37 28 to 47	374 245 to 584
		1950-69	73 in HANES + TNCS	3 2 to 3	6 5 to 7	15 12 to 19	102 76 to 135
Dallas-Ft. Worth							
Skin cancer	Incidence	SNCS 1947-48	10	42 32 to 52	109 80 to 145	436 284 to 679	65446 21196 to 355164

Nonmelanoma skin cancer	Incidence	TNCS 1971-72	4	17 4 to 32	40 9 to 83	116 23 to 317	2137 159 to 77366
Nonmelanoma and actinic keratosis (severe or moderate)	Prevalence	HANES 1971-72	35	30 12 to 52	73 27 to 143	231 72 to 668	6620 773 to 334776
Malignant melanoma	Incidence	TNCS 1969-71	9	20 16 to 24	48 39 to 59	154 116 to 200	7033 3533 to 16708
Malignant melanoma	Mortality	M & M 1950-69	9 in TNCS	13 10 to 16	30 23 to 38	85 62 to 113	1585 849 to 3301
			73 in HANES + TNCS	6 4 to 7	13 10 to 15	32 25 to 40	263 182 to 379

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[a] See text for details of data and of effective wavelengths.

[b] See comment in text on lack of precision.

TABLE 3.5 Estimated Percentage Increase in Skin Cancer for Various Amounts of Ozone Reduction, Using Simple Model and Action Spectrum Midway between that of Erythema and of DNA Damage. Estimates and 90 Percent Confidence Intervals (Shown Underneath Estimate) of Percentage Increase in Skin-Cancer Mortality and Incidence among Whites in Two Localities[a]

					Estimated Increase (%)	
Disease	Rate	Data Source[a]	No. of Localities	Possible Causes[b]	Minn.-St. Paul	Dallas-Ft. Worth
Skin cancer	Incidence	SNCS; Auerbach (1961)	10	F only	62	142
				F,S,FS	34	38
Skin cancer + severe keratosis	Prevalence	HANES; A. J. McDowell (pers. comm.)	First 35	F only	44	95
				F,S,FS	42	90
Nonmelanoma	Incidence	TNCS; Scotto *et al.* (1976[a])	4	F only	35	79
	Mortality	Mason and McKay (1974)	9 in TNCS	F only	5^b	10^c
			75 in HANES	F only	3^b	5^c
				F,S,FS	5^b	-8^c
				F,K_1,K_2	3^b	5^c
				F,S,K_1,K_2,M,P	5^b	10^c
Melanoma	Incidence	TNCS; Cutler and Young (1975)	9	F only	30	66
	Mortality	Mason and McKay (1974)	9 in TNCS	F only	17	36
			75 in HANES	F only	8	16
				F,S,FS	9	-3^c
				F,K_1,K_2	9	17
				F,S,K_1,K_2,M,P	7	13

[a] HANES, Health and Nutrition Examination Survey; SNCS, Second National Cancer Survey; TNCS, Third National Cancer Survey.

[b] F, UV flux; S, solar radiation; K_1, microclimate very hot; K_2, microclimate hot and humid; M, access to melanoma clinics; P, differential pigmentation among whites.

[c] Confidence interval covers zero.

relationship of UV-B and skin cancer may be consistent with the earlier estimate of a biological amplification factor of 2, i.e., a unit increase in UV-B exposure would result in a twofold increase in skin cancer incidence.

2. The incidence of nonmelanoma skin cancer appears to be increasing.
3. The risk of skin cancer is greatest among fair-skinned Caucasians who have a limited ability to tan or who sunburn easily.

These studies are still in progress, and two more locations (San Diego and New Hampshire/Vermont) have now been added to the original sites (Seattle, San Francisco, Detroit, Atlanta, New Mexico, New Orleans, Utah, Minneapolis, St. Paul, and Bethesda).

The NCI is collecting skin melanoma incidence from the 10 locations in the United States. Earlier data analyses indicate that skin melanomas, which predominate in Caucasians, are related to UV-B exposure. A preliminary finding is that the incidence is increasing and that the rate of increase may be greater than expected from earlier surveys. The dose-response relationship between skin melanoma and UV-B appears to be more complicated than that observed for nonmelanomas of the skin.

New research studies are planned or in progress: (1) To ascertain the amount of UV-B reaching the skin by use of newly devised personal dosimeters; field studies are just beginning in contracts funded by EPA. (2) Skin Melanoma Case/Control Studies in new epidemological data bases will provide relevant causative information, e.g., hormone therapy, oral contraceptive usage, exposure to short-term high-intensity solar radiation, occupational-industrial-chemical exposures, and residence mobility. These surveys are planned in two southern and two northern locations.

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4 CLIMATIC IMPACT OF STRATOSPHERIC CHANGE

Chlorofluoromethanes released into the atmosphere remain in the lower region, the troposphere, for many years and absorb radiation from the sun and also reradiated energy from the earth. The effect is a slight warming of the troposphere and a resultant warming of the earth's surface. This is known as the direct or greenhouse effect. Eventually the CFMs rise to the stratosphere, where they participate in the depletion of ozone. This process results in a cooling of the stratosphere, but the effect on surface temperature is small and its sign is in doubt.

This chapter describes the mechanisms that produce the climatic changes noted above and also estimates their magnitudes.

CLIMATE AND CLIMATE CHANGE

Climate is defined for purposes of this report by the statistical properties of weather over a portion of the earth or the whole earth. Climate may refer to any atmospheric level but usually refers to conditions near the surface of the earth. Although climate properly extends to measures of variability (such as ranges and standard deviations), we will concentrate here on averages (arithmetic means).

If we wish to study climatic change, we may look at differences between climatic averages based on two or more successive time intervals of observations. A portion of such differences will be due to the statistical uncertainty of averages taken over limited periods. Madden (NCAR, personal communication) has recently shown that a change between successive nonoverlapping 20-year averages of surface temperature at 60° N must exceed 0.4°C to be statistically significant (that is, to have a probability of less than 5 percent of arising from pure chance). Thus, climate differences must be larger than a certain minimum to be judged "real." To find the limiting differences is a purely statistical problem and has been attacked in different ways.

But after "real" climatic changes have been detected, the question must be answered whether they are human-induced or might have occurred through other causes. It is useful to study historical records of climate to try to understand the characteristics of past climate changes --when people's activities almost certainly had negligible effect. Only if observed changes significantly exceed normally expected changes can we be reasonably certain that human-induced changes have occurred.

Climatic changes have occurred principally over three broad ranges of time scales: hundreds to tens of millions of years, hundred to tens of thousands of years, and hundreds to tens of years. The longest of these scales is probably associated with continental drift and with associated changes in the distribution of land and sea. A noticeable part of the changes at the middle scale is associated in part with predictable changes in the earth-sun geometry. But the reasons for climatic variations on the century scale are unknown and certainly unpredictable.

For example, global average temperature *is believed to have increased* at the rate of about a degree per century from 1880 to about 1940. It has since decreased at about the same rate. Local changes, especially at high latitudes, have been much larger.

Fluctuations on even smaller scales have been of considerable interest. But here, the confusion between "weather" and climate is particularly serious. In order to identify human-induced climate changes in the next century or so, they must be significantly larger than changes expected naturally. But anticipated man-made changes, at least in the next half century or so, are of the same order of magnitude as "natural" changes. Therefore it would take considerable time to be sure about man-made climate changes by observation. The alternative is to predict such changes by physical models.

CLIMATE MODELING

Physical models of the state of the atmosphere rely on numerical solutions of the basic meteorological equations. Most models refer to the atmosphere with its actual composition. But models have also been produced of atmospheres with altered composition. The most complex and realistic models are called GCMs (originally for general circulation models, but they alter also for global climate models). These models are three dimensional. The models are based on solutions of the seven basic equations of meteorology: the gas law, the first law of thermodynamics, the equations of continuity for air and moisture, and the three components of acceleration of Newton's second law. They are solved in small time steps (about 10 minutes) for the seven variables, pressure, temperature, density, moisture, and the three velocity components, subject to suitable boundary conditions. Of course, the earth's surface is a most complex boundary and has to be greatly simplified because of the limited resolution *of the models*. Typically, the horizontal distance between grid points is of the order 500 km, and, in the vertical, there may be 2 to 50 levels.

With proper heat sources and sinks, the models *have* reproduced many of the features of the real atmosphere, such as the general temperature distribution, the circulation, and statistical properties of weather. But because of the noise produced by the weather, the models, just as the real atmosphere, exhibited changes of averages from year to year. But as long as solar radiation, the composition, and the boundary conditions were held constant, these variations in the model were truly statistical.

In more recent GCM's, it was not necessary to begin integrations from an isothermal atmosphere. Integration time can be saved by beginning with a more realistic approximation of the real atmosphere. Even so, the computer time for simulation of much more than a year at 10-minute time steps for each of many grid points is formidable.

GCM's are by no means perfect. Clouds are simulated imperfectly, so is the interaction between air and sea. Scales smoothed out in the model affect the large-scale motion in a manner not modeled perfectly.

Climatic models have also been devised in two or one space dimensions. *Such models save computer time and also permit better insight into the physical processes.* But such models are limited by the difficulty of simulating horizontal transport. It is not at all clear whether models in less than three space dimensions are even qualitatively reliable. However, for certain changes in imposed conditions such as a doubling of CO_2 or a change in solar constant, the 1-D and 2-D models agree, within 25 percent, with the GCM results with regard to computed change in surface temperature.

GCM's can be reconstructed with altered boundary conditions or atmospheric composition. If ozone changes are to be considered, an eighth equation for continuity of ozone has to be added. If the CO_2 content is changed, infrared radiation fluxes are changed. Generally, the altered radiation budgets can be treated well, but, because of the imperfect description of feedbacks involving ocean or clouds, the response of the atmosphere is less certain. Further, any changes in the GCM model climate from its original state to its altered state must exceed significantly the statistical "noise" of the model climate. But, when considering man-made influences, the models have this advantage over the real atmosphere: changes due to changed composition or other features have to exceed *only* the statistical noise--not natural climate changes due to mostly unknown causes.

THE CO_2 PROBLEM

At present, the most serious man-made impact on climate in the next few centuries is believed to be produced by the increasing concentration of CO_2 in the atmosphere, as a result of burning fossil fuels. Global CO_2 content has been measured since at least 1948 when a monitoring program was first established. Reliable observations are available only since 1958. There has been an increase of about 50 percent of the amount of CO_2 released into the atmosphere by combustion of fossil fuels. Presumably, most of the other 50 percent has been taken up by the ocean. The mechanism for this uptake has been clarified quite recently. Whether changes in the biosphere contributed to the increase in CO_2 is not clear. Although this report deals with potential effects of ozone on changes of climate, we will use potential CO_2 effects, which are comparatively well understood, as a yardstick.

Figure 4.1 shows two alternative scenarios for the increase of CO_2 in the next century. One scenario continues with the present increase of burning of fossil fuels, about 4.3 percent per year, multiplied by the fraction of carbon expected to remain in the atmosphere. The other assumes some controls, limiting the growth to 2 percent till 2025, followed by a symmetrical decrease thereafter. It is seen that, by the year 2050, the CO_2 content may easily double, perhaps even triple.

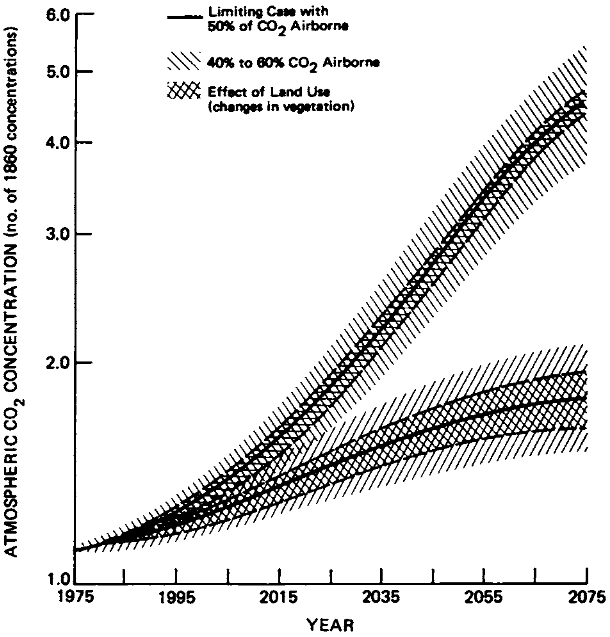

FIGURE 4.1 Projected atmospheric CO_2 concentrations and possible changes in the average surface temperature (after Baes *et al.*, 1976).

Carbon dioxide is nearly transparent to most solar radiation in the visible region of the spectrum, where much of the sun's radiation is concentrated, but it has several strong absorption bands in the infrared, centered near 15 μm. Increasing the CO_2 content in the atmosphere will increase the atmospheric IR opacity with a consequent enhancement in the atmospheric greenhouse effect, which leads to a warming of the surface and troposphere. At the same time, the stratosphere will cool because of the increase in CO_2 IR emission.

Many quantitative models of the probable effect of CO_2 change on climate have been made; Figure 4.1 shows the range of increases of global mean surface temperature. In particular, the best estimate for global average surface temperature change for doubling CO_2 is $3^{\circ}C$ with considerable uncertainty due to the difficulties of atmospheric modeling. In polar regions, however, the temperature increase is likely to be twice as large, in part because of the amplification of the CO_2 warming by ice-albedo feedback. When the atmosphere warms as a result of any cause, ice melts; this reduces the ground's reflective power (albedo); more sunlight is absorbed, and the temperature is increased further.

Since polar regions warm more rapidly than tropical regions, horizontal temperature gradients will decrease, leading to reduced winds. At the tropical tropopause, the temperature should increase by 2-3°C, leading to increased water-vapor concentration in the stratosphere. In the middle stratosphere (30 km) the average cooling is expected to be 5°C (see Manabe and Wetherald, 1975). In addition to temperature changes, increase of CO_2 should also change global regimes of other meteorological variables, e.g., wind and precipitation.

The statistical characteristics of natural climatic variations over decades are not well known, and it appears that the temperature changes due to increased CO_2 will not be detectable as such before the year 2000.

DIRECT EFFECTS OF CFMs ON CLIMATE

The climatic effects of an increase in the atmospheric concentration of CFMs are twofold: (1) An increase of CFMs can perturb the climate directly by enhancing the atmospheric opacity in the 8-12 μm wavelength region and thereby contribute to the atmospheric greenhouse effect. (2) An increase of CFMs can also perturb the climate indirectly by altering the ozone amount or distribution, which will then affect the radiation balance.

Surface Warming

Subsequent to the original publication by Ramanathan (1975) about CFM greenhouse effects, three publications, namely, those of Wang *et al.* (1976), Reck and Fry (1978), and Boyer (1979), have presented one-dimensional model estimates for the global warming due to an increase in CFMs. All but one of these estimates, namely, that of Wang *et al.*, agree within 10 percent of Ramanathan's estimates. Wang *et al.*'s estimate for the surface warming is smaller than Ramanathan's values by about 40 percent. Roughly half of the difference appears to be due to differences in treatment of radiative effects of CFMs; more detailed explanations are available from Ramanathan (1978).

Boyer (1979) has estimated the CFM warming with a Budyko-Sellers type energy balance climate model. This model computes surface temperature change as a function of latitude.

Boyer obtained warming rates about twice as large as those estimated previously by 1-D radiative-convective models. For a uniform mixing ratio of 0.7 ppb of F-11 and 1.9 ppb of F-12, Boyer estimates a global warming of 0.9°C compared with the 1-D model estimate of 0.42°C reported in the CISC (1976) report. He ascribed this change to the ice-albedo feedback mechanism. The approximate doubling of the global warming, i.e., from 0.42 to 0.9°C due to ice-albedo feedback, seems to be a significant overestimation in view of recent studies by Lian and Cess (1977) as well as Manabe and Wetherald's GCM experiments, which suggest that ice-albedo feedback amplifies global warming by a factor of about 1.25. Thus a figure of about 0.5 to 0.55°C for 0.7 ppb of F-11 and 1.9 ppb of F-12 seems indicated.

Temperature Changes above the Surface

A recent study by Dickinson *et al.* (1978) provides the only 3-D model estimates for the direct effects of CFMs. These investigators used the GCM of the National Center for Atmospheric Research. They estimated the response of the GCM climate due to the direct radiative effects of 10 ppb of CFMs and then scaled their results down to CFM concentrations inferred for indefinite continuation of 1975 CFM emission rates. However, Dickinson *et al.*'s GCM results cannot be used to infer CFM-induced surface temperature changes because the model prescribes changes in ocean surface temperatures (for the simulations with CFMs) in addition to prescribing ocean surface temperatures (for the simulations without CFMs).

The GCM results revealed an important aspect of the problem that was not brought out by the earlier 1-D model studies. They indicated that maximum warming due to CFM IR radiative heating occurs near the equatorial tropopause region. This maximum in warming is due to a corresponding maximum in the vertical distribution of CFM radiative heating. The tropical tropopause warming is estimated to be about 2.5°C, which exceeds the surface warming by more than a factor of 2. This effect is potentially important because the cold equatorial tropopause temperature is believed to be the most important factor that limits the water vapor that can enter the stratosphere from the troposphere. If this hypothesis is correct, a 2.5°C warming of the tropical tropopause may increase stratospheric water vapor concentration by as much as 60 percent. A 60 percent uniform increase in stratospheric H_2O can have appreciable effects on ozone chemistry. In addition, the increased stratospheric H_2O through its IR greenhouse effect can amplify the surface warming caused by CFM IR radiative effects.

CLIMATE CHANGES DUE TO OZONE CHANGES

Alterations in atmospheric ozone concentrations can influence the climate in two ways: (1) Ozone contributes to the atmospheric greenhouse effect in the 8-12 μm region and in addition absorbs solar radiation. Hence ozone perturbations can perturb the IR- and solar-radiation fluxes absorbed by the climate system. (2) Changes in stratospheric temperatures caused by ozone perturbations may be transmitted to the troposphere by radiation and dynamical coupling mechanisms.

Tropopause and Stratospheric Temperature Changes

Mahlman *et al.* (1978) describe a GCM experiment that examines the climatic effects of ozone reduction. Mahlman *et al.*'s GCM has 40 vertical levels extending from the ground to about 80 km. Because of this fine vertical resolution, the model is particularly suited to studying ozone effects on stratosphere-mesosphere climate. The model, however, is not designed for examining surface temperature changes, since, like the NCAR GCM used by Dickinson *et al.* for examining CFM effects, the model prescribes ocean surface temperatures.

Mahlman *et al.* estimate the response of the GCM to a 50 percent uniform reduction (from the ground to 80 km) in ozone. The model predicts significant temperature changes in the stratosphere and mesosphere with negligible changes in the lower troposphere. The stratopause (i.e., the 50-60 km region) cools by 23°C and the tropopause cools by about 12°C. Mahlman *et al.*'s calculations cannot be used directly to assess the temperature effects of ozone reductions resulting from CFM injection since the ozone reduction profile due to CFM injection (as predicted by 1-D models) has considerable vertical structure as opposed to the uniform reduction assumed in Mahlman *et al.*'s experiments. For the CFM injection, maximum O_3 reduction occurs above 30 km, and O_3 reduction at the tropopause levels is a factor of 2 to 3 smaller than that above 30 km. Such a vertical distribution of O_3 reduction would minimize the tropopause cooling, since large O_3 reduction in the upper stratosphere would allow more solar radiation to be absorbed at the tropopause level.

Radiative equilibrium calculations by Ramanathan and Dickinson (1979) indicate that temperature decrease at the tropical tropopause due to ozone reduction is about 1-2°C. Note that this is counteracted by direct CFM warming! The net effect is of uncertain sign but is more likely to be warming than cooling.

Surface-Temperature Changes

As to effects of ozone changes on surface temperatures, Ramanathan and Dickinson (1979) have modified the conclusions of earlier CISC reports somewhat. These authors examined how ozone changes alter the radiative energy budget of the earth-troposphere system. They computed the perturbations to tropospheric radiative heating as a function of latitude and season, but their model calculations ignore the feedback effects of additional radiative heating and consequent changes in dynamical processes in the stratosphere.

The most significant aspect of their calculations is that it illustrates the limitations of earlier 1-D model calculations. The earlier 1-D model studies showed that reductions of ozone have two competing effects on the surface-troposphere radiative heating:

1. More solar visible and UV radiation is transmitted through the stratosphere, contributing to warming below.
2. The stratosphere cools, so that less IR radiation is emitted downward, contributing to cooling below.

The two effects are of opposite sign and the same order of magnitude. Ramanathan and Dickinson's detailed analysis confirmed this conclusion but showed that with changed ozone amounts additional solar heating is largely deposited near the surface, whereas additional IR cooling is largely deposited near the upper troposphere. If, as might be the case in higher latitudes, the surface and troposphere are not coupled strongly by vertical mixing processes, such a heating distribution would simultaneously cause warming of the surface and lower-troposphere (~0.3 km) and upper-troposphere cooling. Furthermore, the magnitude of the surface warming in higher latitudes would also depend on the amount of horizontal coupling between low and high latitudes involving meridional transport of energy in the atmosphere and in the oceans. Hence the ozone-climate problem is considerably more complicated than envisioned earlier in 1-D models. The 1-D models assume an extremely efficient coupling between the surface and atmosphere both in the vertical and in the meridional directions, a poor assumption in midlatitude to high-latitude regions.

Ramanathan and Dickinson adopted the ozone reduction profile as computed by 1-D photochemical models for continued injection of CFMs at 1975 emission rates indefinitely into the future (the total column reduction is 19 percent) and obtained a hemispherical mean surface-troposphere radiative flux decrease of about 0.1 W m^{-2} (watts per square meter). This net decrease results from a flux increase to the surface of about 0.4 W m^{-2} (sum of solar flux increase and a relatively smaller decrease in downward emitted IR flux caused by decreased tropospheric O_3) and a decrease of IR flux to the troposphere (primarily to the upper troposphere) of about 0.5 W m^{-2}. As mentioned earlier, whether the net decrease, of 0.1 W m^{-2}, would cool or warm the surface depends strongly on the efficiency of surface-atmosphere coupling processes. Furthermore, since the next flux change is determined by a small difference between two relatively large competing effects, possible errors of about ±50 percent in each of the two flux perturbations mentioned above can change even the sign of the net effect from a maximum decrease in the net flux, to the surface-troposphere system of about -0.5 W m^{-2} to a maximum increase of about 0.3 W m^{-2}. Hence, the change in net radiative flux to the surface-troposphere system, due to the 19 percent steady-state O_3 reduction caused by CFM injections at 1975 rates, is estimated as

$$\Delta q(\Delta O_3) = -0.1 \pm 0.4 \text{ W m}^{-2}$$

The sources of errors considered, in arriving at the ±0.4 W m^{-2} uncertainty limits, are (a) errors in model calculations arising from neglect of dynamical feedback processes in the stratosphere and from radiation model errors; (b) uncertainty in the net change caused by either a lack of coupling or an extremely efficient vertical coupling between surface-temperature system; and (c) errors in vertical distribution of O_3 computed by 1-D photochemical models. For example, if the 19 percent O_3 reduction were distributed uniformly from ground to stratosphere because of effects of circulation not allowed for explicitly in the 1-D photochemical models, the change in net radiative flux would be -0.25 W m^{-2} instead of the -0.1 W m^{-2} quoted above.

Troposphere-Stratosphere Dynamical Coupling

The troposphere and stratosphere are dynamically coupled by propagating planetary-scale waves. The planetary scale waves are longitudinal pressure perturbations with associated wind and temperature perturbations. These perturbations, generated within the troposphere, exist in a wide range of spatial and temporal scales. The energy of waves on planetary scales (i.e., those with wavelengths of the order of 5000 to 10,000 km) propagates upward into the stratosphere. However, the vertical and latitudinal temperature gradients within the stratosphere modulate this upward energy propagation. These temperature gradients can be altered significantly by ozone perturbations, as shown by the studies of Mahlman *et al.* (1978), among several others.

Bates (1977), using a simplified dynamical model, concluded that changes in stratospheric temperature gradients can (by altering the upward propagation of wave energy) produce substantial changes in poleward transport of heat within the troposphere.

However, more sophisticated dynamical models such as that of Mahlman *et al.* (1978) have not exhibited the strong sensitivity of tropospheric circulation to stratospheric changes as inferred from Bates' simple model. Hence we do not expect any important changes in surface climate as a result of the large changes likely in the stratosphere.

COMPARISON OF NET TEMPERATURE CHANGES DUE TO CFMs and CO_2

We present below our current best estimates of various climatic effects of CFM increase. Furthermore, in order to put the CFM effects in better perspective, we compare the CFM effects with the climatic effects of CO_2 increases that are expected in the next 75 years.

The future concentrations of CFMs that are used in our estimates are adopted from Chang's 1-D photochemical model calculations, as reported by the CISC Panel on Chemistry and Transport. Chang considers several scenarios for future CFM emissions. For our purposes here, we assume that the 1976 CFM emission rates are continued indefinitely into the future.

With respect to future increases in CO_2 concentrations, we adopt the projections as reported in the Department of Energy report by Baes *et al.* (1976). The scenarios used by these authors were described above (Figure 4.1).

We have adopted future CO_2 mixing ratios that are a linear average of CO_2 concentrations predicted by the two scenarios. Table 4.1 shows the adopted values for the time history for the ground-level mixing ratios of CFMs and CO_2 and for the change in O_3 due to CFMs increase. The O_3 change is assumed to be linearly proportional to change in CFMs.

Table 4.2 compares expected temperature changes between 1975 and 2050 due to changes of the CFMs and CO_2, based on the scenarios described in Table 4.1.

The uncertainty limits were determined in two steps. First error limits in expected changes of the radiation fluxes were estimated. These are typically only of the order of 10 percent of the changes of the fluxes themselves. An exception is the change in the *net* flux due to change in ozone, because the change is a difference of two fluxes of opposite sign and about the same magnitude. In this case, the uncertainty is far larger than the net

TABLE 4.1 Adopted Model for Ground-Level Mixing Ratios of CFMs and CO_2 and for Percent Change in Total O_3 column as a Function of Time

	CFM Mixing Ratios (ppb)		Column O_3 Change[a]	CO_2 Mixing Ratios
Year	F-11	F-12	%	(ppm)
Early 1900	0	0	0	290
1975	0.1	0.17	2.4	330
2000	0.34	0.53	7.7	413
2050	0.6	1	14	660
∞	0.68	1.46	19	Not known

[a] Note that these changes are slightly larger than those suggested earlier in this report. But the effect of this difference on the conclusions is not important.

TABLE 4.2 Expected Global Surface Warming (in °C) by 2050

	CFM	CO_2
Mean	0.15	2.0
Range	0-0.6	0.9-4.7

flux itself. The error is so large, in fact, that the net warming due to the combination of direct and indirect CFM action has an uncertainty equal to the expected mean.

Given the change in radiation fluxes, we calculate the changes in temperature by atmospheric models. The simplest is based on the assumption of radiative equilibrium. This assumption yielded the smallest temperature changes in Table 4.2. The highest values are based on more complex models, allowing for various kinds of feedback. It turns out that all feedbacks considered so far are positive. One such positive feedback, the ice-albedo feedback, we have discussed already.

Another positive feedback comes about as follows. If radiation produces warming, evaporation is increased. Water vapor is added to the atmosphere. Now, water vapor is a good absorber of IR radiation but transmits sunlight reasonably well. Thus, increased water vapor means an increased greenhouse effect, hence a warmer surface air temperature.

The largest temperature changes in Table 4.2 were obtained by assuming that positive feedbacks increase the radiation-equilibrium temperatures by a factor of about 3.5

Table 4.2 shows that the warming due to the actions of the CFMs is expected to be an order of magnitude smaller than that expected from the increased CO_2. If the CFM emission is continued at its 1976 level, we will have about 10 percent less time to deal with the CO_2 problem than we will have without the CFMs.

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III

Alternatives for the Control of Chlorofluorocarbon Emissions and Options for Their Implementation

INTRODUCTION

This portion of the report, prepared by the Committee on Alternatives for the Reduction of Chlorofluorocarbon Emissions (CARCE), covers three areas:

1. The need for international cooperation in controlling CFC emissions;
2. The feasibility, costs, and impacts of various technological alternatives for reducing CFC emissions; and
3. Regulatory and socioeconomic considerations bearing on U.S. governmental actions to further reduce domestic CFC emissions.

The chlorofluorocarbons in widespread industrial use today have achieved that status primarily because of their unique chemical characteristics. Since they do not react chemically with other substances, they are easily handled and are suitable for use in a variety of processes and equipment. However, this chemical inertness, which makes them so ideal for many purposes, also makes them difficult to recapture and destroy and is thus responsible for the "ozone problem."

The most commonly used CFCs* are F-11, F-12, and F-113,

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*The numbering system used here is that used by DuPont in identifying the CFCs that it manufactures under the tradename Freon. Add 90 to the number, and the resulting three digits give, in order, the number of carbon, hydrogen, and fluorine atoms in a molecule of CFC; there are as many chlorine atoms as needed to fill out the carbon valence of 4. Thus F-11 contains 1 carbon, no hydrogen, 1 fluorine, and 3 chlorines; F-113 contains 2 carbons, no hydrogen, 3 fluorines, and 3 chlorines; F-22 contains with F-22 of importance in certain air-conditioning applications. These substances are virtually hazard-free in use--they are of low toxicity and are neither flammable, carcinogenic, nor teratogenic. These characteristics do not apply to all CFCs, and indeed some are toxic and/or flammable, while others have not been fully tested. Some are relatively inexpensive to produce, while others are either costly to manufacture or are not commercially producible today. Table III.1, taken primarily from a recent DuPont report, lists some of the commonly used CFCs and some possible alternatives and gives some of the more important characteristics of each that determine their suitability for specific applications.

CFCs are used worldwide. U.S. action to ban the use of CFCs in nonessential aerosol sprays reduced U.S. emissions from roughly half of the world total to about a third. Further reduction in U.S. emissions, in the absence of coordinated actions by other countries, will have a proportionately smaller global impact. As noted below, only in a few other countries (Canada, The Netherlands, Sweden, and West Germany) and in the European Economic Community have CFC-restricting measures been adopted or proposed; these have either just gone into effect or will do so in the next few years.

THE DATA BASE

The CFC threat to stratospheric ozone has been a source of concern for less than a decade. From a regulatory point of view, attention initially focused on what was deemed to be the prime "first target" for reduction in use of CFCs--nonessential use as aerosol spray propellants--and within the United States regulations banning such use went into final effect early in 1979. The study here reported deals with potential alternatives for the control of CFC emissions across the broad range of major remaining uses.

When attention turned to other uses of CFCs, it became apparent that basic information was not available in many

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1 carbon, 1 hydrogen, 2 fluorines, and 1 chlorine. CFMs (chlorofluoromethanes) are those CFCs containing only one carbon atom per molecule. A modification of this numbering scheme is used to designate azeotropes (mixtures of two or more CFCs that boil and condense like a single substance), e.g., F-500, F-502.

TABLE III.1 Properties of Some of the Commonly Used Chlorofluorocarbons and Some Possible Substitute CFCs[a]

Fluorocarbon Number and Formula		Boiling Point °F	Vapor Pressure at 70°F, PSIA	Percent Chlorine by Weight	Manufacturing Process	Flammability	Toxicology
11	CCl_3F	75	13	77%	Yes	No	Low
12	CCl_2F_2	-22	85	59%	Yes	No	Low
113	CCl_2FCClF_2	118	6	57%	Yes	No	Low
114	$CClF_2CClF_2$	39	28	42%	Yes	No	Low
21	$CHCl_2F$	48	23	69%	Yes	No	Toxic
22	$CHClF_2$	-41	136	41%	Yes	No	Mutagenic
31	CH_2ClF	16	46	52%	Not commercial	Yes	Toxic
32	$CH_2F_2{}^2$	-61	221	0	Not commercial	Yes	Low
123	$CHCl_2CF_3$	82	11	46%	No	No	Low
124	$CHClFCF_3$	12	49	26%	No	No	Low
125	$CHF_2CF_3{}^b$	-55	179	0	No	No	Not known
132b	$CH_2ClCClF_2$	116	5	53%	No	No	Incomplete
133a	CH_2ClCF_3	45	25	30%	Not commercial in United States	No	Embryotoxic
134a	$CH_2FCF_3{}^b$	-16	86	0	No	No	Incomplete
141b	CH_3CCl_2F	90	10^c	61%	Yes, developmental	Yes	Mutagenic
142b	CH_3CClF_2	14	44	35%	Yes	Yes	Mutagenic
143a	$CH_3CF_3{}^b$	-54	180^c	0	Not commercial	Yes	Incomplete
152a	$CH_3CHF_2{}^b$	-13	77	0	Yes	Yes	Low

[a] Taken primarily from DuPont (1978), page VII-C-8; percent chlorine by weight added.

[b] Contains no chlorine.

[c] Estimated.

areas, including the uses made of CFCs, the emissions resulting from each use, the points in the CFC cycle--production, incorporation in another product, normal use, servicing, and disposal--at which emissions occur, and the changes in this picture that might be expected over the next few decades. To fill this gap, EPA contracted with the Rand Corporation to construct emission profiles for the most important domestic CFC uses, to make projections of future growth, and to identify potential methods for reducing emissions in each use area. Rand in turn subcontracted with International Research and Technology Corporation to conduct the portion of that study pertaining to air conditioning and refrigeration.

The Rand study has been carried out in parallel with our examination of control options and, as this report is written, is not yet complete. EPA has made Rand's preliminary estimates available to us, and we have used them in conducting our study. Because the Rand study has not yet been completed, new information not available to us may cause some discrepancies between statements in this report and those that will appear in the final Rand report. We caution the reader and user of our conclusions that this is an area in which the information base is still deficient and is growing rapidly. Other sources of information--including industrial companies, trade associations, and research institutes--used by CARCE in preparing Part III of this report are listed in Appendix L.

The data on CFC production, use, and emissions that we have used in our study are drawn primarily from four sources: The Rand study, two submissions by the DuPont Company to EPA (DuPont, 1978; 1979), the worldwide data on CFC production and sales reported to the Chemical Manufacturers Association (formerly the Manufacturing Chemists Association) (MCA, 1978), and a study of the use of fluorocarbons in the countries belonging to the Organization for Economic Cooperation and Development (OECD, 1978).

These sources are not all mutually consistent. Some treat only the fully halogenated CFCs* or only the two

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*The fully halogenated CFCs are those that contain only carbon, chlorine, and fluorine. Fully halogenated CFCs do not break down in the troposphere, so that whatever amount is emitted to the atmosphere ultimately reaches the stratosphere. Hydrogen-containing CFCs are those in which atoms of hydrogen replace one or more of the chlorine or fluorine atoms. These CFCs do break down, in differing degrees, in the troposphere, and only a portion of the amount emitted ultimately reaches the stratosphere.

most commonly used of these, F-11 and F-12. Other sources include the hydrogen-containing CFCs or only the most commonly used of these, F-22. The hydrogen-containing CFCs are generally considered less effective as ozone depleters because only a portion of the amount emitted reaches the stratosphere. What is significant for ozone depletion is the amount of chlorine injected into the stratosphere, not the amount of CFC. Of the more commonly used fully halogenated CFCs, F-11 is 77 percent chlorine by weight, while F-114 is only 42 percent chlorine.

An important concept that has emerged from the Rand study is the role of the CFC "bank"--i.e., the quantity of CFC "stored" in products now in use (primarily as refrigerants in air conditioners, refrigerators, and freezers and as material trapped in the cells of rigid urethane foams used as insulation in building walls and in the walls of refrigerators and freezers), which will ultimately be released when the product is disposed of and will thus contribute to emissions many years hence. Even if regulations are imposed now that restrict such uses of CFCs, the "bank" will continue to contribute to global CFC emissions for years to come. In examining CFC uses, it is therefore important to distinguish between "prompt" emissions at the point of use and "delayed" emissions from the "bank."

It is also important to distinguish between CFC production (or sales), use, and emissions. CFC-induced ozone depletion occurs when CFCs reach the stratosphere. Essentially all fully halogenated CFCs emitted (and about 20-50 percent of the hydrogen-containing CFCs emitted) ultimately reach the stratosphere, although they may not do so until many decades after the time of emission. Since CFCs are virtually indestructable in normal use, all CFCs used are ultimately emitted; however, in some uses emission takes place immediately, while in others the CFC is stored in the "bank" and is not emitted until years later. For a given year, production, sales, and usage are virtually equivalent but "emission" is somewhat less, as part of the year's production will not be emitted until many years later. There is also a contribution to that year's emissions from production in earlier years; but because CFC usage has been growing rapidly, the deferred emissions (the banked CFCs) also continue to grow. Another useful concept is that of "life cycle emissions"--the total amount of CFC emissions that will occur during the life of a product, say an air conditioner, manufactured this year. This includes the prompt emissions associated with testing and filling during manufacture, the emissions that occur as a

TABLE III.2 Major Domestic Nonaerosol Applications and Emissions of Fully Halogenated Chlorofluorocarbons[a]

Application	Primary CFCs Used	Estimated Annual Domestic Emissions in Millions of Pounds[b]	
		1976-1977[c]	1990
Refrigerants			
Mobile air conditioning	F-12	83	129
Chillers[d]	F-11, F-12, F-114, F-500[e,f]	15	20
Retail-food-store refrigeration	F-12, F-502[g,h]	13	16
Household refrigerators and freezers[i]	F-12	6	8
Blowing Agents			
Flexible urethane foams: cushioning in furniture, bedding, automobile seats, carpet underlay	F-11	38	59-97
Rigid urethane foams: thermal insulation in buildings, refrigerators and freezers, and transportation; packaging; marine flotation	F-11, F-12	21	83
Reaction injection molding; high-density-foam molded parts for automobiles, furniture, building construction	F-11	<1	<1
Nonurethane foams: polystyrene for thermal insulation and packaging (egg cartons, meat trays, disposable food containers); polyolefins for electric cable insulation, packaging, gaskets and seals, marine products	F-12, F-114	24	71
Solvents			
Industrial cleaning, drying, and degreasing;	F-113	66	160-202

solder flux removal; cleaning electronic assemblies; dry cleaning of garments			
Other Uses			
Sterilization: hospital and institutional sterilization; industrial sterilization of disposal medical and surgical supplies	F-12	12-14	37-43
Liquid fast freezing: frozen fruit, vegetables, seafood	F-12	7	15-30
Fire extinguishing: total flooding systems for computer, electronic, and communications facilities	Halon 1301[j]	<1	1-2
Whipped topping stabilizers	F-115	<1	<1
Presurgical skin cleaning	F-113	<1	<1

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[a] This does not include the hydrogen-containing CFCs, of which the most widely used is F-22.

[b] Based on preliminary estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation, except the estimates for reaction injection molding, whipped topping stabilizers, and presurgical skin cleaning, which are based on data gathered by the CARCE Panel on Industrial Technology.

[c] Refrigerant data for 1976; all other data for 1977.

[d] Chillers are central air-conditioning systems employing both primary (often CFC) and secondary (non-CFC) refrigerants, usually used in large buildings of three or more stories.

[e] F-500 is an azeotrope consisting of 73.8% F-12 and 26.2% F-152a. F-152a is not a fully halogenated CFC, and the F-152a portion is not included in these figures.

[f] F-22 is also used, primarily in the smallest chillers but also in some of the largest; it is not a fully halogenated CFC and is not included in these figures.

[g] F-502 is an azeotrope composed of 48.8% F-22 and 51.2% F-115. F-22 is not a fully halogenated CFC, and the F-22 portion is not included in these figures.

[h] F-22 is also used but is not included in these figures.

[i] Household (central and room) air conditioners, which use F-22, are not included.

[j] Halon 1301 is a bromofluorocarbon. It contains no chlorine.

result of leakage during use, emissions associated with servicing operations, and losses that occur at the end of the equipment's life. Placing a product such as an air conditioner in service today implicitly commits some amount of future CFC production to its future maintenance.

Finally, most of the data that we have had available are estimates, and often the estimates vary from source to source. The Rand data are probably as dependable a source as can be found today, since a serious effort was made to check and double-check all estimates with a variety of sources. Still, there is not complete agreement, within industry, with the Rand figures; moreover, their data are limited to domestic use and to emissions of fully halogenated CFCs only. Information available to us on domestic use and emissions of hydrogen-containing CFCs and on CFC use and emissions outside the United States have been less comprehensive than the Rand estimates. Further, we did not have available to us future global projections analogous to Rand's domestic projections for the year 1990.

Because of all this, we urge the reader not to be misled by what might appear to be undue precision in the numbers that we present. Rather, these should be taken as approximate estimates that represent the best that can be done with the information available today. While the numbers in the tables serve to illustrate quantitatively our findings, these findings represent the judgment of the committee and do not depend on precise values of the numbers.

Table III.2 lists the domestic uses of CFCs that we address in this report, and gives estimates (taken primarily from the Rand study) of (a) the annual rate of emission of fully halogenated CFCs from each use in 1976-1977, and (b) projected 1990 emissions assuming that no further controls are adopted.

DOMESTIC AND GLOBAL TRENDS

In 1974, domestic production of the two most widely used CFCs, F-11 and F-12, totaled approximately 830 million pounds. Aerosol propellants represented the largest single use, accounting for a little more than 60 percent of total production (about 500 million pounds). Total production in the rest of the world was over 1 billion pounds, with aerosol propellants probably accounting for about two thirds of this, or about 670 million pounds.*

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*The OECD countries (excluding the United States) accounted for a little more than 830 million pounds, of which aerosols represented about 72 percent.

The United States thus accounted for nearly half of world use, and, worldwide, aerosol propellants represented about two thirds of total F-11 and F-12 usage.

Worldwide production of F-11 and F-12 had risen steadily until 1974. After that year, production dropped, primarily because of a decrease in U.S. production, presumably reflecting recognition of the threat to stratospheric ozone and the likelihood that aerosol propellant use would soon be banned. In 1977, domestic production of F-11 and F-12 had dropped to about 565 million pounds, while production in the rest of the world remained virtually steady at about 980 million pounds. Although precise data are not available, it seems likely that domestic aerosol use had dropped to about 250 million pounds, while domestic nonaerosol use remained nearly steady at a little more than 300 million pounds. There is no reason to believe that aerosol use of F-11 and F-12 in the rest of the world had changed appreciably. If this is so, then by 1977, the U.S. share in world production had dropped to about 37 percent, and worldwide, aerosol uses had dropped to just under 60 percent of total usage.

It seems likely that by 1980, aerosol uses of F-11 and F-12 within the United States will have virtually disappeared, while other uses are likely to increase. If so, and if the trend for other uses to increase is paralleled in the rest of the world, then the U.S. share in world production will have dropped to less than one third, while aerosol use will still amount to more than one third of total worldwide production.

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5 INTERNATIONAL ASPECTS

The ozone problem is a global one. Chlorofluorocarbons emitted anywhere on earth will ultimately cause reduced concentrations of stratospheric ozone globally. Consequently, no one nation alone can solve this problem.

This chapter discusses actions taken by other nations to control chlorofluorocarbon emissions, considerations likely to affect future decisions by other nations, and the need for a coordinated international approach to the control of CFC emissions. It also discusses the implications for international trade of further actions that the United States may take.

Without comparable action abroad, the United States can have only a modest impact on global CFC emissions, one that could be quickly offset by increases in worldwide use of CFCs. U.S. regulation of CFC emissions would make the most effective contribution to the preservation of stratospheric ozone if based on a strategy of synchronous or tandem domestic and international action. Ultimately, nothing less than global action can deal with this problem, although substantial improvement could result from coordinated action of the primary producer nations.

THE GLOBAL CONTEXT

Thus far, only four other countries have taken action to control CFC emissions. The Canadian Government has announced its intention to ban the use of CFCs in some

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This chapter was prepared by an *ad hoc* working group consisting of Ingo Walter, chairman; Ronald J. Brickman, Sam Gusman, and Herman Pollack.

aerosol products.[1] Sweden (which does not itself produce CFCs) has banned the manufacturing and importing of fluorocarbons in aerosols for nonessential uses, effective June 30, 1979.[2] Pending further scientific information on the ozone-depletion problem, the Dutch Government has required a warning label on aerosol containers, to be followed by a ban unless the scientific evidence of danger becomes less compelling.[3] In West Germany, negotiations between the government and industry have led to a voluntary agreement to reduce the use of CFCs in aerosols by one third (below 1975 levels) by 1979, with a suggested target of a 50 percent reduction by 1981.[4] CFC use in Canada, The Netherlands, Sweden, and West Germany accounted for about 20 percent of the estimated 1974 consumption, outside the United States, of F-11 and F-12, the principal industrial CFCs.[5] The expected impact of their actions would reduce CFC use outside the United States by about 8-10 percent of 1974 levels. (An additional 4-5 percent reduction would be achieved if West Germany increased its current 50 percent target to a 100 percent reduction in nonessential aerosol uses.)

Among the remaining countries, the principal users of CFCs are France, Great Britain, Italy, and Japan.[5] Consumption in these four nations accounted for about 33 percent of the F-11 and F-12 used outside the United States in 1974.[5] Elimination of nonessential aerosol uses in these four countries would reduce non-U.S. CFC use by about 17 percent of 1974 levels.

As a rule, the major CFC-consuming nations are also the major producers. In 1974, within the OECD,* the ten countries (including the United States) producing F-11 and F-12 were among the top 11 consuming nations; they produced 87 percent of the world total and consumed 74 percent. The 15 nonproducing OECD countries consumed only 6 percent of the world total.[5]

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*The Organization for Economic Cooperation and Development (OECD) member nations are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, The Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States. Yugoslavia, while not a member, has special status. The ten OECD countries that produced F-11 and F-12 in 1974 are Australia, Canada, France, Germany, Italy, Japan, The Netherlands, Spain, the United Kingdom, and the United States.

Most of the remaining CFC production and use is in Australia, Spain, India, Argentina, South Africa, the Soviet Union, and the Eastern European countries (and possibly China). CFC use in these countries accounted, in 1974, for 47 percent of the worldwide CFC consumption outside the United States. The rate of growth in CFC production and use in this group of countries could be quite high in the future. In addition, several of the smaller developing countries now have CFC production capacity, and, although the amount produced is currently insignificant, it could grow to important dimensions in the future.

In addition to the policy initiatives at the national level mentioned above, the European Economic Community (EEC)* has undertaken an initiative on the CFC issue. In May 1979, the EEC Commission approved a proposal to require member states, by December 31, 1981, to reduce their aerosol propellant use of CFCs by 30 percent of 1976 levels and to block any further increases in production capacity.[6] These measures, which still require approval of the Council of Ministers, would be reviewed in 1982 to determine whether they should be rescinded, continued, or extended.

Factors Affecting International Variations in CFC Policy

Several factors account for the differences among countries in their current CFC policies and in the likelihood that they will adopt new policy initiatives in the future.

Perhaps the most important determinant of national policy is the perception of the conclusiveness of the scientific evidence of risk. In some nations this differs substantially from the perceptions of the scientific and regulatory community in the United States as reflected in this and previous reports. For example, in the United Kingdom, the Central Unit on Environmental Pollution in the Department of the Environment prepared a paper in 1976 titled *Chlorofluorocarbons and Their Effect on Stratospheric Ozone*,[7] which noted that a predicted 16 percent increase in ultraviolet radiation (corresponding to 8 percent ozone depletion) was "equivalent to the

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*The European Economic Community (EEC) member nations are Belgium, Denmark, France, Germany, Ireland, Italy, Luxembourg, The Netherlands, and the United Kingdom.

increase in exposure incurred by a person moving from Northern England to the south coast of England--an increased risk that most people would accept without further thought even if they were aware of it."* The report went on to state that while ". . . the risk to a single individual is not great . . . one cannot disguise the fact that if the background of UV rises, then both UV exposure and the risk to the general population increases." The report concluded that "such an increased level will not be reached for about 100 years and although regulatory action may be needed long before this, there appears to be no need for precipitate action." (Note, however, that the more recent ozone depletion estimates discussed in this report indicate that *if present CFC emission rates continue*, a 16 percent increase in UV radiation is likely to occur in as little as 20 years, with an eventual increase of 44 percent in a little more than a century; if CFC emissions continue to increase, as is likely in the absence of further regulation, these figures will be much higher.)

Statements by public authorities in other countries--in some cases based on the assessments of their own experts--have expressed similar reservations about the

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*Arguments that compare the risk to an individual with the risk to society as a whole can be misleading. L. Dotto and H. Schiff, in *The Ozone War* (Doubleday, 1978, page 210) give a counterexample: "The average annual temperature in Houston is 69 degrees F., while the average annual temperature in Chicago is 51 degrees. If you move from Houston to Chicago, you voluntarily choose to live in a climate that is, on average, 18 degrees cooler. But it is a very different story to suggest that the *whole world* be cooled down by 18 degrees; not only would *everyone* be subjected to a cooler climate whether they choose to be or not, but the effect on agriculture and the whole ecosystem would undoubtedly be devastating . . . . This is the crucial point about ozone depletion--that one is talking about the *average reduction over the entire earth* . . . and there would, for example, be an absolute increase in skin cancer unless *everyone* moved to a higher latitude. Even if you were to ignore the practical and political difficulties of doing this with four billion people, the fact remains that plants, animals, and crops cannot so readily be shifted around."

nature and magnitude of the CFC-ozone depletion problem. Given such basic differences in assessments of risk and potential damage, one can expect that the degree of international scientific acceptance of the ozone depletion theory and its consequences will fundamentally affect the pace at which control measures are adopted.

Another factor concerns the economic costs of reducing CFC use. One can expect that these costs will tend to correspond to the patterns of CFC production and consumption outlined above. Thus, comparable restrictions would have larger economic impacts in large producing or using countries such as France and Britain than in smaller ones such as Spain and Canada.

A more general factor is overall economic development, measured, for example, by gross national product per capita. Although the five countries that have moved to curtail CFCs are among the world's richest, differences between them and the other major producing and consuming countries that have not taken action are probably not great enough to give this factor determining weight. However, this may not be the case with respect to countries in the developing world.

Another factor is environmental political pressure. The major OECD producer countries all have environmental movements, and pressure from the public on environmental questions has grown in recent years. Nevertheless, the dynamics of environmental politics and the availability of channels of influence can vary markedly from one country to the next, as can the priority accorded the CFC issue among environmental problems.

A related factor is the nature of industry-government relations. In several countries, these relations are closer and less adversarial than in the United States. One consequence is that pollution problems in some of these countries are often handled in a voluntary fashion through industry-government consultation, and industry's point of view may be given special weight in policy formulation.

Another significant dimension that must be considered in any new U.S. initiative with regard to CFCs is its impact on the U.S. position in the international economy. This includes the effects on exports and imports, international investment and multinational corporate operations, the balance of payments, and U.S. commitments under international trade law. If significant damage occurs to the national economy through any of these linkages--or if they significantly reduce the effectiveness of U.S. measures to control CFCs--this would appreciably influence perceptions of the relative merits of alternative policies.

The Case for a Coordinated International Approach

From every point of view it is desirable that the problem of ozone depletion be approached on an international basis. Assessment and choice of U.S. regulatory actions should be made in that context. This is not to say that U.S. action should be contingent on the action of others, for that would place the interests and welfare of the American public entirely in the hands of others. Rather, the approach should be to plan U.S. and international actions as parts of a single strategy and joint endeavor.

The United States has played a pioneering role in identifying the ozone problem, in bringing it to the attention of the world, and in initiating remedial action by banning nonessential uses of aerosols. This appears to have had a "demonstration" effect. It made clear the magnitude of U.S. concern and our willingness to pay a price for increased global welfare. As indicated previously, other industrial countries are following suit, although not yet to the degree or at the pace of the U.S. demonstration. An argument can be made that further U.S. action will contribute to a similar response in other countries.

There is, of course, an opposing view that holds that action by the United States can have a negative impact internationally--hindering international consensus building and opening the United States to charges of seeking unduly to impose its views on others. However, it should be possible to avoid this by the skill, sincerity, and openness with which the United States presents its findings, concerns, and proposals to the international community.

A single strategy for domestic and global action would involve seeking wide international consensus on the need for action and the objectives to be sought. It would be most desirable if that strategy could be defined collectively, although it is appropriate at the same time for the United States to continue to pioneer in initiating change and developing relevant new technology. As part of this strategy, it would be appropriate to phase in any future domestic controls gradually, thus providing industry and business with time in which to plan and to make the transition to new products and technologies. This may also contribute to worldwide emission reduction as a result of adoption of such new technology by industry and business in other countries.

Basic to the development of international agreement and coordination of control is the development of international consensus on the scientific basis for expecting significant health and environmental effects due to CFC emissions, as developed in detail in Part II of this report. The acceptability of these findings, prepared within the context of U.S. institutions, will need to be examined by scientists in other nations. Such critiques, in appropriate international settings, can flush out dissenting views and either create a broader international consensus or bring into sharper focus the substantive scientific questions on which opinion is divided.

The degree of international scientific support of the ozone-depletion theory can be expected to affect the pace at which control measures are adopted. This pace could be quickened were the United States to undertake an active effort to establish an international program of research on this topic and to promote its discussion in every suitable scientific forum. Arrangements might be sought to have the organizations belonging to the International Council of Scientific Unions* place this subject on their agendas so as to advance the science and focus attention upon it.

At the same time, comparable steps might be taken to seek political agreement internationally to proceed with control measures. Standard techniques such as bilateral discussions, nationally sponsored conferences, and placing the subject on the agendas of appropriate international organizations might be employed. The OECD would be an especially desirable institution to so engage, because of its record in dealing with environmental matters, the experience of its secretariat, and its general objective of harmonizing national policies. However, the UN Environmental Program, the World Health Organization, and the UN Economic Commission for Europe (with Eastern Europe in mind) should not be overlooked.

The major contributors to the world CFC problem have shown in other respects a willingness comparable with that

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*The International Council of Scientific Unions (ICSU) is a nongovernmental organization whose members are scientific bodies from all over the world. ICSU is the predominant international spokesman and forum for scientific concerns.

of the United States to regulate environmental pollution. They have sufficient existing legislative authority to restrict CFC production and use, and in general can afford to do so. International efforts aimed at focusing attention on the CFC issue should take into account the different procedures and political-economic contexts of environmental policy making in various countries. The United States should make known its concern about the hazards of CFC emissions not only to scientists and foreign public authorities but also to foreign industry and environmental groups.

INTERNATIONAL TRADE CONSIDERATIONS

When U.S. regulations banning the manufacture and interstate shipment of CFC-propelled aerosols were announced in May 1977, industry's response was muted, for a number of reasons. First, the timetable, which delayed complete implementation of the ban until April 15, 1979, provided sufficient time for an orderly transition to alternative systems. Second, alternatives (e.g., pumps, barrier packs, roll-ons) had already made significant inroads on the marketplace. Third, new valve and propellant systems were emerging that some believed would be more versatile, equally effective, and, in the long run, cheaper than existing systems. Fourth, the ability to use less costly propellants such as hydrocarbons provided marketers with a good alternative as long as the price structure of aerosol products could be maintained. For all of these reasons, many industry observers now believe that the U.S. ban on CFC use in nonessential aerosols has caused very little economic hardship, either domestically or internationally. The aerosol industry had already lost an estimated 1.3 billion unit sales between 1974 and 1976. Although aerosol sales in the United States in 1977 declined by about 10 percent, the industry's prospects through 1985 were felt to be bright.[8]

Foreign marketers have reportedly exhibited strong interest in alternative propellant systems developed in the United States. The aerosol industry overseas is 25 to 35 percent owned by U.S. companies; flows of technology, information, and policy from the U.S. parent companies to their foreign affiliates in regard to CFC substitutes may be an important mechanism for bringing about reductions in CFC emissions overseas from aerosols, both through the activities of the U.S. subsidiaries and by demonstrations and competitive effects on foreign producers.

Possible Impact of Further U.S. Action on International Trade

The international trade implications of further U.S. CFC controls are potentially far more serious. Exports of CFC-related products in 1977 totaled roughly $2 billion, while imports were somewhat less than half of that amount. On the import side, control options that increase U.S. producer costs, such as production taxes, quotas implemented by marketable permits, emission restrictions, and regulations mandating emission control technology, would increase the competitiveness of foreign supplies. Depending on the substitutability of imported and domestic CFC-using products, imports would replace domestically produced goods in the U.S. market. The location of CFC-using production would shift abroad, and total CFCs emitted globally, assuming no comparable action aboard, would not be likely to decline materially. This phenomenon could easily be neutralized by compensatory border taxes or other import restrictions on CFC-using products, although the administrative feasibility and acceptability of this approach is open to question. Since production-related measures plus import measures simply parallel such user-related measures as consumption taxes, these international considerations suggest that it is probably more efficient to proceed directly to the latter. They would apply equally to domestically produced CFC-using products and to imports. Product bans, use restrictions, taxation, permits, and similar measures would presumably affect both domestically produced CFC-using products and imports equally. 1977 data indicate that in the refrigeration and air-conditioning sector, $292 million of imports would be affected, as would approximately $20 million in urethane foams and as much as $118 million in CFCs and precursor chemicals.[9] This is not likely, under the circumstances, to trigger foreign retaliatory trade-policy action.

On the export side, cost-increasing measures bearing on U.S. producers would impair their export competitiveness and encourage increased production abroad. It is likely that the refrigeration/air-conditioning industry would be hardest hit. The United States accounts for over 75 percent of world sales in this industry, including sales from local production by foreign affilitates of American firms.[9] And although the relative amount of licensing and manufacturing overseas is high, exports are substantial both in terms of value ($1.2 billion in 1977) and as a percentage of domestic output of refrigeration and air-conditioning equipment (15 percent). Variations in CFC-use regulations around the world would generally compound supply difficulties and multiply costs for both U.S. and foreign producers. Even in the unlikely event that exports were exempted from producer-related controls --or in the event of consumer-related CFC measures--it is doubtful whether American suppliers would remain competitive in export markets without their domestic sales base. The extent of the disruption would be highly product-specific. The overall trade balance effect on the United States of a ban on use of CFCs in the United States would be significantly adverse in an amount well over $1 billion, because of the strong U.S. competitive position in the refrigeration and air-conditioning sector.

If other nations in time follow the U.S. lead in CFC policy, world market conditions facing American suppliers (and other suppliers of the U.S. market) would improve. Innovational advantages conferred by domestic regulations upon U.S. producers, e.g., knowledge about how to produce, market, and service less-pollutive materials and final products, would become attractive to users in other countries.

Location of Production

Severe regulation of CFC production or use would obviously reduce the attractiveness of the United States as a location for CFC-related production. It is too early to reach firm conclusions on the matter of locational shifting by U.S.-based multinational or by foreign companies. Confusion and uncertainty pervade discussions with CFC producers regarding the effects of potential CFC regulations on capital investment plans. Most existing expansion plans in the United States have already been abandoned or placed on the back burner. At the moment, overcapacity and not expansion is the main problem confronting producers of CFCs and precursor chemicals. If there is to be any shifting, the likely candidates will be found in the urethane chemicals and refrigeration/air-conditioning sectors. This is where strong motives might emerge for building large, efficient plants in or close to rapidly growing markets, where CFCs are not expected to be banned or otherwise restricted for foam-blowing, refrigerant, and other uses. If such shifting effects are indeed significant, and if continued CFC use is deemed economic and energy-efficient abroad, there is little doubt that the United States would lose substantially all of the affected markets in the absence of parallel policy action on the part of foreign governments. There are enough competitive foreign firms in each sector that an attempt to impose U.S. policy on the overseas affiliates of U.S. firms would have little appreciable affect, especially in the longer run.

Trade Policy

U.S. trade policy obligations in areas relating to possible CFC initiatives arise mainly from the General Agreement on Tariffs and Trade (GATT). The United States may not use tariffs to prevent or impede imports under a national CFC policy without either giving tariff compensation in other products or subjecting itself to possible retaliation. Nor may the United States discriminate between supplier countries in altering tariffs, according to the most-favored-nation principle. And in applying other control strategies--import surcharges, fees, levies, or quantitative use restrictions--it must afford foreign suppliers "national treatment." That is, it must treat imports no differently than domestically produced goods. Under Article XI of the GATT, signatories may not employ quantitative restrictions on either imports or exports except where this is necessary to enforce governmental measures to restrict domestic production or sale of a like or similar product. Consequently, CFC-related measures would not violate U.S. international trade policy obligations as long as this condition is fulfilled.

The same principle of "national treatment" has been extended to a broad range of industrial standards by virtue of the Industrial Standards Code negotiated in the Tokyo Round of trade negotiations under GATT. It is conceivable that imports would nevertheless be discriminated against, for example, in the manner in which product standards for refrigerators and air conditioners are applied. That is, foreign suppliers might find such standards more difficult to meet than would domestic manufacturers because of the way the standards are applied. The Code is intended to reduce the possibility of inadvertent or intentional discrimination of this type and accordingly provides for enforcement and dispute-settlement machinery.

Balance of Payments

It is likely that unilateral U.S. action on CFCs would have an adverse balance-of-payments effect. This is composed of the aforementioned adverse balance-of-trade effect, in addition to the possibility of increased capital outflows for investment in foreign plants, particularly in the refrigeration and air-conditioning sector, and possibly reduced investment inflows. It is not possible to estimate the size of these potentially adverse capital flows, however.

Unlike the effects of CFC policy on international trade, location of production, and employment, the balance-of-payments effects are a relatively minor concern. This is because under a system of more or less flexible exchange rates, these effects would make themselves felt as marginal downward pressure on the dollar in foreign exchange markets, which in turn would increase the international competitiveness of U.S. exports in other sectors.

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6 FEASIBILITY, COSTS, AND IMPACTS OF TECHNOLOGICAL ALTERNATIVES

Earlier portions of this report discussed the threat posed to the stratospheric ozone layer by chlorofluorocarbons and other chlorinated substances; the likely consequences of increased ozone depletion on health, plant and animal life, and climate; and the global nature of the problem. In this chapter we discuss the industrial uses of chlorofluorocarbons and related chemicals and attempt to identify those changes in practice that are now, or are likely soon to be, feasible and that would reduce the threat to stratospheric ozone.

We will be concerned, in this chapter, with those changes that are technologically *possible and with their implications for industry. The following chapter of the report will address broader social and economic implications.*

There are a number of areas in which significant reductions in CFC emissions are technologically possible, although with penalties in cost, performance, or safety. In this chapter we identify these areas and estimate the penalties involved, the time needed for implementation of technological changes, and the time required for significant emission reduction (note that these may be quite different). Technological alternatives exist that may be capable of reducing CFC emissions by an amount equivalent to about half of the nearly 300 million pounds of fully halogenated CFCs emitted in the United States from nonaerosol uses during 1977. Some of these alternatives involve substitute chemicals that could replace CFCs in present practice; others involve continued use of CFCs with improved leakage prevention, containment, recovery, and recycling; still others involve new and different technologies. Many of these alternatives could be put into operation within a decade; some could be put into effect sooner.

Costs for the introduction of these alternatives vary widely. Some solvent substitutions could be immediately cost-effective with only small adjustments in factory equipment. Resistance to these changes within industry is usually based on concern that the potential substitute solvents are already or may soon become subject to government regulation because of occupational safety and health considerations. Flexible urethane foams for many end uses can probably be manufactured without CFCs and marketed successfully. In contrast, rigid urethane foams used for thermal insulation depend on the insulating quality of the CFC contained in the foam; without this, their competitive performance edge over other kinds of thermal insulation would be lost. Refrigeration and air conditioning appear to be areas in which reduced dependence on CFCs will not be easy; improved CFC containment and improved procedures for servicing and handling are the leading near-term candidates for reducing CFC emissions in these areas.

Monetary costs of conversion are often not the entire story. Worker and consumer safety considerations usually favor CFCs, and the alternatives often involve risks that are uncertain and may not be completely removable by product and process design. In some cases the risks are obvious, as in the substitution of flammable, explosive, or toxic chemicals for the currently used CFC refrigerants. In other cases the risks may be unknown or controversial; for example, the carcinogenicity of some alternative solvents or foaming agents has not yet been definitively determined. CFCs are generally considered to be among the safest substances known; however some questions about their toxicity remain. We have not addressed the questions of toxicity, carcinogenicity, mutagenicity, teratogenicity, and other hazards associated either with the CFCs themselves or with their potential substitutes, although in some instances where the toxicity or other hazard is particularly relevant we have so indicated. Job loss, business loss, and other dislocations are additional important factors that are not addressed in this chapter.

The unique properties of the CFCs repeatedly enter the following discussion. CFCs have emerged as the best current refrigeration and air-conditioning fluids after many decades of research and development. Their unique combination of stability, safety, and thermodynamic properties is unmatched by any other compounds. CFCs are valued as solvents because of the selectivity they provide. They

TABLE 6.1 Summary of Major Sources of CFC Emissions and Potential for Emission Reduction (for Each Application the Primary CFCs Used are Indicated)[a]

	Air Conditioning			Refrigeration		Plastic Foams			
	Commercial F-11, F-12, F-114, F-500	Residential F-22	Mobile F-12	Commercial F-12, F-502	Residential F-12	Flexible Urethane F-11	Rigid Urethane F-11, F-12	Reaction Injection Molding F-11	Non-urethane F-12, F-114
Current Level of Emissions									
United States	M	L	H	M	L	M	M	L	M
Rest of world	M	L	H	M	L	M	M	L	M
Expected Growth in Emissions									
United States	L	L	L	L	L	H	H	H	H
Rest of world	M	M	M	M	L	H	H	H	H
Source of Emissions									
Manufacture	L	L	L	L	L	H	L	L	*b*
Normal use	L	L	M	L	L	L	M	L	*b*
Service and repair	M	M	H	M	L	L	L	L	*b*
Disposal	L	L	M	L	M	L	H	H	*b*
Alternatives for Reduction									
Substitute material or technology									
Near term	N	*c*	N	N	N	Y	N	Y	*b*
Long term	Y	*c*	Y	Y	Y	Y	Y	Y	Y
Penalty for substitution									
Cost	H	*c*	H	H	H	O	H	O	*b*
Performance	L	*c*	L	L	L	L	H	L	*b*
Added hazard	U	*c*	U	U	U	O	O	O	*b*
Containment, recovery, recycle, or reclamation	Y	N	Y	Y	N	N	Y[d]	N	*b*
Overall Potential for Reduction									
Near Term	L	L	M	L	L	H	L	L	*b*
Long Term	M	L	H	M	M	H	H	L	*b*

	Solvents			Aerosols	Other Uses			
	Degreasing F-113	Solder Flux Removal F-113	Critical Cleaning and Drying F-113	F-11, F-12	Sterilization F-12	Liquid Fast Freezing F-12	Fire Extinguishing Halon 1301	Other Miscellaneous Uses F-113, F-115
Current Level of Emissions								
United States	M	M	M	L	M	M	L	L
Rest of World	M	M	M	H	L	L	L	L
Expected Growth in Emissions								
United States	L	L	M	L	M	M	M	L
Rest of World	L	L	M	M	M	M	M	L
Source of Emissions								
Manufacture	L	L	L	L	L	L	L	L
Normal Use	H	H	H	H	H	H	L	L
Service and repair	L	L	L	L	L	L	L	L
Disposal	L	L	L	L	L	L	L	L
Alternatives for Reduction								
Substitute material or technology								
Near term	Y	Y	N	Y	N	Y	N	Y
Long term	Y	Y	Y	Y	Y	Y	Y	Y
Penalty for substitution								
Cost	M	M	M	L	H	H	M	O
Performance	L	L	H	L	M	M	H	H
Added hazard	U	U	U	L	O	O	M	O
Containment, recovery, recycle, or reclamation	Y	Y	N	N	Y	Y	N	N
Overall Potential for Reduction								
Near Term	M	M	M	H[e]	M	M	L	L
Long Term	H	H	M	H[e]	M	M	L	L

[a] Key: L, Low; M, Medium; H, High; Y, Yes; N, No; O, Zero; U, Unknown.

[b] Four different foam products involved. The categorization differs for product areas.

[c] Present use of F-22 in this application may make it a low-priority area for further development of substitute materials or technologies.

[d] In manufacture only, which contributes about 10 percent of total life-cycle emissions from this use.

[e] U.S. has eliminated aerosol uses. Rest of world has major potential for reduction in aerosol use.

are good cleaning solvents for many contaminants, particularly paraffins and silicone oils, and they do not damage plastic parts or leave corrosive residues. As auxiliary blowing agents in the production of plastic foams, the CFCs' unique combination of chemical inertness, nontoxicity, nonflammability, thermal energy absorption, and low cost makes it extremely difficult to find completely satisfactory substitutes for all foam applications. The chemical stability of the CFCs is an enormous asset in industrial and other applications (although it is this same chemical stability that makes them a threat in the atmosphere). The overall desirability of these chemicals is illustrated by the consistent use of CFCs in competitive industries even when their cost is two or three times as much as that of the next-best alternative materials.

In conducting this study, we turned to two kinds of sources. For numerical estimates of current and future emissions, we relied heavily on the study currently being carried out for EPA by the Rand Corporation and on an earlier report by DuPont (1978). To achieve an understanding of what is technologically feasible and what is not, and why, we engaged in dialogue with a large number of industry experts. Some of this was through formal oral or written presentations to the full CARCE Panel on Industrial Technology; some was in the form of informal conversations with individual panel members. We found a surprising lack of agreement among the experts, and many things turned out to be far more controversial than we had expected. This is sometimes reflected in the text. The judgments in this chapter represent our collective judgment based on all the material that was available to us; the figures in the tables are illustrative estimates, but the judgments do not rest solely on the estimates and projections of the Rand study and the DuPont report.

SUMMARY OF TECHNOLOGICAL ALTERNATIVES FOR REDUCING CFC EMISSIONS

Table 6.1 identifies the major CFC uses addressed in this chapter and indicates, in qualitative categories, the magnitude of their contribution to the ozone problem and the potential for improvement. Table 6.2 lists the more promising technological alternatives for reducing CFC emissions and indicates the potential reduction in stratospheric chlorine input achievable by each. In most cases these technologies are not available today but could be

TABLE 6.2 Most Promising Approaches to CFC Emission Reduction[a]

APPLICATION (principal CFC now used, 1976-1977 annual emissions)	Potential Reduction below Current (1976-1977) Annual Emissions (millions of pounds)[b]	
Alternative to present CFC use	CFCs	Chlorine
REFRIGERANTS		
COMMERCIAL AIR CONDITIONING (F-11, F-12, 15 million pounds)		
Improved service and disposal procedures	4	3
Leakage reduction[c]	3	2
RETAIL-FOOD-STORE REFRIGERATION (F-12, F-502, 13 million pounds)		
Improved factory, service, and disposal procedures	10	6
MOBILE AIR CONDITIONING (F-12, 83 million pounds)		
Improved factory, service, and disposal procedures	41	24
Leakage reduction	12	7
Reduced charge	1-17	1-10
HOUSEHOLD REGRIGERATORS AND FREEZERS (F-12, 6 million pounds)		
None		
BLOWING AGENTS		
FLEXIBLE POLYURETHANE FOAMS (F-11, 38 million pounds)		
Substitution of methylene chloride	27-38	21-30
RIGID POLYURETHANE FOAMS (F-11, 21 million pounds)		
None		
REACTION INJECTION MOLDING (F-11, <1 million pounds)		
Substitution of methylene chloride	<1	<1
Gas frothing	<1	<1
POLYSTYRENE FOAMS (F-12, 19 million pounds)		
None		
POLYOLEFIN FOAMS (F-12, F-114, 5 million pounds)		
None		

TABLE 6.2 (continued)

SOLVENTS		
DEGREASING, CLEANING, AND DRYING (F-113, 13 million pounds)		
Chlorocarbons	13	7
Aqueous solvents	7	4
Containment, recovery, and recycling	5-12	3-7
SOLDER FLUX REMOVAL (F-113, 15 million pounds)		
Water-soluble fluxes	12	7
Containment, recovery, and recycling	3-12	2-7
CRITICAL CLEANING AND DRYING (F-113, 26 million pounds)		
None		
OTHER USES		
STERILIZATION (F-12, 14 million pounds)		
Recovery and recycle	9	5
Carbon dioxide	12	7
Radiation	4	2
Steam	5	3
LIQUID FAST FREEZING (F-12, 7 million pounds)		
Recovery and recycle	3	2
Liquid nitrogen, carbon dioxide, or air blast	7	4
Total potential reduction	157	101

NOTE: POTENTIAL REDUCTIONS DUE TO DIFFERENT ALTERNATIVES ARE NOT ALWAYS ADDITIVE.

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[a] This table summarizes the most promising alternatives identified in the more detailed tables that follow. Alternatives involving substitution of hydrogen-containing CFCs or of other potential ozone-depleting chemicals are *not* included.

[b] The two columns indicate the potential reduction in emission of CFCs that would ultimately reach the stratosphere and the potential reduction in the amount of chlorine ultimately introduced into the stratosphere (calculated by multiplying the total quantity of CFC by the weight fraction of chlorine in the CFC in question; some of the factors involved are F-11, 0.77; F-12, 0.59; F-113, 0.57).

[c] Significant delays in achievement of ultimate emission reduction.

TABLE 6.3 Approaches to CFC Emission Reduction Involving Substitutes That Deplete Ozone But to a Lesser Extent Than the CFCs They Would Replace

Application, CFC Now Used, and Current (1976-1977) Annual Emissions	Potential Substitute	Extent of Substitution Potentially Possible
Commercial air conditioning (F-11, F-12; 15 million pounds)	F-22	More than 50%
Retail-food-store refrigeration (F-12, F-502; 13 million pounds)	F-22	More than 50%
Mobile air conditioning (F-12; 83 million pounds)	F-22	Virtually 100%
Polystyrene foam production (F-12; 19 million pounds)	F-142b	Virtually 100%
Polyolefin foam production (F-12, F-114; 5 million pounds)	F-142b	Virtually 100%
Solder flux removal (F-113; 15 million pounds)	1,1,1-Trichloroethane	Virtually 100%

brought to commercial readiness within the next decade--some in as little as one to two years. Table 6.3 lists additional possible alternatives that involve substitution of other chemicals that cause some ozone depletion, although not to the extent of the fully halogenated CFCs; these are F-22 and F-142b, which are hydrogen-containing CFCs, and 1,1,1-trichloroethane (methyl chloroform).

This section summarizes the key points listed in these tables; the following four sections discuss this material in more detail.

Refrigerants

Mobile air-conditioning systems for automobiles and trucks employ F-12 as a refrigerant and represent the largest single source of domestic emissions at this time (83 million pounds in 1976). No near-term alternative refrigerant is known. Improved factory procedures could achieve emission reductions of 9 million pounds, and recovery and recycling in servicing and disposal could eliminate 32 million pounds, each in the near term. Costs of factory changes should be small, but service and recovery costs will be large. Design changes can yield emission reductions over a period of several years, with 8-10 years required before these changes are fully reflected in the automotive fleet. Examples of these design changes include reduced leakage, which could eliminate 12 million pounds, and reduced charge, which could eliminate up to 17 million pounds. Costs of these changes would be small.

Commercial air-conditioning systems employ various CFC refrigerants; F-11 and F-12 are the principal ones and contributed 15 million pounds of emissions in 1976. Emission reductions can be achieved by improved service and disposal procedures (4 million pounds of CFC) in the near term and by redesign of equipment for reduced leakage (3 million pounds of CFC) over a period of years. These changes can be introduced at modest cost and with no performance or health penalties. Alternative refrigerants could be used, with appropriate design changes, but at a significant increase in cost.

Commercial refrigeration systems employ F-12 and F-502, an azeotrope of F-22 and F-115. Emissions from retail food-store refrigeration systems totaled about 13 million pounds in 1976. (Other commercial systems for food storage and handling and industrial processes may have contributed double this amount, but these were not included in the Rand study and are not treated here.) Emissions could be reduced by containment and recovery during manufacturing (1 million pounds of CFC), improved service procedures (6 million pounds of CFC), and recovery on retirement of equipment (3 million pounds of CFC). These procedural changes entail no appreciable penalties of performance, cost, or health hazard.

Residential air conditioning and refrigeration have lesser potential for emission reduction. Residential air conditioning uses F-22, which presents a much smaller threat to stratospheric ozone than do the fully halogenated CFCs.* Residential refrigerators and freezers use

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*The report *Stratospheric Ozone Depletion by Halocarbons: Chemistry and Transport* (National Academy of Sciences, Washington, D.C., 1979) points out that because F-22 contains hydrogen, it reacts in the troposphere and only 20 percent to 50 percent of the molecules released at the

F-12 in hermetically sealed units, which give rise to minimal emissions during normal use and service and could lend themselves to recycling on disposal of the unit, although the cost would be high.

Mobile air conditioning, commercial air conditioning, and *commercial refrigeration* systems using F-22 as a refrigerant may be possible. F-22 is less effective in depleting stratospheric ozone than are F-11 and F-12; however, because it does cause some degree of ozone depletion the question is whether its use will be allowed if other CFCs are restricted. Since redesign to use F-22 will be costly and will take several years, industry will be reluctant to undertake this until the acceptability of F-22 is resolved. If F-22 were introduced in new equipment only, it would take about a decade to gain the full advantage in terms of reduced emissions. At that time, replacement of other CFCs by F-22 could lead to the equivalent of reducing annual CFC emissions by as much 55 million to 67 million pounds in mobile air conditioning, 7 million to 9 million pounds in commercial air conditioning, and 8 million to 10 million pounds in commercial refrigeration.

Blowing Agents

The use of CFCs as auxiliary blowing agents in plastic foam manufacture is a rapidly growing area of use that by 1990 may exceed mobile air conditioning in its contribution to CFC emissions.

Flexible polyurethane foams are now produced by a process that releases, during the manufacturing process, virtually all of the F-11 used as an auxiliary blowing agent. Domestic emissions from this source in 1977

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earth's surface reach the stratosphere. Because a molecule of F-22 contains only one chlorine atom, as compared with two for F-12 and three for F-11, substitution of F-22 puts 10 percent to 25 percent as much chlorine into the stratosphere per molecule as does F-12 and 7 percent to 17 percent as much as does F-11. Because of the different molecular weights of the three chemicals, this translates to 14 percent to 35 percent as much per pound as F-12, and 11 percent to 27 percent as much per pound as F-11. (It does not, of course, follow that F-22 can be substituted for F-11 or F-12 on a pound-for-pound basis.)

totaled 38 million pounds. More than half of these emissions could be eliminated by substitution of methylene chloride for F-11. With some loss in cushioning properties, and a few years to adjust processes, 70 to 100 percent of the F-11 might be replaced by methylene chloride, although there are some questions about the possible toxicity of this chemical. A return to carbon dioxide foaming without an auxiliary blowing agent is possible, but foam properties would suffer considerably.

No adequate substitute for F-11 in *rigid polyurethane foam* has been found. Carbon dioxide foaming produces foams of poorer thermal insulation value. Alternative insulating materials, e.g., fiberglass or vermiculite, could be substituted in some uses without severe penalties. In other uses, severe performance penalties would be imposed, particularly in those applications in which space is a primary consideration. In 1977, more than 50 million pounds of F-11 were used in the manufacture of rigid methane foams. About one third of this was emitted; the remainder remains locked in the foam, and the amount so contained increases each year. All of this "banked" material will eventually reach the atmosphere.

Reaction injection molding (RIM) for the production of large, high-density urethane foam parts for the automobile, furniture, and construction industries represents a new and rapidly growing use of F-11 blowing agent. Approximately 2 million pounds of F-11 are estimated to have been used in RIM production in 1978, and this usage is expected to increase to at least 10 million pounds by 1990. Little of the F-11 is emitted during manufacture, and emissions are very slow during normal use of the product. Recovery and recycling on disposal is likely to be difficult because of the large number of CFC-containing parts and the very small amount of CFC in each.

Prospects for substituting non-CFC blowing agents, or using other processes (such as frothing with air, nitrogen, or CO_2), are good in the near term if some incentive is provided to encourage the change. A phased reduction in CFC use in RIM over the next three to five years would allow time for substitutes to be developed and implemented without undue hardship on this new and growing industry.

Extruded polystyrene sheet foam production employs F-12, which could be replaced by F-142b, a hydrogen-containing CFC, although at a very large cost penalty. 1977 domestic emissions from this source totaled 16 million pounds, emitted during manufacture. *Polystyrene board* presents a similar situation involving 2 million pounds of F-12 in

1977, but with much slower emission rates. *Polystyrene bead* production yields even smaller emissions. The beads can be foamed using pentane, but flammability introduces significant factory hazards.

Polyolefin foams are produced with the aid of F-12 or F-114, which could be replaced with F-142b. Prompt emission occurs with these materials; 1977 emissions in the United States amounted to about 5 million pounds.

Solvents

The use of CFCs as specialty solvents is another rapidly growing area that may contribute more to CFC emissions by 1990 than will mobile air conditioning.

Certain *degreasing, cleaning,* and *drying* operations employ F-113, which could be replaced by other solvents. Chlorocarbons could be substituted for virtually all of the approximately 13 million pounds* emitted in 1977, and aqueous solvents could be substituted for about 7 million pounds, all emitted promptly. Penalties for substitution should be small for many of these substitutions, assuming that questions about health impacts of the chlorocarbons are favorably resolved. Containment, recovery, and recycling may also be feasible.

F-113 is also used for *solder flux removal*, and prompt emissions of about 15 million pounds per year are involved. 1,1,1-Trichloroethane appears to be an alternative with no appreciable penalties but is itself an ozone-depleter, although to a lesser extent than the fully halogenated CFCs. Rosin flux can also be replaced by water-soluble fluxes in many cases, thereby reducing emissions by about 12 million pounds. Containment, recovery, and recycling is also a possibility.

F-113 is also used for *critical cleaning and drying* of electronic, electrical, and mechanical assemblies, giving rise to emissions that totaled about 26 million pounds in 1977. F-113 is uniquely suited for this purpose, and no potential alternative is known.

Other Uses

The potential for reduction in "other-use" areas is small in an overall sense, but near-term reductions amounting

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*The magnitude of current CFC emissions for this use is only approximately known.

to more than half of the current emissions can be achieved through containment, recovery, and recycling in the two largest of these uses--sterilization and fast food freezing. Long-term alternatives are likely to be developed in all the "other-use" areas.

Sterlization of medically related materials and devices employs F-12 in conjunction with ethylene oxide. This procedure is widely used and resulted in about 14 million pounds of prompt CFC emissions in 1977. Recovery and recycling procedures could reduce these emissions by about half. Carbon dioxide is an alternative auxiliary agent for F-12 in ethylene oxide sterilization; other methods of sterilization (heat and radiation) are partial alternatives (30-40 percent of all sterilization use). For each of these alternatives some performance penalty would be incurred in particular uses, and capital costs for the new systems would be significant.

Liquid fast freezing of foods employs F-12. Total emissions from this source are prompt and amounted to about 7 million pounds in 1977. Alternative systems are available, but penalties are significant. Use of liquid nitrogen or carbon dioxide would involve substantially higher operating costs and a tenfold increase in energy consumption. Use of air-blast systems, while less costly, would result in a loss of product quality. In both instances significant capital investment would be required. Some reduction in CFC emissions can be achieved through improved containment, recovery, and recycling.

Nonessential *aerosol propellant* use has been banned in the United States but is still the major use in the rest of the world, producing CFC emissions in excess of total U.S. emissions from all other uses. Alternatives are available for all but a small fraction of essential uses. This use is not discussed in the present report.

Recovery and Recycling

Prospects for CFC recovery and recycling are similar in a number of areas of application. Recovery and recycling of the higher-boiling CFC liquids that are used in cleaning is feasible, economically attractive, and widely used. The CFC is separated from contaminants by fractional distillation. Containment, recovery, and recycling of the lower-boiling CFC gases used as pneumatogens in plastic foam production is much more difficult, not economical, and not at all established. In a few pilot-plant demonstrations, CFC vapors, along with air and other materials have been passed through carbon beds that adsorb the CFCs and various other materials, but not the air. The bed is then regenerated by exposure to steam in a separate operation, and the CFC, water, and other desorbed contaminants are then condensed, separated, and distilled. CFC recoveries by this process have ranged from 30 to 80 percent, and projected operating costs are high. The toxic nature of unreacted isocyanate contaminants in the CFC presents an added complication.

Other Alternatives Requiring Long-Term Research

Longer-term alternatives, not viable in the near future but meriting further research, exist in some areas of use. (1) *Flexible polyurethane foams* could be produced by chemical blowing, nonchlorinated fluorocarbons, or frothing techniques employing air, carbon dioxide, or nitrogen. At least ten years would be needed to develop and implement these processes. (2) For *rigid polyurethane foams*, whose unique thermal insulating properties depend on the CFC held in the foam cells, a search for an alternative blowing agent that provides comparable insulating quality and does not affect the ozone layer could be undertaken. (3) *Nonurethane foams* can be produced with various alternative materials, but further research is needed to define the optimum processes. (4) *Commercial refrigeration* could in principle be achieved with F-134a, which contains no chlorine, but research is needed to discover a commercially viable manufacturing process for this refrigerant and to establish its safety. Alternative refrigeration cycles might also be possible (e.g., reversed Stirling cycle), but commercial feasibility of such an approach is likely to be many years away, even if the as yet unanswered questions are resolved. (5) *Mobile air-conditioning* systems could be designed to use F-134a or alternative cycles, but these possibilities are also remote. Hermetic design of mobile air-conditioning units is probably feasible, but there is no consensus on the degree of technical difficulty. (6) *Residential refrigerators and freezers* could possibly be operated with F-22 or F-134a. Alternative refrigeration cycles might also be relevant. However, the relatively small potential reduction in emissions from this use suggests that developing such alternatives should have low priority. (7) Containment and recycling of CFCs used in *degreasing, cleaning, and drying* and in *solder flux removal* is an area in need of study. Carbon bed adsorption of the CFC is not efficient, and engineering development will be needed before practical feasibility can be demonstrated. (8) *Liquid fast freezing* and *sterilization* might be carried out with materials that do not contain chlorine, and a search for such chemicals could be productive.

Further technical details and summary tables on the various alternatives and the timing required are given in the technical discussions that follow. These treat the three major use areas--air conditioning and refrigeration, plastic foams, and solvents--and some of the more significant smaller uses.

AIR CONDITIONING AND REFRIGERATION

In the evolution of refrigeration systems during the past 80 years, while many refrigerants have been demonstrated to be technologically feasible, only a few have proved acceptable in terms of the increasing emphasis placed on nontoxicity, nonflammability, manufacturability, material availability, and retail costs.

For compression refrigeration cycles, certain chlorofluorocarbons individually and in mixtures represent the best available candidates for refrigerant usage. For absorption refrigeration systems, lithium bromide-water solutions and water-ammonia solutions have evolved as the best working fluids. The lithium bromide-water combinations are used when water-cooled heat rejection (i.e., evaporative condensation or cooling towers) is economically feasible. The water-ammonia combinations have been used for residential air-conditioning applications that utilize air-cooled condensers. However, the pressure requirements and the toxicity of ammonia limit the suitability of this system.

Mobile Air Conditioning

Mobile air conditioning has become widespread during the past 25 years. Today approximately 80 percent of new automobiles and 40 percent of new trucks are air conditioned. In addition, approximately 1.2 million vehicles are equipped with air conditioning each year by aftermarket installations.

Motor vehicle air conditioning is a major source of CFC emissions--the Rand study estimates approximately 83 million pounds per year in 1976, with a projected growth to 129 million pounds by 1990. The most effective short-range actions to reduce refrigerant losses would be to implement procedures for the recovery and reuse of F-12 during various phases of manufacture, in testing and servicing, and on vehicle disposal and to reduce leakage during normal use through design improvements. Development of hermetically sealed systems for mobile air conditioning will take many years and entail considerable cost and represents at best a long-term potential alternative. Use of alternative vapor-compression refrigerants such as F-22 and F-142b is possible but would require extensive system development (which might take five to seven years) as well as a large industry retooling cost. F-22 introduces only 14 percent to 35 percent as much chlorine (by weight) into the stratosphere as does F-12. However, because F-22 does introduce some chlorine into the stratosphere, it is perceived by industry as potentially subject to regulatory control. There will be considerable reluctance to make the necessary investment in development and redesign without assurance that F-22 use will not be banned or restricted.

There are several alternative refrigerants that could be substituted for F-12 in mobile air conditioners, but each will involve major penalties in performance, reliability, and costs. F-134a may be the best long-range alternative refrigerant candidate because it contains no chlorine; however, there is no currently known practical manufacturing process for this material, and it has not yet been fully tested for toxicity.

Several alternative refrigeration systems have been considered that could totally eliminate the use of CFC refrigerants for mobile air conditioning. At present, however, none of these could be adapted to mobile air conditioning in the short term without significant penalties in size, weight, efficiency, reliability, cost, or safety.

A more deailed discussion of some of the technological possibilities pertinent to mobile air conditioning is found in Appendix I.

Residential Air Conditioning

Most residential air conditioners and central air-conditioning systems use F-22 as a refrigerant. These systems contribute only a small amount of chlorine into the stratosphere. Industry is applying technology for improved system efficiencies, installation procedures, manufacturing processes, and quality control and service operations, all of which will tend to reduce CFC emissions further. Additional controls are unlikely to bring about significant reductions in total ozone-depleting emissions, although provisions for recovery and recycling of refrigerant on disposal of the unit could make a worthwhile contribution.

Commercial/Industrial Air-Conditioning Systems

Large air-conditioning systems (chillers) applied to office buildings, institutions, and industrial buildings and processes normally employ a secondary refrigerant--water--to perform the actual air-conditioning function. Ten percent of the chillers are lithium bromide-water or ammonia-water absorption systems. However, the majority of these air-conditioning systems (90 percent) are CFC compression systems, either positive displacement or centrifugal, using either F-11, F-12, F-114, or F-500. The utilization of a specific CFC refrigerant depends on the particular design and operating specifications.

There are no simple, short-term refrigerant alternatives for replacement in the commercial or industrial market applications. Absorption systems currently on the market are used where economically justified, i.e., where low-cost waste heat is available for powering the refrigeration cycle. Substitution of F-22 for other CFC refrigerants would require major product and system redesign involving significant capital expenditures.

Retail-Food-Store Refrigeration Systems

Emissions of F-12 and F-502 during manufacture and installation of retail-food-store refrigeration systems are less than 1 million pounds per year. Leakage and servicing emissions, however, add about 10 million pounds per year, with the ultimate disposal of equipment adding an additional 3 million pounds per year. Manufacturers and installers of this equipment are already considering steps to reduce leakage from original charging and, more importantly, to reduce losses during servicing operations. Recovery and recycling is technically feasible but may present economic problems. Some shifts from F-12 to F-502 may improve the impact of emissions on ozone reduction. (F-502 is an azeotrope consisting of 48.8 percent F-22 and 51.2 percent F-115.)

Household Refrigerators and Freezers

Emissions from home refrigerators and food freezers are approximately 6 million pounds per year. (This does not include emissions from the foam insulation in refrigerator and freezer walls, which is discussed elsewhere.) Only about 5 to 15 oz of F-12 refrigerant are used per unit. Significant further reduction of initial refrigerant charge below the 5- to 8-oz range may not be practical because of reduced system efficiency with the use of smaller components.

Losses of F-12 during manufacture and testing of refrigerated appliances are currently being minimized through the recovery and recycling of refrigerant in the factory and through introduction of alternative methods of leak testing, such as use of helium as a tracer gas and a mass spectrometer for detection.

Loss during normal use is negligible because household refrigeration units are hermetically sealed and therefore lose very little refrigerant during their useful life. Recharging is not required except in the case of system failure and resultant loss of charge.

The largest loss of F-12 from household refrigerators and freezers is the loss on disposal of the unit at the end of its life. Only when the unit is physically destroyed is its charge emitted to the atmosphere; units not destroyed continue to retain their F-12. Procedures and equipment could be developed to allow a service or salvage operation to recover the CFC charge at the time of major service or disposal; however, there is currently no economic incentive to do so. Frequent inspection at each service or salvage station would be required to assure compliance with any control regulation.

No satisfactory alternative refrigerant is known for small systems such as those used in household appliances. A major obstacle to the substitution of F-22 as a refrigerant is the electrodeposition of copper and copper salts (from the motor windings) on the internal surfaces of the expansion capillary and on compressor and motor-bearing surfaces. Deposition of these materials causes partial restriction of the capillary and resultant malfunction of the refrigeration system. (The use of larger expansion valves or expansion devices could alleviate this problem, and in fact larger systems, such as room air conditioners, are not so severely affected by this phenomenon because larger-diameter capillaries are used that can tolerate some deposition.) F-134a has undergone very limited testing in household refrigerators with little success because of more severe electrodeposition of copper, mechanical failure, and the absence of a satisfactory lubricant. Other refrigerants such as ammonia, sulfur dioxide, or methyl chloride, which were used in earlier years, involve risks associated with toxicity, flammability, corrosivity, and high operating temperatures.

Possible alternative refrigeration cycles or systems considered for household appliance use must meet stringent requirements of energy efficiency. Existing alternatives such as absorption systems have low energy efficiencies.

The prospects for developing a household refrigeration system using a non-CFC refrigerant that would receive general consumer acceptance appear sufficiently remote at this time that it is unlikely that the necessary product development effort will be undertaken.

Summary Tables

Tables 6.4-6.7 give information on the various alternatives to CFC use in air conditioning and refrigeration, including timing considerations, potential reduction in CFCs ultimately reaching the stratosphere, and penalties associated with introduction of alternatives. Alternatives are grouped in three categories: those that we judge to be promising, near-term alternatives (from the point of view of near-term technical feasibility); those that are potential long-term alternatives requiring further research; and those that we consider unlikely or unsuitable.

PLASTIC FOAMS

The use of chlorofluorocarbons as pneumatogens, or blowing agents, in the manufacture of flexible and rigid foams has grown dramatically since these products were introduced to the plastics industry about 25 years ago. The CFC-blown foams are used primarily in the bedding, furniture, transportation, appliances, building and construction, packaging,

TABLE 6.4 Summary of Alternatives for Mobile Air Conditioning

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1976 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
Reduction of emissions						
1. Improve factory procedures	1-3	1-3	9	None	Small	None
2. Reduced leakage	3-5	13-15	12	None	Small	None
3. Recovery and recycling	2-4	2-4	32	None	Large[b]	None
4. Reduced initial charge	3-5	13-15	1-17	None	Small	None
F-22	5-7	15-17	62[c]	Small	Large	Possible health hazard
F-22/F-142b	5-7	15-17	62[c]	Small	Medium	Possible health hazard
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
Hermetic design	5-7	15-17	40-65[d]	Uncertain	Large	None
F-134a	>10	>20	83	Small	Medium	Unknown
Alternative system (e.g., Stirling cycle)	>10	>20	83	Unknown	Large	Unknown
III. ALTERNATIVES CONSIDERED BUT DEEMED TO BE UNSUITABLE FOR ONE OR MORE REASONS						
Other (non-CFC) refrigerants[e]		The available materials have at least one of the following defects: toxicity, flammability, corrosivity, explosivity				
Absorption		Very low efficiency, toxic ammonia, water freezes				
Air cycle		Very low efficiency, high cost				
Thermoelectric		Very costly, very low efficiency				
Steam jet		Very low efficiency, water freezes, needs steam				

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[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation.

[b] If put into operation at the existing large number of service facilities.

[c] Based on the assumption that F-22 and F-142b are 25% as effective in depleting ozone, per pound, as F-12.

[d] Estimate by the CARCE Panel on Industrial Technology.

[e] Ammonia, sulfur dioxide, propane, methyl chloride, etc.

TABLE 6.5 Summary of Alternatives for Commercial Air Conditioning

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1976 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
F-22	5-7	10-20	7-9[b]	Small	Large	Possible health hazard
Leakage reduction	3-5	10-20	3	None	Medium	None
Improved service and disposal	2	2	4	None	Medium	None
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
Hermetic design	5-7	15-17	5-10	Uncertain	Large	None
F-134a	>10	>20	15	Small	Medium	Unknown
Alternative system (e.g., Stirling cycle)	>10	>20	15	Unknown	Large	Unknown
III. ALTERNATIVES CONSIDERED BUT DEEMED TO BE UNSUITABLE FOR ONE OR MORE REASONS						
Other refrigerants[c]		The available materials have at least one of the following defects: toxicity, flammability, corrosivity, explosivity				

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[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation.

[b] Based on the assumption that F-22 is 25% as effective in depleting ozone, per pound, as F-11 and F-12.

[c] Ammonia, sulfur dioxide, propane, methyl chloride, etc.

TABLE 6.6 Summary of Alternatives for Commercial (Retail-Food-Store) Refrigeration

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1976 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
F-22	5-7	20-30	8-10[b]	Small	Large	Possible health hazard
Containment, recovery, recycling	2	2	7	None	Small	None
Recovery and recycling at retirement	1	1	3	None	Small	None
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
F-134a	>10	>20	13	Small	Medium	Unknown
Alternative system (e.g., Stirling cycle)	>10	>20	13	Unknown	Large	Unknown
III. ALTERNATIVES CONSIDERED BUT DEEMED TO BE UNSUITABLE FOR ONE OR MORE REASONS						
Other refrigerants[c]		The available materials have at least one of the following defects: toxicity, flammability, corrosivity, explosivity				

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[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation.

[b] Based on the assumption that F-22 is 25% as effective in depleting ozone, per pound, as F-12.

[c] Ammonia, sulfur dioxide, propane, methyl chloride, etc. Note that ammonia is now used in a few commercial low-temperature systems but is not suitable for more widespread use.

TABLE 6.7 Summary of Alternatives for Household Refrigerators and Freezers

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1976 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction: Performance	Penalty for Reduction: Cost	Penalty for Reduction: Added Hazard
I. PROMISING ALTERNATIVES						
None						
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
F-22	4-8	20-30	5[b]	Small	Large	Possible health hazard
F-134a	>10	>20	6	Small	Medium	Unknown
Stirling cycle	>20	>20	6	Unknown	Large	Unknown
III. ALTERNATIVES CONSIDERED BUT DEEMED TO BE UNSUITABLE FOR ONE OR MORE REASONS						
Other refrigerants[c]		The available materials have at least one of the following defects: toxicity, flammability, corrosivity, explosivity				
Recovery on retirement		Very expensive, owing to small quantities, widely dispersed				

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[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation.

[b] Based on the assumption that F-22 is 25% as effective in depleting ozone, per pound, as F-12.

[c] Ammonia, sulfur dioxide, propane, methyl chloride, etc.

carpet underlay, flotation, and fast-food industries. The bulk of these uses fall into two categories: uses in which the CFC blowing agent affects the quality of the foam but the CFC is not and need not be retained in the final product (e.g., cushioning materials) and uses in which the insulating property of the CFC retained in the foam gives the finished product the desired properties (e.g., insulating materials in refrigerator walls and building construction). This latter use is of particular significance today as the current energy crisis is expected to lead to greatly expanded demand for thermal insulation.

The CFC-blown plastic foams are of four kinds: (1) flexible (open-cell) urethane foams, used primarily for cushioning, in which the CFC is not retained; (2) rigid (closed-cell) urethane foam, used primarily for thermal insulation, in which CFC retention produces the desired low thermal conductivity; (3) reaction injection molding of urethane foam, primarily for the manufacture of large, high-density parts for use in automobiles, furniture, and building construction, in which the blowing agent is retained but not in order to achieve a desired thermal conductivity; and (4) nonurethane foams, which include a variety of types in some of which the CFC is retained while in others it is not.

The Rand study estimates of 1977 and 1990 CFC emissions for the three main types of CFC-blown foams are as follows:

- Flexible Urethane Foams: 1977, 38 million pounds; 1990, 59 million to 97 million pounds
- Rigid Urethane Foams: 1977, 21 million pounds; 1990, 83 million pounds
- Nonurethane Foams: 1977, 24 million pounds; 1990, 71 million pounds.

Production of foams by reaction injection molding (RIM) is a new and growing technology. CFC use in RIM probably amounted to about 2 million pounds in 1978 and is likely to grow to 10 million pounds by 1990.* Since most of the emissions occur on disposal, total emissions during this period are expected to be substantially less than the cumulative total "banked" during this time.

In the absence of government regulation, the use of CFCs in foams of all types is projected to continue to

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*Estimate by CARCE Panel on Industrial Technology.

increase substantially during the next 20 years. This projected growth in CFC use in the United States is likely to be paralleled in other parts of the world, especially in the developed countries.

The rapid growth and widespread use of CFCs in plastic foam manufacturing occurred with good reason. The CFCs supplemented or replaced the older pneumatogen systems (e.g., CO_2 from the reaction of water and isocyanate) for one or more of the following reasons:

- CFCs enable flexible foams of finer and more uniform cell size, and lower density, to be produced.
- The high heat of vaporization of the CFC helps to dissipate the large amount of heat generated in the urethane polymerization reaction.
- The CFCs used in rigid foams (F-11 and F-12) have a very low thermal conductivity, a low vapor pressure at 25°C, and a low rate of diffusion. These factors are all critical to the performance of the closed-cell rigid foam in insulation.
- F-11 is soluble in urethane starting reactants but substantially insoluble in the polymerized foam. It also lowers the viscosity of the resin component for easier processing.
- In contrast to alternative blowing agents such as hydrocarbons, the CFCs are nonflammable.
- The CFCs are deemed to be among the safest substances encountered in industrial practice.

For these reasons, regulations restricting CFC use in the foam industry will carry serious penalties in performance or cost and may have a significant impact on that industry, although for some applications, satisfactory nonfoam products will emerge. The severity of these penalties will be relatively low in flexible urethane foams but will be high in rigid closed-cell foams used for insulation.

The four types of plastic foam products differ markedly from each other both in the total amounts of CFC emitted and when it is emitted--production, normal use, or disposal. They also differ in their suitability for various potential alternatives for reducing CFC emissions. These alternatives fall into four categories:

- Recovery and recycling of CFCs in production, normal use, or disposal.
- Substitution of non-CFC blowing agents for the CFCs.

- Restricting production of the foam product (which may lead to substitution of alternative, nonfoam products).
- New technology that reduces or eliminates emissions of CFCs.

The major conclusions reached about each product are summarized below. Further technological details are given in Appendix J.

Flexible Urethane Open-Cell Foam for Cushioning and Related Applications

CFC emissions from flexible urethane foam occur promptly during manufacture at a comparatively few large sites. There are little or no CFC emissions during normal use or at disposal.

Attempts to recover and recycle the CFC from the plant-processing air stream by absorption on activated charcoal have had only limited success and have not proven to be economically feasible. Research to find a more efficient process is needed.

Prospects for reducing CFC emissions by substitution of methylene chloride appear good. This could be accomplished in one to two years for 70 to 85 percent of the industry production, and in 3 to 5 years for the remaining 15 to 30 percent. Since substitution of methylene chloride for CFC in flexible urethane foam is already taking place to a significant extent, and is economically attractive, implementation of this alternative will have minimum negative impact on industry. Concern that methylene chloride may be carcinogenic creates uncertainties regarding worker health and the possibility of future regulation, although two recent reports (Friedlander *et al.*, 1978; Dow Chemical Company, 1979) suggest the absence of adverse health effects.

For some applications, depending on the loss in cushioning properties that can be accepted, a return to all-CO_2 blowing may be possible. This is likely to take longer to implement.

It may not be necessary to consider restricting the production of flexible urethane foam, in view of the success anticipated from substitution. No new foam technology other than substitution is foreseen in the near future that will eliminate the CFC emission problem.

Rigid Urethane Closed-Cell Foam for Insulation

CFC emissions from rigid urethane foams take place during manufacture (15-30 percent), during normal use (50 percent), and at disposal (20-35 percent). Manufacture takes place at a small number of sites where emissions are large; thereafter emissions occur at a very large number of sites, and emissions at each site are small.

Prospects are good for reducing emissions during manufacture from 30 percent to below 15 percent via process improvement and greater use of foil "cladding." Recovery of the CFC remaining in trim and scrap is not economical at the present price; however, it could become economically viable were the price to rise. Normal-use emissions can also be reduced by better cladding and vapor-impermeable metal foil, for example. However, the emissions that are prevented at these stages will only be delayed, finally occurring on disposal. Prospects for recovery and recycle at disposal are poor becuase of the large number of emitting sites and the small quantity of CFC at each site. Destruction of the CFC by pyrolysis on disposal would be prohibitively expensive.

The potential for substitution of methylene chloride or other non-CFC blowing agent in rigid urethane foams is poor, since no known substitute provides the thermal insulating quality that is essential in the final product. An extensive research program is needed to develop acceptable alternatives to F-11, and the prospects for success cannot be estimated.

Restricting production of rigid insulating foam to reduce CFC emissions would have a large negative impact on the plastic foam industry, some of which might be offset by reallocation among producers of other insulating materials. Substitution of less-efficient insulation could lead to a requirement for additional energy for home heating and cooling and for operating home appliances in which rigid urethane foams are now used.

At least one new foam insulation technology is foreseen that could potentially eliminate the need to use CFC in rigid foams for insulation. Foil-sealed open-celled rigid foams could be evacuated to produce an insulating wall of low thermal conductivity suitable for some applications. Extensive research and development will be needed to determine the feasibility and suitability of this and other new technologies.

Reaction Injection Molding (RIM) of Urethane Foam

CFC emissions from current RIM production of large, high-density, molded plastic parts for automobiles, furniture, and building construction are comparatively small but are growing rapidly. Manufacturing and normal-use emissions are small. More than 90 percent of the CFC is emitted at disposal at a multiplicity of small sites. Thus there is a continuing accumulation of banked CFC from this industry that will become significant by 1990.

The prospects for reducing disposal emissions are not good because of the large number of individual sites, each emitting only a small amount of CFC.

Substitution potential is reportedly good, using non-CFC blowing agents or gas frothing with air, carbon dioxide, or nitrogen. Restricting RIM production would carry a performance penalty. The development of new technology making it possible to produce very-high-density plastic parts without foaming could also reduce CFC emissions; however, because prospects for substitution of other blowing agents are good, such new technology may be unnecessary.

A significant industry and energy impact would result from near-term (1-2 years) restrictions on CFC use for RIM applications. A phased reduction over a longer time period (3-5 years) would give time for substitutes to be developed and should have minimum impact.

Nonurethane Foams

The principal nonurethane foams that use CFC pneumatogens are extruded polystyrene sheet and board stock, polyolefin foams, expanded polystyrene bead foam, and polystyrene loose-fill packaging foam. The largest of these products is the CFC-foamed extruded board stock used for insulation.

Polystyrene Extruded Boards for Insulation: Total emissions are large and growing. For polystyrene-foamed insulation boards, the CFC emissions occur to a limited extent during manufacture, to a larger degree during normal use, and to some extent at disposal. Complete and/or better cladding of extruded boards with impermeable skins could reduce normal use emissions but would increase ultimate disposal emissions.

The potential for substituting non-CFC pneumatogens is better than for rigid polyurethane foam, but still only fair. No viable new foam technology is foreseen that would be cost effective. As with the rigid urethane foam, mandatory restrictions on this use of CFCs in the near future would have substantial negative impact on the plastic foam industry (which might be offset in part by positive impacts on manufacture of other insulating materials), as well as a negative energy impact.

Other Nonurethane Foam Products: The other nonurethane foam products that use CFC blowing agents are the extruded polystyrene sheets (used primarily in food packaging), extruded polyolefin foams, expanded polystyrene bead foam, and polystyrene loose-fill packaging foam. In each case the CFC emissions are prompt, taking place during manufacture or soon thereafter.

Recovery of the CFC from plant and process air is not economic by activated charcoal absorption or any other currently known techniques. The potential for substituting non-CFC blowing agents is only fair. No new foam technology is foreseen for the near future that eliminates the problem.

There would be a significant negative impact on the plastic foam industry from rationing or otherwise curtailing use of CFC for these applications but no direct energy impact.

Summary

In flexible open-cell urethane foams used in cushioning, almost all of the CFC blowing agent is emitted during manufacture. Recovery of the CFC from large quantities of plant air via activated charcoal absorption does not appear to be economically practical. However, substitution of methylene chloride for the F-11 now used could effectively reduce current large emissions to zero in 3 to 5 years without large negative economic impacts on the industry or consumers.

In rigid closed-cell urethane foams used for insulation, only minor reduction in CFC emissions can be obtained via improved manufacturing processes and better cladding, for example. Substitution of non-CFC blowing agents does not appear feasible within the next 3 to 5 years.

In reaction injection molding of large high-density parts for the automobile and construction industries, substitution of non-CFC blowing agents or gas frothing could be developed, which could eliminate CFC emissions

TABLE 6.8 Summary of Alternatives for Flexible Urethane Foams

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1977 Data (in millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
Methylene chloride	2-5	2-5	27-38	Small	None	Possible toxicity
Carbon dioxide	7-10	7-10	38	Large	Large	None
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
Chemical blowing agent (thermally decomposing to emit nitrogen, carbon dioxide, etc.)	>10	>10	38	Large	Large	Unknown
Non-ozone-depleting fluorocarbons (e.g., octafluorocyclobutane)	>10	>10	38	Unknown	Large	Unknown
Frothing with air, nitrogen, and carbon dioxide	>10	>10	38	Unknown	None	None
III. ALTERNATIVES CONSIDERED BUT DEEMED TO BE UNSUITABLE FOR ONE OR MORE REASONS						
Recovery and recycle		Excessively high costs, health hazards with residual isocyanates				
Hydrogen blowing agents--pentane, ethyl ether		Highly flammable				

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[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation.

TABLE 6.9 Summary of Alternatives for Rigid Urethane Foams

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1977 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
At present there is no direct viable substitute for currently used F-11 with comparable insulating value and safety. Implementation of the alternatives below, while suitable for some applications, would make it impossible for rigid-urethane-foam producers to remain competitive with alternate types of insulation in many other applications						
Carbon dioxide	2-5	[b]	21	Medium; number of applications reduced	Large	None
Fiberglass, vermiculite, and other inert inorganic insulation	2-5	[b]	21	Medium; number of applications reduced	Large	None
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
Chlorine-free fluorocarbons	7-10	[b]	21	None	Large	Unknown

Methylene chloride	7-10	[b]	21	Medium	Small	Possible toxicity
Chemical blowing agents thermally decomposing to emit nitrogen, carbon dioxide	7-10	[b]	21	Medium	Large	Unknown
Frothing with air, argon, nitrogen, and carbon dioxide	7-10	[b]	21	None	Medium	None
Recovery and recycle in production	2-5	2-5	3-6	None	Small	None
III. ALTERNATIVES CONSIDERED BUT DEEMED TO BE UNSUITABLE FOR ONE OR MORE REASONS						
Recovery and recycle during normal use	Impractical because of large number of sites and small amount of CFC emissions at each site					
Recovery and recycle during disposal						

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[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation.

[b] Because of the efficient "banking" of the CFC in closed-cell rigid urethane foams, the emissions occur to a minor extent during manufacture (15-30%) and more during normal use (30-50%) and at disposal (20-55%). Therefore, the time to effect reduction in emissions via implementation of a nonozone-depleting alternative will be "immediate" for the minor percentage of production emissions, but futher reductions will occur progressively over a long period of time as already banked CFCs are gradually depleted.

TABLE 6.10 Summary of Alternatives for Urethane Reaction Injection Molding

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1977 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
Methylene chloride	2-5	2-5	<1	Small	None	Possible toxicity
Gas frothing with air, CO_2, N_2	2-5	2-5	<1	Small	None	None
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
Eliminate foaming	2-5	2-5	<1	Small	Small	None
III. ALTERNATIVES CONSIDERED BUT DEEMED TO BE UNSUITABLE FOR ONE OR MORE REASONS						
Recovery and recycle during production, normal use, and disposal		Impractical because of large number of sites and small amount of CFC emissions at each site				

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[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation.

TABLE 6.11 Summary of Alternatives for Polyolefin (Nonurethane) Foams

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC emissions, Based on 1977 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
F-142b	2-5	2-5	4[b]	Small	Large	Possible toxicity; flammable
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
F-22	2-5	2-5	4[b]	Medium	None	Possible toxicity
Frothing with air, carbon dioxide, and nitrogen	7-10	7-10	5	Medium	None	None
Frothing with pentane or other hydrocarbons	7-10	7-10	5	Medium	None	Fire hazard in manufacture
III. ALTERNATIVES CONSIDERED BUT DEEMED TO BE UNSUITABLE FOR ONE OR MORE REASONS						
Methyl chloride		Permeates out too rapidly; foam collapses				
Methylene chloride		Poor cell size and uniformity; foam collapses				
Recovery and recycle		Too many small sites, little CFC at any one site, high cost of collection and recovery				

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[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation.

[b] Based on the assumption that F-142b and F-22 are 25% as effective in depleting ozone, per pound, as F-12 and F-114.

TABLE 6.12 Summary of Alternatives for Extruded Polystyrene (Nonurethane) Sheet

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1977 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
F-142b	7-10	7-10	12[b]	None	Large	Possible toxicity
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
F-22	3-5	3-5	12[b]	Medium	None	Possible toxicity
Methyl chloride	3-5	3-5	16	Small	None	Possible toxicity
Methylene chloride	3-5	3-5	16	Small	None	Possible toxicity
Pentane	3-5	3-5	16	None	None	Flammable
III. ALTERNATIVES CONSIDERED BUT DEEMED TO BE UNSUITABLE FOR ONE OR MORE REASONS						
Recovery and recycle		Not practical because of high dilution				
Frothing with air, carbon dioxide, or nitrogen		Inferior quality foam				

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[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation.
[b] Based on the assumption that F-142b and F-22 are 25% as effective in depleting ozone, per pound, as F-12.

TABLE 6.13 Summary of Alternatives for Extruded Polystyrene (Nonurethane) Board

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1977 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
F-142b	7-10	7-50[b]	2[c]	Unknown	Medium	Possible toxicity
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
F-22	7-10	7-50[b]	2[c]	Medium	None	Possible toxicity
III. ALTERNATIVES CONSIDERED BUT DEEMED TO BE UNSUITABLE FOR ONE OR MORE REASONS						
Methyl chloride		Permeates out of foam too rapidly and lowers thermal insulation value				
Methylene chloride		Too strong a solvent, causes foam collapse; too high boiling point; permeates out of foam too rapidly				
Pentane		Flammability hazard				
Recovery and recycle		Too many small sites, little CFC at any one site, high cost of collection and reprocessing				
Frothing with air, carbon dioxide, and nitrogen		Insulation factor inferior				

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[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation.

[b] Immediate benefit of substitution would be to eliminate production loss of 15-20%. Later normal-use benefit of substitution would be to eliminate 30-50% of CFC emissions during normal use over 50-year period. Disposal emissions of 30-50% would be eliminated at disposal after 50 years of normal use of CFC already in the bank.

[c] Based on the assumption that F-142b and F-22 are 25% as effective in depleting ozone, per pound, as F-12.

TABLE 6.14 Summary of Alternatives for Expanded Polystyrene (Nonurethane) Beads

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1977 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
100% pentane	1-2	1-2	1	None	None	Flammability
F-142b	2-5	2-5	$<1^b$	None	High	Possible toxicity
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
Methylene chloride	7-10	7-10	1	Believed to be inferior	None	Possible toxicity
Methyl chloride	7-10	7-10	1	Believed to be inferior	None	Possible toxicity
F-22	7-10	7-10	$<1^b$	Believed to be inferior	Medium	Possible toxicity
III. ALTERNATIVES CONSIDERED BUT DEEMED TO BE UNSUITABLE FOR ONE OR MORE REASONS						
Recovery and recycle		Recovery of mixed CFC/pentane from large volume of plant process air not practical. Incomplete recovery at high cost with activated charcoal				

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[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation.

[b] Based on the assumption that F-142b and F-22 are 25% as effective in depleting ozone, per pound, as F-12.

within the next 3 to 5 years. No large negative impacts on the industry or energy are foreseen.

In the nonurethane extruded polystyrene foam boards used for insulation, only minor reduction in CFC emissions can be obtained via improved processing and better cladding, for example. Substitution of non-CFC blowing agents in the near future is not likely. There would be large negative industry and energy impact of curtailing CFC use.

In the remaining segments of the nonurethane foam industry, the extruded polystyrene sheet products, extruded polyolefin foams, expanded polystyrene bead foams, and polystyrene loose fill for packing are the most important. CFC emissions occur mostly during manufacture, and there is no good economic process known for recovering the CFC from large quantities of plant air. Substitution of non-CFC blowing agents is not possible in the near future. There would be a large negative industry impact of any immediate curtailment of CFC use, but no energy impact.

Extensive research will be required to develop economically feasible CFC recovery processes and to find satisfactory non-CFC substitute blowing agents for producing the rigid urethane foam used in insulation and the nonurethane foams. These must be considered long-term options.

These judgments are summarized in Tables 6.8-6.14.

SOLVENTS

Chlorofluorocarbons are used as solvents for cleaning and drying in specialized applications, primarily in the electronics industry. Their use is small when compared with other solvents, but solvent use is a significant source of CFC emissions.

F-113 is by far the most important CFC solvent. It is unique in its combination of characteristics, and it has found many industrial applications in spite of its relatively high cost. Nevertheless, in some applications substantial quantities of F-113 could be replaced by non-CFC chlorocarbon solvents with little or no penalty in factory practice, product performance, and health and safety factors. In other applications no viable alternative is available.

In many cases CFCs would not be used were it not for concern that alternative solvents (usually chlorocarbons) will be banned on the basis of the threat they pose to occupational health or lower-atmosphere pollution. Even though regulation of many of the chlorocarbons has not materialized (for example, 1,1,1-trichloroethane and methylene chloride), industry has in many cases chosen to introduce F-113 where it may not have been the ideal choice. Resolution of regulatory uncertainties affecting the non-CFC solvents would do much to clarify the status of these chemicals as potential viable alternatives to F-113.

The Rand study estimates that about 66 million pounds of F-113 were used (and emitted) as solvents in the United States in 1977, despite the fact that it is two to three times as expensive as alternative solvents. In general, F-113 is used for cleaning equipment of very high unit value, and the price of the solvent is not a major consideration in its selection. There is considerable uncertainty in the projected growth of F-113 use. Extrapolation of historical data suggest that usage could increase by a factor of 2 or 3 by 1990.

F-113 has an attractive combination of characteristics that are unique and irreplaceable in some applications. It has useful but limited solvent power, which is extremely important in cleaning complex electrical and electronic assemblies where compatibility with a variety of organic, inorganic, and metallic materials is essential. It poses minimal occupational health problems, and it is not flammable. These factors are particularly important where maintenance cleaning must be carried out on installed equipment in environments that are difficult to control. It is available in very pure form and does not degrade in use. This is important in cleaning electronics assemblies where residual chlorides or fluorides from solvent decomposition could cause corrosion and limit service life of the equipment. The stability of F-113 enables it to be used without stabilizing additives that can cause health problems and leave residues.

F-113 is often combined with other materials that enhance its solvent power. Azeotropes are favored because their composition does not normally change in use or in distillation for recycling. Stabilizers are needed, however, when azeotropes are employed.

A number of alternative chlorocarbons compete in solvent cleaning and drying applications. 1,1,1-Trichloroethane (also called methyl chloroform) is the foremost of these. It has higher solvent power than F-113 and therefore tends to compete with the azeotropes rather than the pure CFC. It is not flammable. Stabilizers are often added to 1,1,1-trichloroethane, and while it is possible that stabilizer residues or hydrolysis products will affect electronic equipment, this solvent has been used extensively and successfully in the electronics industry. 1,1,1-Trichloroethane may constitute a threat to the ozone layer, however, and for this reason caution should be observed in considering it as a viable substitute for F-113.*

Trichloroethylene is similar in many respects to 1,1,1-trichloroethane. Industry has tended to move away from trichloroethylene in recent years owing to concern about its possible carcinogenicity. Perchloroethylene is used extensively in the dry cleaning of clothing, but has also been reported to be carcinogenic. Methylene chloride is another possible alternative to F-113. Methylene chloride is an excellent solvent, and is widely used in situations where CFCs are not appropriate because of their low solvent power.

The four chlorocarbons mentioned have many of the favorable characteristics exhibited by F-113 and its azeotropes. Carcinogenicity, mutagenicity, and teratogenicity have been measured for each, but the data are often conflicting. There is therefore some question as to whether their use is likely to be restricted by Federal regulation from a health standpoint. These solvents should be considered as potential alternatives to F-113. In view of their relatively low cost they are likely to be favored by industry if the threat of regulation is removed.

The quantitative estimates quoted below on CFC use as solvents are based on discussions with industry experts and on the report by DuPont (1978).

Degreasing, Cleaning, and Drying

Degreasing, cleaning, and drying of manufactured parts are important in many industries. It is estimated that

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*The report, *Stratospheric Ozone Depletion by Halocarbons: Chemistry and Transport* (National Academy of Sciences, Washington, D.C., 1979) reports that as a result of tropospheric breakdown, 10 to 20 percent of the 1,1,1-trichloroethane released at the earth's surface reaches the stratosphere. F-113 is 57 percent chlorine, and 1,1,1-trichloroethane is 80% chlorine by weight. Thus, 1,1,1-trichloroethane will introduce 14 percent to 28 percent as much chlorine into the stratosphere as will F-113 for equal weights emitted.

about 20 percent of the F-113 produced is used in degreasing, cleaning, and drying operations; however, CFC use for this purpose is small in comparison with the use of chlorocarbons and other solvents. F-113 is used in the form of an azeotrope, because high solvent power is important. In view of the high cost of F-113 it is surprising that it finds applications to this degree in cleaning and drying of manufactured parts (as opposed to assembled equipment); this may be because, whereas the alternative chlorocarbons are suspected to be carcinogens, F-113 and its azeotropes are believed to be outstanding in terms of safety and health. Substitution of other materials for F-113 for degreasing, cleaning, and drying would probably not cause a major problem from a technological point of view.

Acetone is used in some drying processes, but it is unsafe because of its high degree of flammability. Factory fires are not unusual when acetone is used in large volumes, and this presents a threat to employee safety. Quantitative historical data, however, are difficult to obtain in this connection. Protective measures are expensive and unproven in effectiveness, and it is likely that acetone will continue to be replaced by nonflammable drying solvents.

Degreasing can also be accomplished by means of aqueous solvents in some cases. The solutions are usually alkaline and contain detergents. In critical applications, where they may be alternatives to CFCs, aqueous cleaners are possible sources of ionic residues and, consequently, are not favored, although aqueous solvents are being used for some degreasing operations in the electronics industry. Processing steps that immediately precede immersion in aqueous solutions (e.g., electroplating) are obvious choices. Waste-water disposal problems are considerable.

It has been estimated that there are over one million degreasing units (both liquid and vapor types) in the United States today, and the number is growing rapidly. (See EPA, 1979.) A typical industrial unit may be expected to emit a few thousand pounds of solvent per year, but the actual emissions depend on the facility size and degree of control. The larger units tend to be located in manufacturing environments and, consequently, are amenable to measures for controlling emissions. These measures include covers, refrigerated vapor barriers, carbon adsorption units for capturing emitted vapors, and operating procedures that maximize drainage of solvent from the cleaned parts.

Solvent emission control and reclamation are increasingly employed in connection with large degreasing stations. These operations are clearly cost-effective with relatively short pay-back times for investment, and further penetration of the technology can be expected. Smaller degreasing units are widely dispersed, and solvent reclamation is likely to be less cost-effective.

However, while reclamation is technologically feasible for chlorocarbon solvents, it is less so for CFCs. It is true that CFCs can be purified readily by distillation, but carbon adsorption of the vapors is much less efficient for CFCs than it is for chlorocarbons, and the practical use of this technology for CFCs has not been established.

Solder-Flux Removal

The removal of solder flux is an important operation in electronic equipment manufacture. Rosin flux is used predominantly, and 1,1,1-trichloroethane, perchloroethylene, and F-113 azeotropes are used extensively for flux removal. In this process the solvent power must be high enough to dissolve the rosin but not so high that it will attack organic materials that may be present in components on the printed wiring boards. It is estimated that about 20 percent of the F-113 produced is used in defluxing circuits. If the regulatory threat to 1,1,1-trichloroethane were removed, it is likely that CFC usage in solder-flux removal would drop sharply.

In present factory practice, mass soldering and flux removal are carried out on the same machines. Solvent emission is high, and modification to minimize these emissions will be very costly. About 10,000 of these machines are used in the U.S. electronics industry, and a plant investment totaling about $100 million would be required to reduce emissions substantially. This would be a significant burden in a competitive industry.

Water-soluble fluxes have been considered as an alternative to rosin for many years. The industry has resisted this development because these fluxes are corrosive and must be carefully removed, but there is recent evidence that water-soluble fluxes are being used successfully in California, where air pollution laws are most stringent. To convert all existing mass soldering machines to water-soluble fluxes would probably cost about \$100 million. Since mass soldering installations have life spans of about 10 years, it would be possible to convert the industry gradually to low-solvent emissions by regulating new installations. Emission control equipment or water-soluble flux equipment would create a relatively small financial burden if installed at the time of establishing a new station. This approach would be far less disruptive and less expensive than requiring conversion of existing machinery.

However, the suitability of water-soluble fluxes is a matter of considerable controversy among experts in the field. Many believe that product performance will suffer in consequence of ionic residues on circuits. Also, waste-water disposal may give rise to significant additional manufacturing costs.

Critical Cleaning and Drying

About 40 percent of the F-113 used is employed in connection with critical cleaning and drying of electronic, electrical, and mechanical assemblies. (F-11 may be used as a propellant in these operations, but CO_2 or other propellants can be substituted for the F-11.) In these cleaning and drying operations involving assemblies, it is extremely important that the solvent be effective in the removal of oily contaminants but benign in contact with plastics and other organic materials. In addition, residues must be avoided. The conditions under which the cleaning is done present special challenges to the health and safety of employees if dangerous substances are used.

F-113 is unique in meeting these demands, and no other solvents have been found to be acceptable. Chlorocarbons often cause crazing of plastics. Ketones, ethers, alcohols, hydrocarbons, and other oganic solvents present fire hazards and possible health problems. In many of these specialized applications of F-113, diligent search by users has failed to identify substitute solvents that do not have significant disadvantages.

In factory cleaning of assemblies, emission control will be difficult and costly. The assemblies tend to be large and poorly adapted to cleaning within enclosures. The structures are complex, and much solvent will be carried out of the cleaning station. Maintenance cleaning of installed equipment is an even greater problem. The environments are difficult or impossible to control.

Examples include radio transmission stations, aircraft electronics systems, telephone switching equipment, computer hardware, and repair centers for consumer electronics. At this time there appears to be no alternative to CFC solvent cleaning of assembled electronic, electrical, and critical mechanical equipment. The cost of eliminating CFCs from this area is difficult to estimate, but billions of dollars would be involved in terms of new equipment and product quality penalties.

Other Uses of F-113

There are also a number of smaller volume applications that account for about 17 percent of F-113 usage. It is used as a chemical intermediate, a chemical reaction medium, a cutting fluid, a carrier medium, and a dry-cleaning agent for garments. Alternatives will be difficult to find in most of these uses. Dry cleaning of garments (which accounts for about 3 percent of F-113 use) might be an area of unusual growth if perchloroethylene were to come under regulatory pressure.

Summary Tables

Tables 6.15-6.17 summarize the possible alternatives to F-113 in solvent applications.

OTHER USES

Other-use areas include, in roughly the order of decreasing current market size, sterilization, liquid fast freezing, proprietary applications for specialty products, fire extinguishing, stabilizing whipped toppings, and presurgical skin cleaning. In each instance, the use of CFCs has evolved primarily during the last decade because of uniquely advantageous properties of these materials. Available data are limited in these areas, but total U.S. emissions probably do not exceed 20 million pounds per year. The "other-use" areas represent in the aggregate about 7 percent of total CFC emissions and, assuming improvement in containment and increased use of recovery and recycle techniques in sterilization and fast-freezing applications, are not expected to increase as a fraction of total emissions in 1990.

TABLE 6.15 Summary of Alternatives for Degreasing, Cleaning, and Drying

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1977 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
Chlorocarbons[b]	1	1	13	Small	None	Possible health hazard
Aqueous cleaners	1-2	1-2	7	Small	Medium	Possible water pollution
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
Containment, recovery, and recycling	1-3	1-3	5-12	Small	Medium	None

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[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation and on estimates from DuPont (1978) and estimates made by the CARCE Panel on Industrial Technology.

[b] This group includes methylene chloride, trichloroethylene, perchloroethylene, and 1,1,1-trichloroethane.

TABLE 6.16 Summary of Alternatives for Solder-Flux Removal

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1977 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
1,1,1-Trichloroethane	1	1	12[b]	Small	None	Possible health hazard
Water-soluble fluxes	2-5	2-5	12	Small, but controversial	Medium	Possible water pollution
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
Containment, recovery, and recycling	2-10	2-10	3-12	None	Medium	None

[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation and on estimates from DuPont (1978) and estimates made by the CARCE Panel on Industrial Technology.

[b] Based on the assumption that 1,1,1-trichloroethane is 25% as effective in depleting ozone, per pound, as F-113.

TABLE 6.17 Summary of Alternatives for Critical Cleaning of Electrical, Electronic, and Mechanical Assemblies

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1977 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
None						
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
None						
III. ALTERNATIVES CONSIDERED BUT DEEMED TO BE UNSUITABLE FOR ONE OR MORE REASONS						
Containment, recovery, and recycling		Very high cost, if feasible				
Other solvents		Reduction in product quality through solvent attack on materials, also health and safety hazards				

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[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation and on estimates from DuPont (1978) and estimates made by the CARCE Panel on Industrial Technology.

The current market size and future market potential make unlikely any significant research effort to seek cost-effective alternatives of competitive quality as substitutes. However, there exist alternatives in most of these uses that could be substituted if the sacrifices in cost and/or quality of performance are deemed justified. In sterilization and liquid fast freezing (the two largest of the "other-use" areas) there are opportunities for emission reduction through improved methods of containment, recovery, or recycling. Some fraction of this can be achieved through improved training and more rigorous reporting procedures, but to achieve the full reduction indicated would require capital investments that are almost as large as the capital cost of the original equipment installed for these services.

Sterilization

Sterilization represents more than 50 percent of the total emissions for the "other-use" areas. In 1977, about 60-80 percent of the estimated 12 million to 14 million pounds of F-12 emissions came from the industrial sterilization of drugs and disposable medical and surgical supplies. The remainder was from sterilization in hospital and institutional applications.

In comparison with other existing sterilizing methods, the use of CFCs provides advantages in one or more of the following: safety, performance (and, particularly, consistency of performance), quality retention of material sterilized, cost, and convenience. As a result, usage has been growing rapidly.

Nearly all of the CFC use is in the form of a mixture of 88 percent F-12 with 12 percent ethylene oxide. Ethylene oxide is the most effective gas sterilant, but it is flammable, explosive, and toxic. Dilution of ethylene oxide with either CO_2 or F-12 eliminates the fire and explosion hazard and sharply reduces the toxicity. The F-12/ethylene oxide mixture is two to three times as effective as the CO_2/ethylene oxide mixture, operates at much lower pressure, and gives more consistent performance. The lower pressure results in lower costs of equipment and handling for both the sterilizer and the gas sterilant cylinders.

In the United States there are roughly 200 industrial sterilizers and roughly 6000 sterilizers in hospital and institutional use, with the latter approximately equally divided between chamber-type hospital units and desk-top units for clinics, offices, and other institutions. The total investment for equipment at original cost is about $40 million to $60 million, and this equipment cannot be used with other techniques.

The cost of the 200 industrial sterilizers in operation is about $100,000 each, and the average cost of gas sterilant is about $85,000 per year for each unit. Recovery and recycling methods are currently under active study and some are in initial use. For one of these, a reduction in use and emissions of 60 to 80 percent is claimed with a payout of less than two years for the $125,000 estimated cost of the equipment. In a second approach, which involves use of specially designed plastic bags for the materials sterilized, the F-12 requirement is claimed to be only one third of that for normal use.

Hospital-unit sterilizing chambers are about 5 percent the size of the industrial units. The second conservation method for industrial sterilizers could be applicable to the hospital units.

The proving and full implementation of recovery techniques would require a minimum of 5 years. Where implemented, these techniques could reduce emissions by 40 percent.

Other sterilization techniques are available and could be substituted for the F-12/ethylene oxide mixture. However, the existing F-12/ethylene oxide equipment is not suitable for use with any of these alternative methods, and a major investment in new equipment would be required. Steam sterilization is the most widely used alternative method and is the lowest in cost. Its use degrades product quality, and its use in replacement of CFC probably could be achieved only through government mandate.

Liquid Fast Freezing

The second largest of the "other-use" areas is liquid fast freezing of food. The first commercial system using food-grade F-12 as a liquid food freezant was installed in 1968. There are now about 30 such systems in operation, representing an investment of about $10 million. About 300 million pounds per year of specialty foods are processed, with a value of about $200 million. Freezant use rate is an important element of cost control. F-12 use is about 0.02 pound per pound of food frozen. Manufacturers of equipment and of CFCs and the food processors are emphasizing reduction of F-12 use. According to the Rand study, improvements in control could yield about a 40 percent reduction in F-12 use and thereby hold this CFC usage in 1990 close to current levels, even with expected growth in the industry. Routine reporting of procedures could provide an improved information base on CFC consumption and could thus help in achieving reduction goals.

Alternative technologies are in commercial operation and could be substituted for F-12 freezant at a sacrifice in food quality and cost. The CFC technique has penetrated the market primarily for highly valued foods, where it possesses cost and quality advantages.

Liquid nitrogen systems use 9 to 10 times more energy and liquid CO_2 systems 17 to 20 times more energy. Savings in energy from CFC use represent, at current consumption levels, the equivalent of about 800 barrels of oil per year. Quality of the product, using either nitrogen or CO_2, is similar (but CFC products are clearly superior in some specific uses), and cost will be severalfold greater. Overall replacement of F-12 freezant with nitrogen or CO_2 could represent an additional operating cost of about $6 million per year and an additional investment cost severalfold greater than the investment in present CFC systems.

Replacement of F-12 freezing with air-blast techniques would result in poorer product quality. Even though lower in operating cost, such substitution is not considered likely.

Fire Extinguishing

The Halon 1301 fluorocarbon used in fire-extinguishing applications is a bromofluorocarbon (BFC) rather than a chlorofluorocarbon. Concern has been voiced that ozone depletion resulting from BFC emissions might be greater, per pound, than that associated with CFCs.

The current sales and emissions in this area are small, but sales are projected to grow rapidly. Emissions are primarily from testing and inadvertent discharge and from actual fires and are forecast to increase much more slowly.

There are about 10,000 BFC total flooding fire-protection systems installed. About 80 percent are in spaces containing electronic equipment (computer rooms, telephone exchanges, aircraft control rooms, for example) that might be damaged by conventional fire-extinguishing agents. All of this usage has developed in the past decade.

The BFC system has unique advantages in personnel safety and fire control, and it appears to be an essential area of use. Strict control procedures are basic to fire-protection facilities. The cost of the BFC (about five times that of F-12) encourages conservation. There should be no need for imposition of additional controls.

Stabilizing Whipped Toppings

Use of food-grade F-115 as a whipped-topping stabilizer is small and exemplifies the market penetration in applications in which CFCs provide unique advantages. Nitrous oxide is used without F-115 for most of this market, but product quality is lower and full utilization of the product cannot be achieved. The CFC is used as an additive to the nitrous oxide propellant and results in a tenfold or more increase in the retention time for physical stability. The CFC provides consistent quality, permits whipped toppings of about half the butterfat content otherwise required, and allows the entire container contents to be used.

Current sales of whipped toppings are about 100 million units and are about equally split between the institutional 15-oz size and the retail 7-oz container. CFC is used in those applications in which added stability is important, representing about 25 percent of the market. CFC content per container is 0.095 oz and 0.15 oz, respectively, for the 7-oz and 15-oz sizes. Emissions are thus less than 200,000 pounds per year. About 15 companies are producers of the CFC product.

Although providing a clear performance advantage, eliminating use of F-115 in this service should not cause any significant costs to society or industry.

Presurgical Skin Cleaning

The use of F-113 in hospital rooms as a presurgical skin cleaner is another small use reflecting the unique advantages of CFCs. F-113 is an excellent solvent for removal of potentially bacteria-laden oils from the skin. The F-113 also improves adhesion of surgical drapes.

Diethyl ether (DEE), the skin cleaning material that F-113 replaced, could be brought back into use. DEE is

TABLE 6.18 Summary of Alternatives for Sterilization Applications

				Penalty for Reduction		
Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1977 Data (in Millions of Pounds per Year)[a]	Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
Containment, recovery, and recycling	2-5	2-5	6	None	Small	None
Containment, recovery, and recycling	7-10	7-10	9	None	Large	None
Carbon dioxide-ethylene oxide (near term)	2-5	2-5	5	Large	Large	None
Carbon dioxide-ethylene oxide (long term)	7-10	7-10	12	Large	Large	None
Radiation (near term)	2-5	2-5	4	Unknown	Large	Low
Steam	1-5	1-5	5	Medium	Large	None
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
Radiation (long term)	5-10	5-10	12	Unknown	Large	Low
Fluorocarbons not containing chlorine	8-12	8-12	12	Unknown	Unknown	Unknown
III. ALTERNATIVES CONSIDERED BUT DEEMED TO BE UNSUITABLE FOR ONE OR MORE REASONS						
Colo Chemical (glutaraldehyde)		Cost and performance penalties prohibitive				

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[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation.

TABLE 6.19 Summary of Alternatives for Liquid Fast-Freezing Applications

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1977 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
Containment, recovery, and recycling	3-7	3-7	2-3	None	Large	None
Liquid nitrogen	2-5	2-5	6-7	Medium	Large[b]	None
Liquid carbon dioxide	2-5	2-5	6-7	Medium	Large[b]	None
Air-blast system	2-5	2-5	6-7	Large	Large[c]	None
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
Fluorocarbons not containing chlorine[d]	8-12	8-12	6-7	Small	Small	Unknown

[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation.

[b] Energy consumption is increased by about a factor of 10 for liquid nitrogen and by a factor of nearly 20 for liquid carbon dioxide. Capital costs for new equipment would also be very large.

[c] Operating costs would be lower but capital costs for new equipment would be large.

[d] Small size of market makes it doubtful that a search for new materials can be justified.

TABLE 6.20 Summary of Alternatives for Fire-Extinguishing Applications

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC emissions, Based on 1977 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
Carbon dioxide extinguishers (near term)	2-5	2-5	<0.1	Large	Medium	Medium
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
None						
III. ALTERNATIVES CONSIDERED BUT DEEMED TO BE UNSUITABLE FOR ONE OR MORE REASONS						
Carbon dioxide extinguishers (long term)		Hazardous to personnel				
Conventional chemical extinguishers		Destructive to electronic and other specialized equipment				

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[a] Based on preliminary emission data and reduction estimates, provided by EPA, drawn from a study being conducted by the Rand Corporation.

TABLE 6.21 Summary of Alternatives for Stabilized Whipped Toppings

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1977 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
Nitrous oxide	1-4	1-4	~0.2	Large	Small	None
II. POTENTIAL ALTERNATIVES REQUIRING FURTHER RESEARCH						
None						
III. ALTERNATIVES CONSIDERED BUT DEEMED TO BE UNSUITABLE FOR ONE OR MORE PERSONS						
Carbon dioxide		The acidic character of these preparations leads to unsatisfactory shelf life				
Additives to improve nitrous oxide performance		Development costs prohibitive				

[a] Data from DuPont (1978).

TABLE 6.22 Summary of Alternatives for Presurgical Skin Cleaning

Alternative	Time to Implement (Years)	Time to Full Effectiveness (Years)	Potential Reduction in Annual Ozone-Depleting CFC Emissions, Based on 1977 Data (in Millions of Pounds per Year)[a]	Penalty for Reduction		
				Performance	Cost	Added Hazard
I. PROMISING ALTERNATIVES						
Diethyl ether (DEE)	1-3[b]	1-3[b]	0.1	Small	None	Flammability
Alcohols	1-2	1-2	0.1	Large	None	None

[a] Data from DuPont (1978).
[b] Hospital regulations against use of DEE would have to be repealed.

highly flammable. Replacement by the nonflammable F-113 has served to reduce the risk of fire and explosions in hospital operating rooms. F-113 is also less toxic than DEE. Many hospitals now prohibit use of DEE in this application.

Summary Tables

Tables 6.18-6.22 summarize the alternatives for these uses.

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7 REGULATORY AND SOCIOECONOMIC CONSIDERATIONS

The preceding chapter addressed such questions as

- *What measures for reducing CFC emissions are technologically feasible now or are likely to become so in the near future?*
- *What penalties would be associated with such measures, either in cost, performance, or associated hazards?*
- *How long would such measures take to implement, and how effective would they be?*

This chapter addresses issues that the policymaker and regulator must consider in assessing the technologically possible options and selecting strategies for implementing one or more of them. We address such questions as

- *What governmental actions will induce industry to adopt the measures identified above?*
- *What will be the consequences of these governmental actions? What will their effectiveness be in reducing the threat to stratospheric ozone, and what will be their other social and economic consequences?*
- *Can we determine whether the costs associated with a particular strategy are justified by the benefits expected? Is it possible to define a level of control that represents an optimum balance between costs and benefits?*

The word "cost," when used without qualification in this chapter, is used in the broad sense of "disbenefit" rather than in the narrow sense of a monetary payment.

In this chapter, we attempt to provide guidance to those who must assess the benefits and costs--however incommensurable--of alternative measures for reducing CFC emissions, by summarizing the state of current knowledge in this area in a manner that will be useful to the policymaker. Our analysis is designed to clarify two principal questions: (1) What are the likely consequences of alternative control strategies, in terms of their effectiveness in reducing CFC emissions and their other economic and noneconomic impacts? (2) Do the methodology and the information exist to make it possible for the policymaker to define an "optimal" level of CFC reduction, i.e., a level beyond which it is in effect more costly for society to impose controls than to suffer the consequences of CFC emissions?

The major portion of our analysis addresses the first question by providing information on the impacts of alternative control strategies and their expected effects in reducing CFC emissions. No attempt is made to assess the net benefits, economic or otherwise, that would result from a given level of CFC emission reduction. Instead, the amount of CFCs "not emitted" over a period of time is taken as a surrogate measure of the benefits of regulation. (Of course, reduced CFC emissions can be translated, in turn, into reduced health and environmental harms, as discussed in Part II of this report.) The policymaker is provided with a set of possible control strategies, an indication of their effectiveness in terms of CFCs not emitted, a discussion of the economic and noneconomic implications of each, and some cautionary remarks about uncertainty and the unavailability of certain important pieces of information. The discussion is couched in a format that we believe will be useful in assessing the cost-effectiveness of regulatory options. For a given level of CFC reduction, we address the question: What are the relative advantages and disadvantages of alternative control strategies?

Throughout the discussion, we address only domestic actions applying to U.S. citizens and firms. Thus the indicator of CFCs not emitted refers to the United States alone; similarly, the evaluation of the costs of control--in the broadest sense--is based on the United States alone. International implications of U.S. domestic policy and the possibilities of international coordination have been discussed in a previous chapter.

The final section of this chapter addresses the second question through a review and evaluation of three benefit-cost studies that have been carried out on the CFC problem. These studies attempted to assess in commensurable terms the trade-offs between the costs of controls and the advantages to be gained by reducing CFC emissions. We have attempted to determine what can be learned from these studies to provide guidance for the policymaker in assessing the available technological alternatives and control strategies.

Our primary conclusions are the following:

1. It is not possible to determine, from the information available today, a strict economic rationale for adopting a particular regulatory strategy, in the sense of choosing a strategy having benefits that demonstrably exceed its costs. The need for ethical judgments and the presence of technological as well as economic uncertainties require decisions to be made politically.

2. Even if a decision is made to regulate, and a level of reduction in CFC use agreed on, no single regulatory approach stands out as optimum across the full range of applications. Where reasonably effective and safe substutute products are available and would be adopted if they were cost-effective, a tax on CFC consumption--initially low but increasing on a regular scheduled basis --would induce change within industry without too severe an impact. Such a tax might even culminate in a ban. A system of permits or quotas, or immediate imposition of selective bans, would be more difficult to administer and only marginally more effective unless they were very stringent, which would introduce a risk of causing major disruption in some industries. Where substitutes are not available, a tax would serve only to increase costs and possibly drive certain users out of the market, without inducing technological changes. Where substitutes are available but of questionable acceptability from a health and safety standpoint, any inducement to change might have an ultimately undesirable impact. Here incentives for recovery and recycling might be a better solution.

3. Time-phased (graduated) approaches result in less disruption to industry than do sudden changes. Scheduled phasing of restrictions on CFC use will help industry plan, reduce adjustment costs, and deter introduction of new CFC uses.

4. In the absence of a nonhazardous substitute, any restriction on the use of CFC refrigerants for food preservation could have detrimental impacts far in excess of any benefits in terms of ozone protection.

SELECTION AND DEFINITION OF CONTROL OPTIONS

CFCs are used in a number of highly diverse products and processes and by a wide range of different industries. Products incorporating or made with CFCs meet different needs of consumers, and the various uses are valued differently by many social groups. This diversity presents a regulatory picture that is highly complex; there are a large number of possible regulatory control options, and they all have different economic, social, and administrative implications.

We have attempted to reduce the large number of possible control options. In doing so, we have tried to include all options worthy of serious consideration and to eliminate those that are inapplicable or unrealistic. In this section, we state the considerations and assumptions that have guided our choice of specific regulatory alternatives. In subsequent sections, we assess and compare the implications of each option considered.

There are at least two fundamental dimensions in the definition of control stragegies. One concerns the *scope* of regulation: which industries, classes of CFCs, processes, and products will be the target of controls, and how will the burden be allocated? The second conerns the *mechanism* to be used: how will the controls be effected--by setting standards, banning, levying taxes, or some other means? Each of these is discussed in turn.

Scope of Regulation

Chapter 6 discussed the commonly used chlorofluorocarbons, their applications, their relative contribution to the ozone problem, and the chemicals that could potentially substitute for them. For the present discussion it is useful simply to distinguish among

(a) The widely used, fully halogenated (nonhydrogenated) CFCs, primarily F-11 and F-12, which do not react with other chemicals in the troposphere, reach the stratosphere intact, and are believed to pose the biggest threat to stratospheric ozone;

(b) The hydrogen-containing CFCs, primarily F-22, which constitute a much smaller threat to stratospheric ozone since they do break down in the troposphere; and

(c) Chlorinated substances other than CFCs that may be potential substitutes for CFCs in certain uses but that may themselves pose a hazard to ozone in the stratosphere.

It is also helpful to distinguish between those CFC applications in which the CFC is used in the manufacturing process but is not retained in the finished product (e.g., flexible cushioning foams, industrial solvents, fast food freezing) and those in which the CFC becomes an essential part of the final product (e.g., rigid insulating foams, air conditioners, refrigerators). In the former case, whatever CFC emissions occur do so in the factory and are at least potentially susceptible to recapture and recycling technology, whereas the end product is of no concern from the CFC-emission point of view. In the latter case emissions may occur during shipping and installation, throughout the lifetime of the product, during servicing, or on disposal, usually at widely dispersed locations. While factory recapture and recycling can contribute some improvement, recycling during servicing and on final disposal could be a more meaningful step in emissions reduction if it were technologically and economically feasible.

We have chosen to consider five main groupings of CFCs or CFC uses as targets of controls:

- All CFCs, both fully halogenated and hydrogen-containing;
- All fully halogenated CFCs (i.e., all CFCs except F-22 and other hydrogen-containing CFCs);
- All CFCs used in manufacturing rigid insulating foams (primarily F-11);
- All CFC uses other than refrigeration and air conditioning;
- All CFC uses other than refrigeration of food and essential medical supplies and stationary air conditioning.

The possibility of exempting F-22 and other hydrogen-containing CFCs from regulatory action is considered because they pose less of a threat to stratospheric ozone, per pound emitted, than do the fully halogenated CFCs. Rigid insulating foams are considered separately because they are a growing source of emissions, they emit throughout their lifetime with virtually no possibility of recapture, and there are viable substitutes, at least for certain uses, in the market today. Refrigeration and air conditioning are considered separately since a case might be made for exempting them from controls because of their very high value to society, the lack of adequate substitutes for CFC refrigerants, and the high costs of eliminating CFCs in this application. Automobile air conditioning is arguably less essential than other

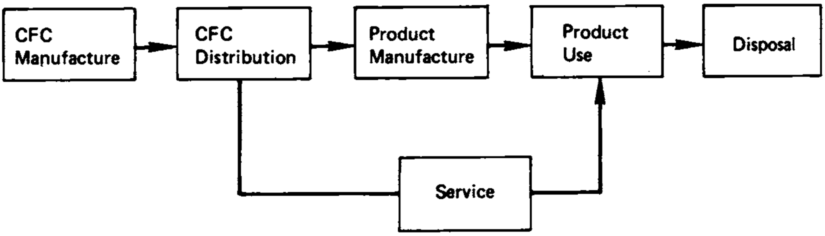

FIGURE 7.1 CFC production and use.

refrigeration and is now the largest single source of domestic emissions; therefore, a separate grouping was created in which mobile air conditioning as well as all nonrefrigeration uses are targets for control, while refrigeration and stationary air conditioning are excluded.

The chain of CFC manufacture, use, and disposal is illustrated schematically in Figure 7.1. For the most part, a company participates in only one or two of the steps in the chain. For example, the chemical firms manufacturing CFCs participate to a limited extent in CFC distribution but not in further downstream applications. Likewise, manufacturers of automobiles, home appliances, and chillers, for example, may also participate in the service sector but do not extend upstream into CFC manufacture and distribution. It is helpful to keep this in mind when considering the points in the chain at which different regulatory mechanisms might be applied. It is also worth noting that while there are only five U.S. CFC manufacturers, there are several hundred thousand service and repair facilities and millions of product users. Thus the further away from manufacturing that controls are applied, the more points of application there are, and the more complex implementation becomes.

Mechanisms of Control

Seven broad strategies for controlling or reducing CFC emissions have been considered. These are

1. Bans--either bans of all CFCs or bans for specific uses (e.g., prohibiting aerosol propellant uses, as has already been done);
2. Control-technology standards (e.g., requiring the best available control technology for reducing emissions; requiring containment, recapture, and recycling in

manufacturing and other industrial "in-plant" operations such as use of solvents);

3. Taxes on production or use (e.g., a surcharge on CFC-containing products);
4. Quotas implemented by marketable permits (e.g., government might specify overall ceilings for production or use, allowing firms to buy or sell "rights" to each other, within the overall limit);
5. A deposit-refund system (purchase of refrigerators might require a deposit of $50 for the CFC contained, which would be refunded when the refrigerator was turned in to a recycling center at the end of its usable life);
6. Recycling on disposal (government might require and subsidize collection centers for refrigeration equipment);
7. Public education and warning labels (government might require labels on CFC-containing products drawing attention to the environmental danger they pose).

These strategies can be applied individually or in combination for a total industry regulatory strategy.

Several items of the standard regulatory repertoire are missing from the above list. Most obvious of these is the absence of a "point-source emission standard" or "new-source performance standard" limiting the concentration of CFC that can be released to or found in the atmosphere. CFC emissions at the factory are difficult to monitor directly, so that attainment of any "point-source emission standard" would have to be evaluated by running a plant material balance, often over a variety of processes and activities. Not only would such a system be difficult and costly to administer, it would be hard to establish reasonable industry standards in the absence of extensive experience with applicable control technology. The same difficulties apply to "point-source" emission taxes.

Another approach missing from this list is the setting of quotas for the whole industry, e.g., all use of CFCs might be cut by 10 percent. This regulatory strategy is like a nonmarketable permit system, and would be less efficient economically since all uses, no matter how essential or how easy or difficult to control, would be treated alike.

Another standard approach--setting specifications for "safe" disposal--was also discarded. Aside from pyrolysis, which is both costly and polluting, no feasible methods exist for "denaturing" CFCs or perpetually containing them. Thus, recycling is the only immediately practical disposal option. Because of the difficulty in recapturing and recycling the CFCs retained in insulating foams, recycling on product disposal was considered feasible primarily in connection with CFC refrigerants. Containment, recovery, and recycling in the factory is potentially feasible in the manufacture of flexible foams and in the use of solvents, as well as in some of the smaller CFC uses.

Bans When the United States first acted to limit CFC emissions it opted for a ban on nonessential aerosol uses. This strategy could be expanded to other domestic uses of CFCs, or to all uses. A ban may be directed at a specific product or use, such as CFC use in the manufacture of flexible foams, or it may be directed at the manufacture of all CFCs or particular CFCs.

This approach relies on the force of law to end all or certain uses of CFCs. The uses are made illegal, and potentially severe penalties are prescribed to punish those in violation. Administrative agencies, law enforcement agencies, and the courts are used to police and enforce such prohibitions.

Much of the appeal of this approach is that, ideally, it can be simple and clear-cut. It can completely eliminate entire classes of CFC emission sources. However, a ban may require exemptions for highly valued uses in which no viable alternatives exist. If the criteria for exemption are not clearly defined and the exempted uses not easy to distinguish from those banned, this approach could quickly grow in complexity.

The primary problem with banning all CFC use is that the cost to society varies markedly from one use to another. The cost of the ban on aerosol propellant use appears to have been relatively low because, for the most part, acceptable substitutes were available. This is not the case for many other uses.

Standards for Control Technology Control technology standards fall into two major categories: standards defining specific emission control methods or equipment (technology standards) to be used in specified manufacturing or other activities involving CFCs, and requirements specifying that "best management practices" (e.g., better control of leaks and other fugitive emissions) be applied by those servicing or disposing of products containing CFCs. This approach uses the power of law to force industry to take specific measures designed to achieve a reduction of CFC emissions. Sanctions are provided to punish those who fail to comply with the standards (and to deter those considering violation). Penalties can be set to eliminate the economic benefit of noncompliance.

Compulsory application of designated emission-control technologies allows continued product use but with the added cost of the control measures. In some instances, this will yield the competitive edge to an alternative product or technology. In others, innovation in control technology may serve to keep the CFCs competitive. Emission-control steps can be implemented at appropriate points in the CFC use chain. This approach can be combined with a system of economic incentives to motivate those regulated to carry through with their compliance programs.

Taxes on Production or Use Taxes or surcharges have considerable appeal in that overall CFC use can be reduced by increasing the cost without the need for government decision as to where reductions should be made. Instead, this determination is made by the market. Where viable but more costly alternatives exist, a forced increase in CFC cost can lead to substitution if the increased cost exceeds the pre-existing cost differential. From a theoretical perspective the impact of a tax on production or on use is the same, and a uniform tax on production would be the simplest to administer (if only because there are far fewer producers than users). Its success would require that appropriate steps be taken to impose a similar tax on imports. As noted in Chapter 5, use-related measures may be an efficient way to deal with the overall issue, taking importation of CFC-containing products into account.

Any of these approaches toward taxing CFCs has the advantage that manufacturers know in advance how large the "price" will be, and the decision on how to adjust is left up to the individual business, which has incentives to find the least-costly approach. In order to facilitate economic adjustments, the tax can be phased in gradually and increased step by step until substitutes for CFCs are economically efficient. Another advantage is that the tax provides revenue that can be used to offset the program's administrative cost or to fund further research on stratospheric ozone effects. While there has traditionally been resistance in this country to such targeted use of tax revenues, there may be a countervailing trend developing as a result of recent pressures to reduce the burdens on the general taxpaying public.

A key feature of the tax strategy is that demand is affected only by the price of the product (including tax), with no *a priori* distinction made between essential and nonessential uses. Products could be taxed differentially, but this would increase the administrative complexity of the program. It would also substitute administrative or political judgments of relative importance for an impersonal bidding process.

Quotas Implemented by Marketable Permits The purpose of this strategy would be to hold CFC production or specific CFC uses to predetermined levels while minimizing direct government intervention in deciding which competing uses should get the limited supply. (The use of this option for some CFC applications need not preclude the use of other regulatory measures as well.) Initially, shares could be allocated on a "grandfather" basis, i.e., in proportion to historical output or use. Thereafter, firms (including importers) would be free to buy and sell rights from each other. It differs from the tax strategy in that affected producers or major users (as a group) would be able to plan production levels, but there would be some initial uncertainty as to costs. The desired result is the same--reduction of CFC use. The exchange of such permits might create antitrust problems. A period of advance notice would be desirable to minimize market perturbations.

Deposit-Refund Systems A particularly difficult aspect of CFC control is the large reservoir of CFCs contained in existing refrigeration equipment, which is released to the atmosphere during servicing or when the equipment is eventually discarded, long after production. Incentives for recovery at the point of service or disposal are currently lacking. Such incentives can, in principle, be provided by a deposit-refund system. The system could be applied either to the CFC-containing equipment or to the CFCs themselves. In the former case, additional measures will be required to ensure that the CFCs contained in the equipment are collected and recycled.

A pure refund has the disadvantages of (1) not being self-financing and (2) subsidizing new production (since, for example, if refrigerators are worth more as scrap because of the refund, consumers will be encouraged to buy new refrigerators more often, thus stimulating CFC production). To offset these problems, a deposit on purchase of new refrigerators would provide revenues to support refunds for proper collection of old refrigerators and would discourage purchase of new refrigerators and consequent production of additional CFC by effectively raising the initial price. Applicability of a similar system to automobile air conditioners could be explored.

Implementation of a deposit-refund system should incorporate a provision whereby each deposit would be invested, to be returned with compound interest, to compensate for the effects of inflation. It should be feasible to use deposits on new refrigeration equipment to finance immediate refunds on old equipment for which no deposit was ever paid. The size of the refund required to make the system work remains to be determined, as does the question of how to make the system pay for itself initially. Quasi-public or even private agencies could maintain the deposit-refund system. The long lag between purchasing and disposing of refrigeration equipment may make it difficult to return such equipment at the end of its life to the point of purchase. Thus the system should be a nationwide one that allows return to any collection center for a refund. To be effective, the refund must be greater than the cost of delivering the refrigerator, which suggests that many well-distributed collection centers will be needed.

Recycling on Disposal One of the key attributes of CFCs is their chemical stability and inertness. They are not actually consumed or destroyed in any of their uses. Emissions to the atmosphere invariably result not only from losses during manufacture and normal use but also on disposal of CFC-containing products. Emissions could be reduced if, on disposal of the product, the CFCs contained therein were recovered and recycled. Recycling, in the simplest case, means physical capture of contaminated or used CFC refrigerants from refrigerators and automobile air conditioners, and removal of dirt or contaminants by simple (high-pressure) distillation. Removal of CFCs from foams and subsequent recycling would be more costly and technologically difficult.

To encourage the creation of regional CFC recycling activities, either capital grants or operating subsidies could be considered. Such activities should be collocated with possible customers for the recycled product. The actual owners of the recycling centers could be municipalities, not-for-profit "resource recovery centers" of broader capabilities, or private firms. Note that a limit, or tax on CFC production--in contrast to use--could create a powerful incentive for recycling.

The recycled products would presumably be only slightly less valuable than the virgin material, so a recycler would have a salable product offering income potential. However, small local recyclers would have difficulty finding suitable market outlets, since most first-tier consumers are large firms. Moreover, they would have difficulty obtaining the contaminated CFCs unless they could offer to pay a reasonable price per pound for it from metal scrap dealers, junkyards, and auto service centers, for example. For the above reasons, and because of strong scale economies in the required capital equipment itself, it appears likely that recycling operations cannot be too decentralized.

Education and Labeling Education programs on the harmful effect of stratospheric ozone depletion for humans and the biosphere are also strategies. They can heighten an individual's awareness of the problem. To the extent that a person is motivated, he or she can take action to avoid use of products manufactured with CFCs and can dispose of appliances containing CFCs in such a way that the CFCs are recycled, provided facilities are available.

Mandatory printed warning labels have been used in the case of cigarettes, where there has been concern about their health effects. Warning labels are being used in Holland on aerosol cans so that individuals can make informed choices. This technique is not new and is of questionable effectiveness in reducing use. However, where there is no public consensus on what action to take, or as a first step, labeling helps those who are predisposed to cooperate to be able to do so.

Economic Incentives versus Traditional Regulatory Approaches

A word or two may be in order concerning the relative effectiveness of economic measures, such as taxes, and regulatory controls, such as quotas and emission control standards. (Note that a quota is a regulatory control that can be implemented by economic mechanisms such as marketable permits.) The two relate to two different but potent incentives that affect business decisions.

Economic measures appeal to the principle of minimizing costs or maximizing profits, and businesses using this principle as a basis for decisions are likely to respond rationally and predictably to measures such as a tax on CFCs as raw materials; they will reduce their use of CFCs as long as the marginal cost of reduced use is less than the tax they would have to pay. Regulatory measures appeal to a company's commitment to the rule of law--seasoned with a dash of fear of punishment or reluctance to bear the costs and/or the stigma of being a lawbreaker.

Both approaches can be effective. Businesses generally seek to reduce costs and shy away from inputs whose prices are rising. Businesses also often tend to be law-abiding even when a narrow assessment of economic costs and benefits suggests that noncompliance would be economically advantageous.

Both approaches contain pitfalls as well. The success of a tax depends on whether legislative and administrative bodies will set and keep the tax high enough to induce the desired effect. Antitax lobbying may direct attention to the economic burden associated with the tax rather than to its desired impact and may succeed in keeping the tax rate sufficiently low that it creates no real incentive to cut use. This is apparently what has rendered the effluent taxes of several European nations ineffective (Johnson and Brown, 1976, page 56). The success of a regulatory measure depends on the costs of compliance, the penalties for noncompliance, the effectiveness of enforcement, and the presence or absence of a measure of societal opprobrium attached to the regulated behavior. In this country the "polluter" now bears a social stigma and may suffer secondary penalties, such as loss of good will, which can ultimately have economic consequences.

Regulatory standards are sometimes contrasted unfavorably with economic approaches like emission taxes on the ground that standards are less efficient, less cost-effective, and stimulate less technological innovation. While there is merit to this criticism, it fails to take into account some of the realities that affect implementation of both standards and economic incentives. For example, to identify a tax ($X per pound of emissions) that would achieve economic efficiency, the full benefits of pollution control would have to be quantified, which can only be done in theory. (Of course, to devise an optimal standard requires essentially the same information.) Hence this particular argument is somewhat hypothetical.

Uniform standards are less cost-effective than a uniform tax program in a world where the marginal costs of emissions control vary widely from source to source. Uniform standards force all sources to achieve the same level of control, even though the marginal cost of compliance for some sources is far higher than that for others. A tax set to achieve the same aggregate level of emission reduction would allow flexible response reflecting cost difference; as a result any given level of abatement would cost society less.

Bans, nonmarketable permits, and control technology standards may create less incentive for emission control than would taxes. If a standard specifies a given technology, there is no incentive to improve. If, as is more common, it establishes an emission level or control level, it does create an incentive to find the least expensive ways of achieving that standard. Such incentives have proven effective in air-pollution control programs. On the other hand, the standard dissuades industry from developing ways of achieving higher levels of control, which could then become "best available technology" and be imposed by regulation. A tax paid on all CFC use would create an incentive to find ways of further reducing emissions (at a marginal cost lower than the tax).

The Control Options

The 5 CFC-use groupings and 7 regulatory mechanisms set forth above yield 35 possible regulatory options. We have selected 15 of these for analysis, on the basis of a variety of considerations having to do with the point in the CFC use chain at which emissions occur and the practical difficulties associated with certain kinds of controls. The control options selected fall into five broad categories, viz., bans, taxes, quotas implemented by marketable permits, emission-control technology standards, and disposal standards.

The effectiveness of both taxes and permits or quotas depends on the level at which they are set. We have considered two levels of taxes: one that would induce readjustment in CFC usage in situations in which alternative products are already nearly competitive or control strategies nearly economical and one that would increase CFC costs sufficiently to induce changes in areas where alternatives are not so near at hand. We have assumed, in a general way, that the first of these would be accomplished by a tax roughly equivalent to or severalfold greater than the cost of the CFCs and that the second would be achieved by a tax roughly an order of magnitude larger. Our assessment does not depend on knowing just how large these taxes are, and we have denoted them as "modest" and "high." Additional study will be required to establish appropriate taxing levels more precisely, and a tax, if imposed, would doubtless have to be adjusted step by step as its effectiveness and market impacts are observed.

We have considered three levels of quotas: one that would maintain the status quo and two that would have the same impact on emissions as the "modest" and "high" taxes. These two quota-permit measures thus are equivalent in effectiveness to taxes at the two levels but differ in implementation and enforcement (although we recognize that in practice differences in implementation could result in differences in effectiveness).

The 15 options selected for examination are shown in Table 7.1. In all these options, consideration could be given to government-provided financial assistance, where needed, to permit retooling and retraining. For the tax options, such financial assistance could be funded by tax revenues. For the permit options, it could be funded by permit fees. For all options, and particularly for the ban options, consideration could be given to exemptions for "essential" uses such as hospital sterilization. And for all options, implementation can either be immediate or phased in over a period of years.

EFFECTIVENESS OF THE CONTROL OPTIONS

Reductions in CFC emissions can be brought about by banning certain uses, by requiring certain emission control or recycling technologies, or by measures that raise the costs of CFC use and thus induce substitution or reduce demand. (Note that mandatory emission controls also serve to raise the cost of CFC use and may thus lead to reduced demand for CFC-related products.)

The overall effectiveness of any option other than a specific ban depends on three components:

- The effectiveness of the technology;
- The extent of substitution of other processes or designs not using CFCs;
- The extent of reduction in consumer demand for products.

TABLE 7.1 The Fifteen Control Options Selected for Examination

Option	Objective	Primary CFCs Affected	Industries Affected	Possible Modes of Implementation	Potential Exemptions or Special Treatment[a]
Bans					
(1) Ban all CFCs	Eliminate all U.S. contributions to global CFC emissions	All CFCs	All CFC-producing and-using industries	Ban on production, sale, or use within the United States of all CFCs	Small-quantity uses essential to health and safety, e.g., sterilizing medical and surgical supplies, fire extinguishing
(2) Ban all fully halogenated CFCs	Eliminate all U.S. contributions to global emissions of those CFCs that pose the greatest threat to the ozone layer	F-11, F-12, F-113, F-114	All CFC-producing and-using industries except household air conditioning	Ban on production, sale, or use within the United States of fully halogenated CFCs	Same as (1)
(3) Ban use of CFCs to produce rigid insulating foam	Eliminate a major U.S. source of virtually unrecoverable CFC emissions	F-11, F-12	CFC producers, foam suppliers and fabricators, construction and building materials, refrigerators and freezers	Ban on production, sale, or use within the United States of rigid insulating foam blown with CFC	Insulating panels for thin-wall refrigerators
(4) Ban all CFC uses other than refrigerants	Eliminate all U.S. contributions to global CFC emissions except those perceived as most essential to material standard of living	F-11, F-12, F-113, F-114	All CFC-producing and -using industries other than air conditioning and refrigeration	Ban on CFC sale or use within the United States for nonrefrigeration purposes	Same as (1)
(5) Ban all CFC uses other than refrigeration of food and essential medical supplies and stationary air conditioning	Eliminate all U.S. contributions to global CFC emissions except those most essential to health and industry	F-11, F-12, F-113, F-114	All CFC-producing and-using industries other than commerical and household refrigeration	Ban on CFC sale or use within the United States for purposes other than refrigeration of food and medical supplies and stationary air conditioning	Same as (1)

Taxes and Quotas

(6) Tax on all fully halogenated CFCs	Reduce U.S. contribution to global emissions of those CFCs that pose the greatest threat to the ozone layers	F-11, F-12, F-113, F-114	All CFC-producing and -using industries except household air conditioning	Tax on production or sales of fully halogenated CFCs and of equipment or material made with or containing fully halogenated CFCs (taxes may be "tuned" by gradually increasing rates until the desired restriction in CFC use is achieved)	None
(7) Quotas for all fully halogenated CFCs	Same as (6)	Same as (6)	Same as (6)	Ceilings on production or sale of fully halogenated CFCs, or on purchases by individual firms, implemented by marketable permits (quotas may be set to freeze use at current levels or to reduce use to any desired level)	None
(8) Tax on CFC uses other than as refrigerants	Reduce U.S. contributions to global CFC emissions except those perceived as most essential to material standard of living	F-11, F-12, F-113, F-114	All CFC-producing and-using industries other than air conditioning and refrigeration	Tax on sales of CFCs for nonrefrigeration use or on production or sale of nonrefrigeration equipment of material made with or containing CFCs; taxes may be tuned as in (6)	None
(9) Quotas for CFC uses other than as refrigerants	Same as (8)	Same as (8)	Same as (8)	Ceilings on purchases of CFCs for nonrefrigeration use or on purchases of nonrefrigeration equipment or material made with or containing CFCs; quotas may be set and may be implemented by permits as in (7)	None

TABLE 7.1 (continued)

Option	Objective	Primary CFCs Affected	Industries Affected	Possible Modes of Implementation	Potential Exemptions or Special Treatment[a]
(10) Tax on CFC uses other than refrigeration of food and essential medical supplies and stationary air conditioning	Reduce U.S. contributions to global CFC emissions except those most essential to health and industry	F-11, F-12, F-113, F-114	All CFC-producing and-using industries other than commerical and household refrigeration	Tax on sales of CFCs or on production, sale, or purchase of equipment or material made with or containing CFCs for use other than refrigeration of food and medical supplies and stationary air conditioning; taxes may be tuned as in (6)	None
(11) Quotas for CFC uses other than refrigeration of food and essential medical supplies and stationary air conditioning	Same as (10)	Same as (10)	Same as (10)	Ceiling on purchases of CFCs or on production, sale, or purchase of equipment or material made with or containing CFCs, for use other than refrigeration of food and medical supplies and stationary air conditioning; quotas may be set and may be implemented by permits as in (7)	None
Control Technology and Recycling					
(12) Mandatory emission control technology in all manufacturing operations	Reduce U.S. contributions to global CFC emissions from manufacturing	All CFCs	All CFC-producing and-using industries	Identify an appropriate "best available control technology" (BACT) for each major CFC-emitting manufacturing process; these may include emission capture, containing, recycling, or destruction and may include "best management practice" (BMP) such as control of fugitive emissions and "best	Very small manufacturing operations and those for which no economically or technologically feasible control technology exists

				design practice" (BDP) such as hermetically sealed equipment; require BACT, BMP, or BDP, or combinations, to be installed in all manufacturing facilities; induce use by tax incentives or subsidies. NOTE THAT THIS APPROACH WILL REQUIRE PERIODIC UPDATING (IF STANDARDS ARE NOT TO STIFLE DEVELOPMENT OF NEW TECHNOLOGY) AND INSPECTING	
(13) Mandatory emission control technology in refrigeration and air conditioning servicing and repair	Reduce U.S. contributions to global CFC emissions from servicing of refrieration equipment	F-11, F-12, F-22	Refrigeration and air-conditioning manufacturers and service and repair industries; refrigerant manufacturers	Identify and require BACT, BMP, or BDP, or combinations, as in (12); induce use by tax incentives or subsidies. NOTE THAT THIS APPROACH WILL TEND TO INDUCE USE OF FULLY SEALED REFRIGERATION EQUIPMENT	None
(14) Mandatory recycling of CFCs used in refrigeration and air conditioning	Reduce U.S. contribution to global CFC emissions from disposal of refrigeration equipment	F-11, F-12, F-22	Refrigeration and air-conditioning manufacturers and service and repair industries; refriggerant manufacturers; possibly dealers and other sales outlets	Require all used refrigeration equipment to be sent on disposal to authorized recycling center for reclamation of CFCs; require all spent refrigerant from rechargeable equipment to be sent to authorized recycling center. Responsibility for pickup, sorting, and maintenance of recycling centers could be divided among owners, dealers, and government bodies	Large central air-conditioning systems and built-in refrigeration systems that cannot readily be removed from the structure and transported may require special provisions for draining refrigerant to return to recycling center or to dealer

TABLE 7.1 (continued)

Option	Objective	Primary CFCs Affected	Industries Affected	Possible Modes of Implementation	Potential Exemptions or Special Treatment[a]
(15) Refundable deposit on CFCs in refrigeration and air-conditioning equipment	Reduce U.S. contribution to global CFC emissions from servicing and disposal of refrigeration equipment	F-11, F-12, F-22	Refrigeration and air-conditioning manufacturers and service and repair industries; refrigerant manufacturers; possibly dealers and other sales outlets	Require deposit on purchase of equipment or refrigerant. For nonrechargeable equipment, deposit is refunded on disposal of equipment at authorized recycling center. For rechargeable equipment, deposit is refunded on return of spent refrigerant to authorized recycling center.	Large central air-conditioning systems and built-in refrigeration systems that cannot readily be removed from the structure and transported may require special provisions for draining refrigerant to return to recycling center or to dealer

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[a] Potential exemptions or special treatment is indicated for essential purposes in the case of bans, where CFC use for these purposes would otherwise be forbidden, but not in the case of options that reduce but do not forbid use; under such options the essential uses would be permitted but would be more costly.

There are uncertainties in each of these components for all control options examined, except a complete ban. The first component is fundamentally technology-limited. An estimate might be made of emission reductions achievable by employing various specific available technologies in particular ways, but it is difficult to take future technological innovation into account. The other two components cannot be estimated precisely without a better understanding than we have now of the responses of industrial users and eventual consumers of CFC-related products to changes in CFC prices.

The effectiveness of a strategy also depends on its timing. Since CFCs accumulate in the atmosphere, it is the total accumulation over a period of time, rather than the emission rate at any one moment, that determines effectiveness. A strategy that takes time to implement but works well in the long run may thus be more effective than one that can be implemented quickly but accomplishes relatively little.

The following discussion assesses the potential effectiveness of the basic strategies under consideration: bans, taxes, quotas and marketable permits, and control and disposal requirements. The technology-based component is estimated quantitatively for all the major strategies. This is followed by a discussion of the ways in which implementation of these strategies may be limited, in practice, by lack of important information and by the need for compromise in administration. Finally, possible negative feedbacks arising from world-market responses are discussed.

Potential Effectiveness of the Control Options

The maximum possible effectiveness of the 15 options defined previously can best be examined in relation to a "baseline" representing the total emissions projected to occur as a result of domestic CFC use over the period 1978 to 1990 if no further regulatory action is taken. To understand what this baseline represents, it is important to be clear about the distinction between use and emissions.

CFC Usage and Life-Cycle Emissions Since all the CFC used in a product ultimately escapes to the atmosphere, the total emissions to be expected from a given year's production is equal to the total amount of CFCs produced, or sold, or used during that year. It is *not* equal to the total emissions in that year. For prompt emitters, such as flexible foams, virtually all of the CFC used is emitted during or immediately after manufacture, and CFC usage is equivalent to CFC emissions. In the case of slow emitters, such as refrigerators and rigid foams, the bulk of the CFC is retained in the product until years later, when it escapes on ultimate disposal; some CFC may also be emitted during normal product use and servicing. For such products only a portion--sometimes a small portion--of the CFCs used in a given year are emitted that same year; the rest enters the CFC "bank" and is emitted later. Similarly, only a portion of the year's emissions come from that year's production; the remainder comes from the "bank" and represents contributions from the production of previous years. CFC use is increasing, and the size of the "bank" is increasing too; the Rand study estimates that by 1990 the domestic CFC "bank" will be growing at a rate of about 160 million pounds per year. As long as the bank size continues to grow, total annual emissions will be less than total annual production.

The rate of ozone depletion depends on the rate of actual CFC emissions to the atmosphere. Production figures are, however, easier to obtain and more reliable than emission figures, which must be estimated. Moreover, since all the CFC produced will eventually be emitted, and since the average time that CFCs stay in the "bank" (10-30 years) is shorter than the average time it takes for emitted CFCs to reach the stratosphere (20-50 years), a case can be made for considering each year's total CFC production, in place of annual emissions, as a measure of the damage to stratospheric ozone. A year's production, or usage, may be thought of as equivalent to the total amount of CFC that will ultimately be emitted as a result of manufacturing and service activities carried out during that year, i.e., as the total emissions expected during the full life cycle of products manufactured that year, or "total life-cycle emissions" for the year. In the case of rigid urethane foams, this equivalence is accurate. In the case of air-conditioning equipment, which may require replacement charges during the course of its useful life, the CFC refrigerant required as replacement charge for a piece of equipment manufactured this year may not be produced until some future year. It is thus not part of this year's production, but it is included in this year's "total life-cycle emissions" for air conditioners. Similarly, the CFC refrigerant produced this year and used as replacement charge for an air conditioner produced in an earlier year is included in this year's production but in the earlier year's "total life-cycle emissions."

It is important to note that a sudden ban on CFC production would not result in an immediate cessation of emissions, as emissions from the "bank" would continue for several decades or longer. Moreover, such a ban would probably not be complete, since in all likelihood it would allow for a certain level of continued production to be used as replacement charge in existing air-conditioning equipment. Moreover, once emissions declined, their impact on stratospheric ozone would continue to be felt for many decades.

With this understanding in mind, we will for the remainder of this chapter distinguish between actual emissions of CFC in a given year, as reported in Table III.2, and emissions that will occur at some time--now or in the future--as a result of activities carried out during that year. This latter concept will be called "CFC use," and it is almost, but not quite, equivalent to the amount of CFCs actually produced or used during that year. It is more nearly equivalent to that year's "total life-cycle emissions," but we will avoid that phrase in order to avoid confusion with actual emissions.

We will use figures taken from the Rand study, and since that study is confined to fully halogenated CFCs, the figures we present reflect that limitation. Thus, for example, household air conditioning, which uses F-22 as a refrigerant, is not included in our tables, nor are other refrigeration applications using F-22 and F-152a.

Baseline Estimates Estimated domestic CFC usage is shown in Table 7.2 for the five major categories, and principal subcategories, of CFC applications. Estimates have been made for the years 1978, 1985, and 1990, on the basis of the Rand projections. In 1978, refrigeration and air conditioning constitute the largest category of use, accounting for 41 percent of the CFCs produced. Mobile air conditioning alone represents 25 percent of the total. By 1985, however, blowing agents will have surpassed refrigerants as the largest category of use, and by 1990 refrigerants are predicted to fall to 24 percent of the total. The fastest-growing subcategory is rigid urethane foams, predicted to increase nearly fourfold from 58 million pounds in 1978 to 223 million pounds in 1990, an annual growth rate of 12 percent. By 1990, rigid urethane

TABLE 7.2 Baseline Estimates of Domestic Nonaerosol Usage of Fully Halogenated CFCs--1978, 1985, 1990[a]

	Estimated CFC Usage in Millions of Pounds		
Application	1978	1985	1990
Refrigerants	*157*	*175*	*188*
Mobile air conditioning	94	105	113
Chillers[b]	12	16	18
Retail food stores	11	11	11
Household refrigerators and freezers	7	8	10
Other refrigerant uses[c]	33	35	36
Blowing Agents	*123*	*227*	*381*
Flexible urethane foams	38	58	79
Rigid urethane foams	58	127	223
Reaction injection molding[d]	[f]	[f]	[f]
Nonurethane foams	27	42	79
Solvents	*81*	*122*	*163*
Other Uses	*22*	*41*	*62*
Sterilization	15	27	40
Liquid fast freezing	7	14	22
Other[e]	[f]	[f]	[f]
TOTAL NONAEROSOLS	383	565	794

[a] The figures shown in this table are estimates of total life-cycle emissions and are based on preliminary estimates for 1976-1977 and 1990, provided by EPA and drawn from a study being conducted by the Rand Corporation and on data reported by DuPont (1978). Estimates for 1978 and 1985 were calculated by assuming a constant exponential growth from 1976-1977 to 1990.

[b] Chillers are central air-conditioning systems employing both a primary (usually CFC) and a secondary (non-CFC) refrigerant, usually used in large buildings of three or more stories.

[c] "Other refrigerant uses" includes a variety of applications, some of which use hydrogen-containing CFCs as well as fully halogenated CFCs. These applications include food processing and handling other than in retail stores (e.g., transportation, warehouses); industrial process refrigeration; small appliances (e.g., water coolers, icemakers, dehumidifiers). These applications were not addressed in the Rand study.

[d] CFC use for reaction injection molding is very small and was not included in the Rand or DuPont analyses.

[e] "Other" includes fire extinguishing, whipped-topping stabilizing, and presurgical skin cleaning. CFC use in these areas is very small and was not included in the Rand or DuPont analyses.

[f] Applications in which very small amount of CFC are used.

TABLE 7.3 Baseline Estimates of Domestic Use of Fully Halogenated CFCs in Four Specific Product Groupings (in Millions of Pounds)[a]

Usage Category	1978	1985	1990	Sum: 1978-1990
Total nonaerosols use	383	565	794	7355
Rigid urethane foams	58	127	223	1605
All uses other than refrigeration and air conditioning	226	390	606	5105
All uses other than refrigeration and stationary air conditioning	320	495	719	6345

[a] Based on the data in Table 7.2.

foams are predicted to account for 28 percent of total CFC production.

Regulatory strategies will be evaluated in terms of their effectiveness in reducing use of fully halogenated CFCs in four product groupings: total nonaerosols, rigid urethane foams, all uses except refrigeration and air conditioning, and all uses except refrigeration and stationary air conditioning.

The baseline estimates for the four groupings are presented in Table 7.3. The data were calculated by aggregating the data presented in Table 7.2. The fourth column, captioned "Sum: 1978-1990," estimates the total emissions expected to result from service activities and products manufactured during that 13-year period.

Traditional Regulatory Strategies The impact on emissions of a ban on CFC production or use can be directly assessed if one assumes that it will be implemented effectively. Banning any of the products or product groups would eliminate all of the baseline use identified for that product, or set of products, in Tables 7.2 and 7.3. Thus, the imposition of a ban represents a baseline against which to compare the effectiveness of the alternative regulatory strategies.

Table 7.4 presents rough estimates of the reduction in CFC use that could be brought about through the use of readily identified emission control technology, equipment modification, and manufacturing process changes that are available now or are likely to become available in the near future. These estimates are based on assessments of control technologies and their effectiveness made by Rand. Examination of a few of the major products illustrates the considerations involved. For rigid urethane foams, CFC usage is reduced by 145 million pounds over the period 1978-1990. This is less than 10 percent of the total baseline usage for that product. The low level of controllability stems from the manner in which rigid foam CFC emissions occur. Most of the releases (more than two thirds) take place after the product leaves the factory, i.e., during its period of normal usage and subsequent disposal. The CFC contained within the closed cells of the foam leaks out slowly, over a period of several decades. Rigid foams are mainly employed as building and refrigeration insulation, hence they have a long functional lifetime during which emissions gradually occur. Since the products are widely dispersed and only small quantities of CFC are contained in each installation,

TABLE 7.4 Estimated Reduction in Domestic CFC Use That Could be Achieved over the Period 1978-1990, through Process Control Technology and Equipment Modification (Estimates in Millions of Pounds)[a]

Usage Category	Baseline	Reduction in Usage	Reduction as Percentage of Total Domestic Nonaerosol Use
Total nonaerosol use	7355	1390	19%
Rigid urethane foams	1605	145	2%
All uses other than refrigeration and air conditioning	5105	670	9%
All uses other than refrigeration and stationary air conditioning	6345	1160	16%

[a] Estimates made by CARCE Panel on Socioeconomic Impacts based on information provided by EPA drawn from a study being conducted by the Rand Corporation.

capture and recycle of the residual CFC at the point of final disposal constitutes a virtually insurmountable logistical, administrative, and economic challenge. Cladding of the foam would substantially reduce the emissions during the period of product use, but these emissions would only be postponed, not eliminated. The difficulty of recovery at disposal would remain. Therefore, emission reduction can be effectively implemented only during manufacture and then primarily by recovering the CFC contained in trimmed or waste foam. Since rigid urethane foams represent 27 percent of 1990 CFC usage, their low susceptibility to emission reduction via process control has a large impact on the total reduction achievable through emission-control technologies.

The degree of control achievable for other nonrefrigeration products is slightly higher. Here reductions are primarily achieved by implementing recapture and reuse systems for those products classified by Rand as "prompt emitters," i.e., those for which nearly all the emissions occur during the manufacturing process. Flexible foams are representative of this class of products. Rand estimates that 30 percent of the manufacturing emissions could be eliminated. A higher level of control might be possible, but only half the emissions occur in an area in which recapture can be easily accomplished, and a limit is imposed by the effectiveness of the carbon adsorption beds employed for recovery, which is about 80 percent. Thus, even in this area, process control is only a partial answer.

Mobile air conditioning offers greater opportunities. It is a large source of emissions, and one that has been judged to be 70 percent controllable. That is not to say that control would be inexpensive or easily accomplished. The Rand study suggests the following among the list of possible control opportunities: 90 percent reduction in leak testing and other factory CFC usages; 34 percent reduction in charge size; 67 percent reduction in normal leakage through improved hoses, etc.; elimination of venting during normal recharge, with 80 percent CFC recovery during required venting; 40 percent CFC recovery at disposal; and 50 percent reduction of miscellaneous losses. Clearly, this is an ambitious program. This assessment is based on present understanding of emission processes, and, since there are substantial gaps in this understanding, the results are speculative. Although it is suggested that large gains might be achieved through emission control, the costs might be prohibitive. In any case, additional data are needed before implementing the more-costly control steps.

Nontraditional Strategies Rough estimates of the reduction in CFC use that might be induced by taxing CFCs are shown in Table 7.5. The "modest" tax, which might be on the order of the CFC price, was defined as that sufficient to motivate substitution of certain other products and processes and conservation of CFCs by means that are nearly competitive now. The "high" tax, which might be an order of magnitude greater than the CFC price, should induce certain more costly changes as time goes on.

Table 7.5 indicates that the "modest" tax could bring about roughly the same total reduction in usage that was estimated in Table 7.4 for process-control technology. Less reduction is induced in the case of rigid foams because for many applications in which space is a prime consideration there is no directly competitive alternative. On the other hand, a somewhat greater reduction could be achieved for flexible foams, primarily through the greater market penetration of alternative blowing agents, such as methylene chloride.* Reductions in use of CFCs as solvents would be nearly the same whether a tax strategy or a control technology strategy were adopted but would be achieved primarily through increased use of substitutes such as methyl chloroform and methylene chloride in degreasing, cleaning, and drying and by substitution of water-soluble fluxes in soldering applications.

The "high" tax could lead to a significantly greater reduction in use. Altogether, nearly 30 percent of the total CFC use over the period from 1978 to 1990 could be eliminated. The reduction would be brought about by essentially the same technological substitutions induced by the "modest" tax but carried to greater lengths.

Quotas (which would be implemented by marketable permits) were considered at three levels: one that would maintain the 1978 status quo and two that would achieve the same effects as the two levels of taxes. The reduction in CFC use associated with the first of these is simply the difference between the 1978-1990 projections

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*However, if methylene chloride use were restricted through regulation, this would not only remove a potential substitute for CFCs from the market but would increase the demand for CFCs in flexible-foam production.

TABLE 7.5 Estimated Reduction in Domestic CFC Use That Could Be Achieved over the Period 1978-1990 through a Tax (Estimates in Millions of Pounds)[a]

		"Modest" Tax		"High" Tax	
Usage Category	Baseline	Reduction in Usage	Reduction as Percentage of Total Domestic Nonaerosol Use	Reduction in Usage	Reduction as Percentage of Total Domestic Nonaerosol Use
Total nonaerosols use	7355	1255	17%	2105	29%
Rigid urethane foams	1605	24	<1%	78	1%
All uses other than refrigeration and air conditioning	5105	700	10%	1380	19%
All uses other than refrigeration and stationary air conditioning	6345	1065	14%	1840	25%

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[a] Estimates made by CARCE Panel on Socioeconomic Impacts based on information provided by EPA, drawn from a study being conducted by the Rand Corporation.

TABLE 7.6 Estimated Reduction in Domestic CFC Use That Could Be Achieved over the Period 1978-1990, by Maintaining 1978 Use Levels through a Quota/Marketable Permit System (Estimates in Millions of Pounds)[a]

Usage Category	Baseline	Reduction in Usage	Reduction as Percentage of Total Domestic Nonaerosol Use
Total nonaerosol use	7355	2376	32%
Rigid urethane foams	1605	851	12%
All uses other than refrigeration and air conditioning	5105	2167	30%
All uses other than refrigeration and stationary air conditioning	6345	2185	30%

[a] Based on Tables 7.2 and 7.3.

in Table 7.3 and the 1978 figures in Table 7.2 multiplied by 13 (the number of years in the period) and is shown in Table 7.6. Reductions in use associated with the other two levels are identical to those associated with the two levels of taxes, shown in Table 7.5.

Summary The estimates shown in Tables 7.4-7.6 represent qualitative judgments; precise values of numbers should not be taken too seriously. The broad implications of these estimates are as follows:

- A ban on all fully halogenated CFCs could eliminate as much as 7000 million pounds of domestic CFC use over the period 1978-1980.
- Partial bans could have significant effects. A ban on CFC use in rigid urethane foams could eliminate 1600 million pounds. A ban on all uses other than refrigeration and air conditioning could eliminate 5100 million pounds. Bringing automobile air conditioning under this ban as well could result in elimination of a total of 6300 million pounds.

- Process-control technology and equipment modifications, taxes, or quotas would all result in eliminating smaller amounts of CFC use, generally up to about 15-30 percent (overall, or in specific areas of use) as much as could be eliminated by a ban. The smallest effect of these measures would be on the production of rigid urethane foams.

Although not indicated in the tables, calculations for the individual years 1978, 1985, and 1990 suggest that these reductions in CFC use would increase progressively with time, so that the reduction in 1990 annual CFC use could be as much as 50-100 percent greater than the average reduction over the period 1978-1990.

The estimates in Tables 7.4-7.6 all assume that the measures adopted work as expected; this may be unduly optimistic, and therefore the estimates should be taken as upper limits to what can be accomplished. In actuality, a number of practical considerations may limit the degree of reduction in CFC use that can be achieved.

Implementation-Related Limits to Effectiveness

The effectiveness, in practice, of any control option may be limited to some degree by practical difficulties. Also, the response to an option may involve some unintended secondary effects capable of eroding its ultimate effectiveness. The principal factors that could limit the gains in emission control theoretically available from the options under study include the following:

- Lack of key economic and technological data needed to regulate efficiently;
- The political need to adapt regulations to perceived equity concerns;
- Responses of world markets to U.S. regulatory actions.

Key Economic and Technological Uncertainties For those options that limit the availability of CFCs and/or increase their cost to users, the price-elasticity of CFC demand and the cross-elasticities of substitution are critical factors. These elasticities are not known as well as they need to be for estimating the amount of substitution or reduction in demand for classes of CFC-containing products that might take place. This is a key element of the overall effectiveness of the market-based strategies, viz., taxes and quotas. Elasticities will vary from use to use, depending in general on the cost of the next most desirable substitute. Thus significant demand for rigid foams may continue despite a "modest" tax on CFCs because the available substitutes (fiberglass, cellulose, rock wool) are considerably less cost-effective as insulation in many applications, especially those in which space limitations are important (e.g., insulation in walls of refrigerators and freezers). Other foam products, however, are more easily replaced (as in some packing materials), and some might simply be eliminated (for example, supersoft foams as fabric backings in clothing).

A related uncertainty concerns the availability and cost of technological substitutes. In some applications, solvents, for example, CFCs have recently replaced other substances that could be reintroduced. Some uses, however (including mobile air conditioning and some kinds of foams), have evolved in response to CFC availability. Many of these applications are very new, and there has been little or no incentive as yet to seek or develop substitutes for CFCs. Thus it is difficult to say, on the basis of substitutes available today and their present costs, what might become available or how costs might change if an economic incentive were applied.

Control technology for CFC emission reduction is another key area of uncertainty. There has been no strong incentive to date to develop effective equipment to capture and recyle CFCs, although taxes, control standards, and quota/permits would create such an incentive. The actual cost of hypothetical equipment modifications is also largely unknown. These uncertainties make it difficult to determine the extent to which a technology-based strategy would actually reduce emissions. Also, it is difficult to estimate the extent of consumer demand reduction that would result from carrying over the cost of control technology into final product price.

In the absence of reasonably accurate indicators of the probable response of users and consumers to increased CFC costs, tax levels cannot be set *a priori* to yield a desired level of emission reduction. This is sometimes taken as an argument against a taxation strategy. One way to acquire the necessary information is to begin taxing at a low level, with a planned schedule of gradual increases. The observed response can then be used to make additional regulatory adjustments, which need not be limited to raising the tax itself, but could also take the form of permits and quota systems or control technology requirements. However, this kind of experimental or "tuning" approach can lead to uncertainties that can also carry penalties, such as those associated with the postponement of major investment decisions until uncertainties are resolved.

Further complicating the problem of setting the initial level of the tax is the likelihood that there may be only a limited set of effective ranges in which a tax will achieve significant reductions in CFC emissions. The same is true of emission reductions brought about by imposition of quotas and permits. Figure 7.2 illustrates this concept. As the price of CFCs rises (for any reason) sharp reductions in use (and hence in emissions) may occur when certain cost thresholds are passed, beyond which the use of some process control technology, equipment modification, or a substitute product becomes cost-effective. Between these intervals of minimal slope in the demand curve, CFC use and related emissions continue to fall as price increases but do so less sharply. If the location of these minimal slope regions along the demand axis were known, it would be possible to set tax levels effectively. Without this knowledge, however, taxes set arbitrarily are likely to be less efficient. Similar reasoning applies to quotas, which should be set with the objective of achieving the greatest reduction in emissions at the smallest adjustment cost to industry.

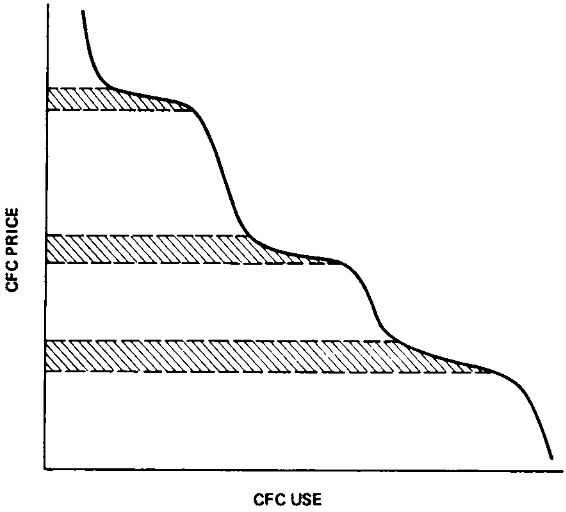

FIGURE 7.2 Regions of minimal slope in a CFC demand curve.

The choice of strategy depends in large part on the risk of being wrong and the consequences thereof. For example, if CFC emissions have sharply increasing marginal health costs beyond some point, taxes are less desirable than quotas. The taxes could allow an increase in CFC demand to produce a dangerous increase in emissions before the political system had time to respond with much higher taxes. There would, in any case, be under this strategy a need to alter taxes frequently as CFC demand changed, and this would make administration of a tax system cumbersome. If, on the other hand, the marginal cost of CFC emissions is relatively constant over a wide range, taxes are superior to quotas. In these circumstances, a tax would not have to be changed, but quotas might have to be frequently altered.

Uncertainty over the future cost and availability of control technologies can also hamper the implementation and long-term effectiveness of some control strategies, especially those specifying technology-based standards of practice for emissions control. In the broadest sense, control technology can be thought of as comprising three elements: direct use of equipment for emission control and recycling ("best available control technology," or BACT), housekeeping or management practices ("best management practice," or BMP), and product design practices ("best design practice," or BDP). An example of BDP is fully sealed, nonrechargeable air-conditioning equipment. A rigid specification of "best" practices in any or all of these categories tends to freeze both the technology and the effectiveness of the strategy. If a firm must invest money to meet today's standards of practice, it has an added disincentive to change, even if better practices are developed. Thus an unknown increment of future effectiveness in emission control may be foregone by too-early specification.

This risk is avoided by the market-based tax, permit, and quota strategies. Where the incentive to improve control technology, housekeeping, and design practices comes from increasing CFC costs and/or limiting supply, there is a continuing inducement to develop effective techniques to conserve. New technologies enter the picture as they become feasible.

Uncertainty over the scope and cost of future regulation is a major concern to industry. While no regulatory strategy can entirely alleviate this problem, it should be noted that a marketable permit/quota system operates in such a way as to cushion the adverse effects of subsequent adjustments. Thus, let us suppose that we discover past regulations to have been overly lax. With a tax or standards scheme, higher taxes or tougher standards will impose large wealth losses on CFC producers and increase their uncertainty about future taxes and standards. With a quota scheme, the government would have to step in and buy (and hold) some of the permits, thereby bidding up their price. The resulting capital gains for CFC producers would offset part of or, in some cases, more than the added cost of controlling emissions. As a general matter, if the permit holder expects that his permits will increase in value at the same time as he increases expenditures for emission controls, or decrease in value when he decreases such expenditures (as would occur if the government sold permits from its inventory), the risk he bears due to changes in policy is mitigated. Under the tax system, this risk is exacerbated.

Adjusting Regulations to Perceived Equity Concerns The history of regulatory practice in the United States (a recent example is the administration of the Fuel Use Act) has demonstrated the need to temper the application of blanket policies to avoid undue impact on particular groups. In so doing, the effectiveness of the policy is traded off against the value of equitable treatment. The greater the perceived inequity, the greater, typically, is the reduction in potential effectiveness.

In the case of CFC uses, market-based strategies run the risk of driving the cost of air conditioning (though probably not refrigeration) to the point where some groups of users can no longer afford it. Air conditioning may provide health benefits for certain groups, e.g., asthmatics and people with severe allergies. Widespread introduction of air conditioning into warm climates has certainly reduced the extent to which people are subjected to physiological stress due to heat and humidity. To protect such health benefits, exemptions from taxation or special quotas or permits might seem justifiable to some people. These would be difficult to administer. Other health-related uses of CFCs, notably in sterilization of medical supplies, might also be candidates for exemption.

A problem also arises in any use for which no effective substitute for CFCs exists. Economic hardship due to inability to find substitutes at reasonable cost might be regarded as a criterion for establishing exemptions (as with the Fuel Use Act). The same considerations apply to the establishment of standards of emission-control practice. Where BACT or BMP imposes a severe economic penalty on industry, grounds for exemption might be established.

Another type of equity concern arises in connection with the potential impact of CFC regulation on businesses. As noted earlier, a tax or emission standard could result in a more or less sharp reduction in the market value of a business investment, while at the same time imposing higher operating costs. This creates an argument, if not a legal case, for payment of compensation to affected parties. It should be noted that the marketable permit system--alone among the options--has the virtue of providing such compensation automatically. Thus to reduce CFC emissions the government simply buys marketable permits at the going price.

World Market Responses U.S. action to control CFC use and emissions must be considered in the context of a world market. Regulatory strategies that indirectly encourage increased emissions in other countries are not desirable. Unilateral control of the use of CFCs in air-conditioning and refrigeration equipment could have a perverse effect. Currently, the United States dominates the world market in these products. If U.S. products can no longer compete on the world market, because of outright bans or higher prices induced by taxes, marketable permits, and quotas or mandatory control technology, then products made in other countries will quickly replace them. A corollary situation arises with regard to imports. Policies that increase the competitiveness in the United States of imported products made with or containing CFCs are also self-limiting. Among these are permit and quota systems and stringent standards for emission control that drive up the cost of domestically produced goods. Taxes on the sale within the United States of products made with or containing CFCs (assuming feasibility under present trade agreements) would control imports, but taxes imposed on raw CFCs sold within the United States would not.

IMPACTS OF THE CONTROL OPTIONS

In this section we address the overall impacts of the control options identified above. These impacts should be taken into account in any assessment of the "costs" of these options. We make no attempt to assess the "benefits" that would result from these options; instead, we use the degree of reduction in CFC emissions possible under each option as a measure of "effectiveness" and as a surrogate for benefits.

When a household considers the pros and cons (i.e., benefits and costs) of a major family decision, say, a move to another city, it soon becomes evident that many of the factors involved can easily be reduced to monetary equivalents, while others cannot or can be only very crudely. Costs of housing, food, local taxes, and so on are directly comparable. Trade-offs between other attributes of a given location can be monetized to the extent that money can buy equivalent satisfactions in other ways. Trade-offs between discretionary income and leisure time or distance to work can be dealt with, in principle, in a similar manner. Aesthetic and health considerations, cultural shock, and remoteness from family and friends are more difficult to evaluate because the "equivalents" of these things are essentially undefinable. But the various factors must be weighed against each other in terms of their relative contribution to the family's overall welfare. One way or another, however imperfect the analytical process--identification of relevant attributes and the assignment of relative weights to each--such decisions are made every day. Indeed, most private decisions of this kind are made without any explicit framework for comparing and weighting the factors that enter the decision.

For a nation, the problem of arriving at a major decision is inherently far more complex. One reason is that there are more stakeholders, with diverse interests and values. Another is that the factors or attributes deserving of consideration are not easily sorted out into distinct (nonoverlapping) categories. The political process is designed to handle decision making in which many factors cannot be treated explicitly. However, this intuitive or heuristic political approach is less than satisfactory in cases where the subject matter is of a technical nature that is not easily assimilated by nonspecialists. The purpose of an explicit impact analysis is to unravel a highly complex skein of interwoven strands into their most essential (and easily understood) components.

It is quite difficult to identify all the different factors that contribute to human welfare--so as not to omit any important ones--without unwittingly including some factors many times. An example should make the problem clearer. Any list of the "stakeholders" in the present case would have to include the following:

- Raw material producers (e.g., fluorspar mines)
- Chemical companies
- Manufacturers of CFC-containing products, such as refrigeration equipment or insulation
- Employees of the above
- Unions representing these workers
- Stockholders (including pension funds, etc.) of the affected industries
- Consumers of products of the affected industries
- People, especially light-skinned people, regularly exposed to UV-B
- Owners of structures or products that will deteriorate more rapidly as a result of increased UV-B exposure
- Food producers affected by changing climatic conditions
- Consumers affected by food prices

Clearly a given individual may be simultaneously involved in a number of different ways, even, conceivably, most of them. One would seek quantifiable indicators of the degree of impact experienced (over time) by each "stakeholder." Gross measures, such as change in gross national product or sectoral output, obviously encompass some of the effects on CFC producers (including suppliers and customers), but such indicators also measure, indirectly, effects on employment and employees incomes. This is clearer if one considers the impact of expansion or contraction of an industrial activity in a given location. If a firm receives a big new contract, it presumably adds workers to the payroll and dividends for the stockholders, both of whom subsequently add to the local level of spending for such items as groceries, furniture, and automobiles. It also buys more raw materials from suppliers, with similar consequences. Clearly, if the firm loses a contract (or a line of business) the logic is the same, but the results are negative instead of positive. To sum up all of these incremental additions to (or subtractions from) incomes, spending, production, and profits separately is not legitimate, since the same dollars are being counted several times. Such a detailed mapping of impacts is necessary only if one is interested in tracing distributional impacts on different stakeholders quite precisely. Unemployment, for instance, is obviously an indicator of differential impact.

TABLE 7.7 The Likelihood that Various Technological Control Measures Will be Induced by Certain Regulatory or Economic Control Strategies

	Commercial Air Conditioning				
	Reduce Manufacturing	Leakage Reduction		Recovery and Recycling	
	Losses	Design	Service	Service	Disposal
"Modest" tax[a]	Yes	No	Possibly	No	No
"High" tax[a]	Yes	Possibly	Yes	Possibly	Possibly
Deposit-refund[b]	No	No	Yes	Yes	Possibly
Quotas and marketable use permits[c]	Yes	Possibly	Yes	No	No
Emissions standard	Possibly	No	No	No	No

	Mobile Air Conditioning				
	Reduce Manufacturing	Leakage Reduction		Recovery and Recycling	
	Losses	Design	Service	Service	Disposal
"Modest" tax[a]	Yes	No	Possibly	No	No
"High" tax[a]	Yes	Possibly	Yes	No	No
Deposit-refund[b]	No	No	Yes	No	Possibly
Quotas and marketable use permits[c]	Yes	No	Yes	No	No
Emissions standard	Possibly	No	No	No	No

TABLE 7.7 (continued)

	Commercial Refrigeration				
	Reduce Manufacturing Losses	Leakage Reduction		Recovery and Recycling	
		Design	Service	Service	Disposal
"Modest" tax[a]	No	No	No	No	No
"High" tax[a]	Yes	Possibly	Yes	Possibly	Possibly
Deposit-refund[b]	No	No	Yes	Yes	Possibly
Quotas and marketable use permits[c]	Yes	Possibly	Yes	No	No
Emissions standard	Possibly	No	No	No	No

	Flexible Urethane Foam	Rigid Urethane Foam		
	Manufacture with Methylene Chloride	Reduction in Amount Manufactured with CFCs	Manufacturing Recovery and Recycling (15-30%)	Recovery and Recycling at Disposal
"Modest" tax[a]	Yes	No	Yes	No
"High" tax[a]	Yes	Yes	Yes	No
Deposit-refund[b]	No	Yes	Yes	No
Quotas and marketable use permits[c]	Yes	Yes	Yes	No
Emissions standard	Yes	Possibly	No	No

	Nonurethane Foams		Reaction Injection Molding	
	Manufacture with Alternative Blowing Agents (e.g., F-142b or Pentane)	Recovery and Recycling	Manufacture with Methylene Chloride	Manufacture with Frothing Gas
"Modest" tax[a]	No	No	Possibly	Possibly
"High" tax[a]	Possibly	Possibly	Yes	Yes
Deposit-refund[b]	Possibly	Possibly	No	No
Quotas and marketables use permits[c]	Yes	Possibly	Yes	Yes
Emissions standard	Yes	Possibly	No	No

	Degreasing, Cleaning and Drying		
	Alternative Solvents (Chlorocarbons)	Aqueous Cleaners	Recovery and Recycling
"Modest" tax[a]	No	No	No
"High" tax[a]	Possibly	Possibly	Possibly
Deposit-refund[b]	Yes	Yes	Yes
Quotas and marketable use permits[c]	Yes	Yes	Yes
Emissions standard	Possibly	Possibly	Possibly

TABLE 7.7 (continued)

	Solder Flux Removal		
	Alternative Solvent (e.g., 1,1,1-Trichloroethane	Water-Soluble Fluxes	Recovery and Recycling
"Modest" tax[a]	No	No	No
"High" tax[a]	Possibly	Possibly	Possibly
Deposit-refund[b]	Yes	Yes	Yes
Quotas and marketable use permits[c]	Yes	Yes	Yes
Emissions standard	Possibly	Possibly	Possibly

	Gas Sterilization		
	Alternative Carrier (e.g., CO_2)	Alternative Sterilization (e.g., Steam or Radiation)	Recovery and Recycling
"Modest" tax[a]	Possibly	Possibly	No
"High" tax[a]	Yes	Yes	Possibly
Deposit-refund[b]	No	No	No
Quotas and marketable use permits[c]	Yes	Yes	Yes
Emissions standard	Possibly	Possibly	Possibly

	Liquid Fast Freezing	
	Other Coolants (Liquid Nitrogen, Carbon Dioxide, Air Blast)	Recovery and Recycling
"Modest" tax[a]	Possibly	Possibly
"High" tax[a]	Yes	Yes
Deposit-refund[b]	No	No
Quotas and marketable use permits[c]	Yes	Yes
Emissions standard	Possibly	Possibly

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[a] In general, a tax will be ineffective in stimulating recovery and recycling unless the recycled material can be used tax-free or can be used to generate a tax credit. The latter arrangement would be much like a deposit refund. A tax will have an indirect influence on redesign to reduce leakage in the sense that it will affect service costs. The magnitude of the tax will be important. The "high" tax indicated here may have to be orders of magnitude larger than the basic price of the CFCs; the "modest" tax may have to be at least severalfold as large as the basic CFC price.

[b] The deposit-refund could have different forms. If the refund could be claimed on the basis of impure and diluted material, an equipment manufacturer might buy recovered material from any available source. It is possible that the equipment manufacturer would find it economic to establish a CFC return arrangement with service and disposal agencies.

[c] Quotas will be ineffective in stimulating recovery and recycling unless an equipment manufacturer or service agency can augment its quotas to the extent that recycled CFCs are used.

TABLE 7.8 Adverse Impacts of the Control Options in Relation to Their Effectiveness[a]

Control Option	EFFECTIVENESS: Maximum Potential Reduction in CFC Emissions, Expressed as Billions of Pounds of CFC that Would Not Be Emitted over the Period 1978-1990 as a Result of the Control Option[b]	ECONOMIC IMPACTS					OTHER FACTORS			
		Consumer Surplus		Value Added	Cost to Government	Balance of Payments	Health		Energy Demand	Difficulty of Enforceability
		Aggregate	Distributional				Aggregate	Distributional		
Bans										
All CFCs banned	8-9	High	High	High	Low	High	Medium	Medium	Medium	Low
All fully halogenated CFCs banned[c]	7.4	Medium	High	High	Low	Medium	Medium	Low	Medium	Low
Use of CFCs in rigid foams banned	1.6	Low	Low	Low	Low	Low	Low	Low	Medium	Low
All uses banned except refrigeration and air conditioning	5.1	Low	Low	Medium	Low	Low	Medium	Low	Medium	Low
All uses except refrigeration and stationary air conditioning banned	6.3	Medium	Medium	Medium	Low	Medium	Medium	Low	Medium	Low
Taxes and Quotas										
On all fully halogenated CFCs[c]										
"Modest" tax	1.3	Low	Low	Low	Benefit	None	Low	Low	Low	Medium
"High" tax	2.1	Low	Low	Low	Benefit	Benefit	Low	Low	Low	Medium
Quota equivalent to maintaining 1978 emissions	2.4	Low	Low	Low	None	None	Low	Low	Low	Medium
Quota equivalent to "modest" tax	1.3	Low	Low	Low	None	None	Low	Low	Low	Medium
Quota equivalent to "high" tax	2.1	Low	Low	Low	None	Benefit	Low	Low	Low	Medium
On all uses except refrigeration and air conditioning										
"Modest" tax	<1	None	None	None	Benefit	None	Low	Low	Low	Medium
"High" tax	1.4	Low	Low	Low	Benefit	Benefit	Low	Low	Low	Medium
Quota equivalent to maintaining 1978 emissions	2.2	None	None	None	None	None	Low	Low	Low	Medium
Quota equivalent to "modest" tax	<1	None	None	None	None	None	Low	Low	Low	Medium
Quota equivalent to "high" tax	1.4	Low	Low	Low	None	Benefit	Low	Low	Low	Medium

On all uses except refrigeration and stationary air conditioning										
"Modest" tax	1.1	None	Low	None	Benefit	Benefit	Low	Low	Low	Medium
"High" tax	1.8	Low	Low	Low	Benefit	Benefit	Low	Low	Low	Medium
Quota equivalent to maintaining 1978 emissions	2.2	None	Low	None	None	Benefit	Low	Low	Low	Medium
Quota equivalent to "modest" tax	1.1	None	Low	None	None	Benefit	Low	Low	Low	Medium
Quota equivalent to "high" tax	1.8	Low	Low	Low	None	Benefit	Low	Low	Low	Medium
Emissions Control Technology										
On all manufacturing operations	<1	None	None	Benefit	High	Medium	None	None	None	High
On refrigeration and air-conditioning servicing	<1	Low	Low	Benefit	High	Medium	None	None	None	High
Disposal Technology										
Mandatory recycling of CFCs used in refrigeration and air conditioning	<1	None	Low	None	High	Benefit	None	None	None	High
Refundable deposit on CFCs used in refrigeration and air conditioning	<1	None	Low	None	Low	Benefit	None	None	None	High

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[a] High indicates a large adverse impact; Low a small adverse impact; Benefit a beneficial impact. Thus the ideal control option would have a large effectiveness and ratings of Low, None, or Benefit in most of the remaining columns. Estimates made by the CARCE Panel on Socioeconomic Impacts.

[b] Figures taken from Tables 7.4, 7.5, and 7.6 or calculated from the data used in constructing those tables.

[c] In effect, all CFCs except F-22, virtually all of whose use is in stationary air conditioning.

The Impact Matrix

To facilitate comparison between control options, we have developed two tabular displays. Table 7.7 indicates, in a qualitative way, which of the technologically feasible measures identified in Chapter 6 might be undertaken in response to some of the major classes of control options outlined here. Bans have not been included on the assumption that a ban would simply serve to shut off a certain industrial activity rather than to induce modifications. While two levels of taxes are shown, different levels of quotas are not indicated; the more stringent the quota on, say, CFC purchases, the more likely it is to induce substitution and recycling. Entries in this table are simply "Yes," "No," and "Possibly"; the latter may also be interpreted to mean "to a limited extent only."

Table 7.8 indicates in matrix form both the likely effectiveness and the expected economic and other impacts of the 15 control options identified earlier, including bans and several levels of quotas. Each row of this table represents one of the 15 control options. The first column gives a measure of effectiveness. The other columns represent categories of impact and are explained on the following pages.

The impact categories fall into three groups. The first consists of five quantifiable economic measures of impact:

- Consumer surplus (aggregate),
- Consumer surplus (distributional),
- Value added,
- Cost to government,
- Balance-of-payments.

The second consists of two indicators of "side effects" of the control options, i.e., effects other than those due to reduced CFC emissions, namely,

- Effects on health,
- Effects on energy demand.

The third consists of one indicator of the administrative difficulties of implementing the options, namely,

- Difficulty of enforceability.

We believe that these eight aspects are the most useful ones in differentiating among the various options.

For each control option, we have indicated in the matrix under each column heading whether the impact of that option is "high," "medium," "low," or whether there is none. These relative rankings are clearly matters of judgment and offer at best only rough qualitative guidance to the decisionmaker. Nevertheless, we believe this approach is useful and leads to certain clear conclusions.

Explanation of the Impact Categories

We now turn to an explanation of the eight impact categories shown in the table and the reasoning behind the rankings.

Measures of Economic Impact The economy can be viewed equally well from the standpoint of outputs or inputs. There is a circular flow of money from consumers to producers, in the form of consumer expenditure, and back again to consumers in the form of wages and profits. Changes in the money flow can be measured at any point: production, expenditure, or income.* It makes sense to estimate and record several of these indicators independently to ensure self-consistency and to provide insight with regard to distributional impacts. However, it is important not to actually add up--explicitly or implicitly--impacts on production and income (or employment), production and expenditure, or expenditure and income. To do so would be double counting.

It is important to emphasize that no economic indicator is by itself a satisfactory measure of social welfare. For some purposes, macroindicators like GNP are often used as if they were welfare measures, but this is essentially a confession of methodological and empirical shortcomings. In a general equilibrium context (in which a control action is considered likely to have sufficiently great ramifications throughout society to require that they all be taken into account) we are not well equipped to make quantitative estimates of welfare effects. However, for dealing with problems of narrower scope--and the control of CFC emissions is such--one can safely adopt a "partial-equilibrium" approach. That is, we can

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*Gross national product (GNP), for example, can be defined interchangeably in terms of final outputs, final expenditures by consumers (including taxes), or gross income received by individuals.

assume that imposing controls on CFC production or use would be a relatively minor perturbation on society as a whole. If this is true, the *relative* changes in social welfare associated with different CFC control strategies can, in principle, be analyzed in a more satisfactory manner. What follows is asserted without any attempt to fill in the necessary theoretical background. In line with conventional usage in economics we equate "welfare" with "net benefits" (or benefits less costs) and state that the total net benefits per year associated with production of a given product has two components. These are *consumer surplus*, defined as the sum of what individuals would be willing to pay for the product in excess of the actual selling price, and *producer surplus*, defined as the difference between the selling price of the product and the total cost of production, including taxes and interest payments.

In a static framework, producer surplus can be regarded, essentially, as profits. In a dynamic framework --if the industry is to continue--profits are the return on past equity investment and thus become a cost of capital needed to provide for the future. If an industry is cut back or shut down because of government regulations, there will be welfare losses to both consumers of that product and producers of it.* These losses must be considered in their time dimension. For monetary (and monetizable) benefits, a present value (discounted) analysis is appropriate, as noted later in the discussion of benefit-cost analysis.

Every product has substitutes. If a specific CFC-containing product--say, rigid-foam insulation--were to be banned, consumers would switch to other products having lower performance and/or higher costs, in short, offering reduced consumer surplus. Clearly, in this situation the *net* welfare loss (per year) due to the ban on rigid foams is computed by subtracting the consumer surplus for the best substitute from the consumer surplus for the banned product. The same procedure would apply to the producer surplus. Except for possible transitional problems, it is probably not unreasonable to assume that the producer surplus of the substitute product is likely to be as high, or nearly as high, as that of the product that was banned.

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*These losses *can* be added up, but it must be emphasized that the calculation is not a simple summation of lost production and lost consumption.

Thus, the net aggregate social welfare loss is almost entirely the differential effect on consumers--the difference in quality, performance, cost, and consumer satisfaction between the product and its next-best substitute--and that is represented in the matrix by consumer surplus.

While consumer surplus in the aggregate is, in some sense, the "most appropriate" measure, distributional effects or local differences must be taken into consideration as well. Differential regional impacts on consumers relate primarily to climatic and demographic characteristics. The southern part of the United States is warmer in summer and correspondingly more dependent on air conditioning (especially of automobiles) than is the northern part. Thus CFC control options affecting automobile air conditioners will have differential regional impacts. Similarly, though perhaps less important, control options affecting rigid plastic foam insulating panels might be expected to have greater importance in areas with cold climates and greater heating costs, although such insulation also serves to reduce the need for air conditioning in warm climates. Such distributional effects of policy options have disproportionate importance in our democratic system of government. Potential losers are more easily identified and--*ipso facto*--better organized and more influential than potential gainers. We have therefore rated the options with regard to distributional, as well as aggregate, consumer surplus.

Value-added reflects the differential impact on producers. CFC manufacturers and major industrial users are, almost by definition, "localized" in a small number of communities. Value-added is, roughly, the cost of labor, so cuts in production means loss of value-added, which translates into localized loss of income and jobs. The political importance of this sort of impact can hardly be overemphasized.

Cost to government is another significant impact. It is true that the costs of government are spread thinly among all taxpayers, which means almost all citizens. However, government is highly sensitive to "budgetary impact" because the governmental costs of regulation must be explicitly allocated by both Congress and the Executive Branch in competition with many other claimants for limited public-sector resources. Practically speaking, control options with high budgetary costs will be more difficult to implement than options with low budgetary costs.

Balance-of-payments effects are still another differential impact. Because of persistent long-term balance-of-payment deficits, the U.S. dollar has, in recent years, lost ground against currencies of countries with large surplus accounts. This raises the real cost of U.S. imports and contributes to domestic inflation. It also erodes the position of the dollar as a major reserve currency. The real economic and/or political benefits of reserve status are open to debate, but the United States is under very strong pressure to control its deficit. Thus, if any CFC control option were to have the effect of encouraging imports or discouraging U.S. exports, this would be an adverse factor.

Noneconomic Impacts *Health effects* are viewed to have two major components: hazards for the worker in manufacturing and hazards for the consumer deprived of a product.

Substitutes for CFCs as refrigerants are likely to be toxic to workers and pose potential problems for consumers. A major substitution of flammable chemicals as blowing agents for foams and solvents would add increased risks to workers producing foams and using solvents. In particular, pentane substitution might be stimulated by measures that increase costs of CFCs or directly limit their use. If fiberglass is substituted for rigid urethane insulating foams, there will be an increased occupational health risk among installers and handlers of insulating materials. There could be increased risk of infection in hospitals if use of throwaway presterilized medical and surgical supplies is abandoned and there is a reversion to other sterilization methods.

These impacts are not distributed evenly but are concentrated on worker health, vary geographically, and hit hardest those least able to pay for higher-priced substitutes.

The severity of these effects on public health varies with regulatory strategies chosen. They are most severe if all CFCs are banned and are lessened with regulation aimed at specific uses. They are also less for taxes and quotas than for bans.

The demand for nonrenewable sources of energy could increase if use of rigid urethane foam insulation is restricted. Rigid foam is very cost-effective, especially where space is at a premium. Less-effective substitutes for foam insulation, coupled with reduced efficiency in air conditioning using non-CFC refrigerants, could result in greater net energy expenditure for space cooling. If less-efficient insulation is used in appliances, they will also require more energy to run. If products derived from petroleum are substituted for CFCs, this too could have an impact on the energy situation.

There are other side effects not included in the matrix. Municipal water supplies could be affected in arid climates where evaporative cooling can be substituted for air conditioning using refrigerants. Many such locations are already experiencing summer water-supply problems. If as a result of recycling or restricting production of CFCs, there is a decrease in the use of the raw materials used in manufacturing CFCs, these resources (notably fluorspar) will be conserved for future generations. However, some precursors are by-products of other processes, and a reduction in CFC production would require finding new markets for these by-products to prevent their accumulation and disposal as wastes.

No significant potential impacts on the biosphere were identified for any of the regulatory strategies. There might be some increased demand for fiber and rubber products if the use of CFCs in the production of flexible and extruded closed-cell foams for packaging, padding backings, and cushions is limited. However, this demand could be reduced by using alternate methods of foam blowing, or low-quality fiber could be partially supplied by recycled paper and wood products, thus reducing the need for virgin materials.

Implementation and Enforcement A final criterion in evaluating alternative regulatory options is their ease of implementation and enforcement. This dimension includes the expected burdens placed on the regulatory agency in the initial preparation and application of regulations, in monitoring for noncompliance, and in administering sanctions.

Bans are relatively easy to implement and enforce. The enforcer has only one concern: are CFCs being produced or used in industries where they have been banned? In general, the more sweeping the ban, for example, a ban on all CFCs produced and used, the easier the enforcement.

More selective (partial) bans create greater enforcement problems. When considering the relative merits of banning different uses, it should be borne in mind that the greater the cost to society of losing a use, the greater the resulting enforcement problems; this is because there will be powerful incentives for concerned parties to circumvent the prohibition. Furthermore, selective rather than comprehensive bans--or partial bans with no exemptions rather than partial bans with exemptions (as with the case of nonessential and essential aerosol uses) --open doors for noncompliance and cheating practices that are difficult to detect. Finally, the greater the "sophistication" of the regulation, the greater the administrative complexities and difficulties of enforcement.

CFC control-technology standards present more numerous and often more intractable problems of enforcement. The enforcer must consider both whether the regulated sources have taken measures needed to control emissions (e.g., installed vapor recovery systems) and whether those measures are operating effectively. Moreover, initial implementation problems are considerably more onerous for standards than for bans. The standard must first be developed for a particular industrial or servicing process. This includes determining to whom the standards will apply (coverage) and what they will require (content). The content of a standard may be general ("best available technology," "lowest achievable emission rate") followed by industry-specific regulations taking into account both technological feasibility and economic impact. The application of the standards to particular sources of emissions, including development of compliance schedules, will likely involve extensive negotiations over technical, economic, and timing issues. Procedures will have to be developed by which new sources can demonstrate compliance with regulations before beginning operations. Compliance can be achieved through individual enforcement actions or through permit programs under which each source's permit will embody its legal control obligations. Enforcement may include compliance monitoring (self-reporting field inspections, continuous monitors) and a series of escalating actions (warning letters, administrative orders, and lawsuits, for example). Traditional regulatory sanctions have been designed to be punitive; however, recent programs have set penalties at levels that eliminate the economic benefit of noncompliance. It is difficult to estimate, initially, how severe such penalties might need to be.

The fewer the number of sources to which the standard applies, the less the problems of implementation and enforcement. Thus, from this point of view, the task is simplified if controls are placed on CFC producers (five U.S. producers currently), on home refrigerator manufacturers (36), or on liquid fast-freezing installations (30) than on solvent users (72,000). The down time required, both to install control equipment and to revamp manufacturing procedures, and possible short-term problems with control equipment availability, would have to be taken into account to avoid short-term industry-wide disruptions. Standards can also be placed on servicing and repair of refrigeration and air-conditioning equipment. Given the large number of shops involved (more than 100,000 in the case of mobile air conditioning), the problems of detecting noncompliance and applying a penalty schedule would be severe. Once again, the selective use of exemptions will exacerbate enforcement difficulties.

Because such methods as taxes and marketable permits have had few practical applications in this country thus far, their administrative implications are somewhat conjectural. It is often assumed that they pose fewer burdens on the administrator than such traditional approaches as control technology standards. This is in large part because they assign decision-making responsibility for the nature and extent of control measures undertaken to industry rather than to the administering agency. In addition, certain characteristics of CFCs tend to avoid some of the administrative difficulties that have discouraged use of taxes in other environmental problems. Because all CFCs produced are ultimately emitted, one can tax production rather than use or emissions. This limits the number of entities to be taxed and avoids the necessity for monitoring emissions. Similar administrative simplifications (in contrast to other pollutants) apply to other regulatory approaches such as quota/permits or bans.

However, international trade considerations can introduce substantial complexities associated with imports (see Chapter 5). Moreover, one should not conclude that taxes and permits are the administrator's dream that their most enthusiastic advocates imply. Taxes in general are difficult to calibrate initially to desired levels of CFC reduction because uses are highly variable and because user trade-offs, elasticities, and price limits are complex and poorly known. Therefore, constant monitoring is required, for some time at least, requiring information on sales and inventories. Only in this way can the regulator know that the level of tax charged is in fact achieving the desired reduction in CFC emissions rather than simply increasing production costs. Moreover taxes will have to be collected, either putting additional burdens on already strained tax-collecting agencies or giving new responsibilities to other services. Auditing will be necessary, coupled with the imposition of penalties for delinquents. Additional administrative burdens may also be required in connection with the disposition of tax revenues, if the latter are earmarked for any special purpose.

Initial implementation of a marketable permit scheme also has administrative aspects. The number of allowable permits will have to be adjusted to some "acceptable" initial level of CFC use, procedures will have to be developed for the issuing or auctioning of permits, and permit-trading transactions will have to be monitored to assess continued effectiveness of the overall strategy. The administrative difficulties associated with "fine tuning" are minor; the government simply buys (or sells) permits at the going price. The drawbacks of this scheme are likely to be mainly political.

Controls on disposal and recycling present quite different implications for the regulator/enforcer. Mandatory recycling of CFCs in refrigeration and air-conditioning equipment could be the legal responsibility of the owner, dealer, and/or contractor. Without any monetary incentive, enforcement of this control option is apt to be extremely difficult. The use of existing systems, such as municipal collection systems, could reduce these difficulties somewhat but will not eliminate them.

A refundable deposit gives the owner (or dealer or contractor) an incentive to dispose of CFCs properly or to recycle. But there are the added administrative costs of collecting the deposits and issuing refunds.

For any option in which recycling plays a major role, effective enforcement implies the creation and geographical distribution of recycling centers; if government intervenes in this process, as would appear necessary at least initially, additional administrative burdens are likely.

REVIEW AND EVALUATION OF THREE STUDIES OF BENEFITS AND COSTS

Thus far we have considered only the costs and other impacts of various control strategies, using "effectiveness" --as measured by reduction in emissions--as a surrogate for benefits. We now turn to an examination of three previous studies that dealt explicitly with benefits as well as costs.

The CFC-ozone problem has stimulated several attempts to assess the economic benefits and costs of regulating CFCs. These are, in part, extensions of the economic research done in the Climatic Impact Assessment Program (CIAP), a study of the likely effects of the proposed high-altitude supersonic transport on stratospheric ozone (U.S. Department of Transportation, 1975). The first benefit-cost study of the CFC problem was completed for the U.S. Environmental Protection Agency in 1976 (see d'Arge *et al.*, 1976). Two additional studies have recently become available, one by Bailey (1978), also done for EPA, and another carried out by Systems Control Incorporated (SCI, 1978) for the National Science Foundation. All three of these studies predate the ban on nonessential aerosol uses of CFCs, and their findings encompass the potential benefits and costs of that action as well as of the further controls now under consideration.

We have reviewed these three studies, and we present our conclusions here for two reasons. First, to highlight some methodological problems with benefit-cost analysis that should be taken into account in interpreting the results of studies such as the three examined here. Second, to indicate the extent to which the results of these three studies may be useful to the decision maker facing today's question of whether to regulate chlorofluorocarbon use and if so, how.

The purpose of the three studies, as of all benefit-cost analyses, is to provide the policymaker with a structured framework for comparing policy alternatives whose consequences may differ with respect to a number of attributes relating to health, the environment, industry economics, and the like. Ideally, rather than face a complex array of diverse outcome measures, each expressed in different units, a policymaker would prefer to have the dimensionality of the data reduced to a few quantities, provided that one could have confidence that those numbers properly reflect societal values. In classical benefit-cost analysis, an attempt is made to express all outcomes in common, usually monetary, units, so that an explicit comparison can be made between the benefits and costs of alternative actions. On the other hand, it may be more acceptable in many circumstances to terminate the commensuration at the point where two or more numbers, rather than one, are used to summarize the impacts. Cost-effectiveness analysis, for example, requires a single measure of cost and a single measure of benefit (or effectiveness) but does not require explicit commensuration between the two.

A danger with such analyses is that their conclusions may be interpreted as more definitive than is justified by the degree of certainty in the physical, biological, economic, and social outcomes anticipated or by the degree of confidence that the value measures applied reflect appropriate social concerns. While benefit-cost analysis can be a valuable aid to informed decision making, its results in and of themselves should not be viewed as providing definitive conclusions for policy purposes. Rather, such results should be accompanied by extensive sensitivity analyses, the purposes of which are (1) to reveal which conclusions stand up to wide variations in assumptions and which do not and (2) to indicate specifically what judgments and values are most crucial in determining the results.

The three available benefit-cost studies of CFC regulation, like all benefit-cost analyses applied to environmental problems, share a number of methodological problems. These include the following:

1. *Measuring environmental benefits.* For example, measuring the benefits corresponding to the reduced damages resulting from CFC control may involve valuing in commensurate terms reductions in risk to human health, ecological effects, and economic values; there is no easy or obviously correct way to do this.
2. *Measuring the costs of regulation.* For example, the costs of emission controls and the lost value of excluded CFC uses depend in complex ways on the availability of new production technologies and substitutes for CFCs and therefore are hard to estimate accurately.
3. *Discounting the future.* For example, how should damage to future generations be weighted relative to today's economic welfare; should these be discounted at a market rate of return, or do ethical issues alter the analysis?
4. *Uncertainty.* For example, are the expected value and the likelihood of damages appropriate measures, or should a very small probability of catastrophe be weighted more heavily than would be suggested by multiplying the probability of occurrence by the value of the damage if it does occur?

In addition, and in part because of these problems, there is the difficulty of identifying and incorporating into the analysis all conceivable (or at least all significant) costs and benefits associated with reducing

CFC emissions. There is a tendency, which must be guarded against, to identify and include those that most lend themselves to measurements and to exclude, perhaps inadvertently, those that do not. The three studies considered here differ from each other in what has been included and what has been omitted.

We have evaluated each of the three studies (d'Arge *et al.*, 1976; Bailey, 1978; and SCI, 1978) in the context of the specific problems noted above, and we have summarized and compared the results and recommendations of each. The three studies have much in common, both in their approach and in their results. Despite a wide range of scenarios and assumptions, they agree on the following conclusions:

- Adoption of a low discount rate, i.e., one weighted toward future generations, leads to the conclusion that even for very severe regulatory actions (e.g., a near total CFC ban) the benefits exceed the costs, while adoption of a high discount rate implies that only for limited action (e.g., a ban on aerosols and other nonessential uses) do benefits appear to exceed costs.
- In the absence of control actions by other nations, the benefits accruing to the United States alone from stringent domestic control measures are less than the costs of those measures.
- The benefits of delaying further U.S. bans until better information is available *may* turn out to exceed the costs of such delayed action (although the three studies differ considerably in their approaches to this question and in their treatment of uncertainties and of controls other than bans).

On balance, we believe that formal analyses of this type can serve a useful role in the policy-formation process. They can help to separate and structure the key issues in a systematic way, and they can highlight the principal trade-offs (e.g., present costs versus future benefits; economic benefits versus safety concerns) and the value judgments that would be implicit in any decision. They can also focus attention on the major uncertainties that bear on policy decisions, by indicating the range of assumptions that would lead to various conclusions and by suggesting the value of strategies that involve seeking or waiting for further information. At the same time, it is important that policymakers recognize the limitations of such analyses and understand the dependence of the "conclusions" on the assumptions and values that underlie them, before transforming their findings into policy.

Methodological Problems in Benefit-Cost Analysis of CFC Regulation

We focus on the four methodological problems identified above: measuring the environmental and health benefits of reduced CFC emissions; measuring the costs of reducing emissions; valuation of future benefits and costs (discounting); and uncertainty in the assessment of benefits and costs.

Measurement of Benefits A traditional benefit-cost analysis expresses all valued outcomes in commensurate units. A monetary measure (e.g., dollars) is the natural choice of units in which to measure the value of those benefits (goods and services) that are sold in private markets. On the other hand, some impacts, particularly those that affect health and the environment, involve considerations that society does not measure in dollars or trade: human life, quality of life, and continued viability of environment for particular species, for example. Hence, expressing these factors in dollar terms involves the imposition of particular judgments that may or may not agree with those that would emerge from political processes or be consistent with other concepts of the interests of society at large. Approaches that stop short of complete commensuration of all outcomes are possible. The cost-effectiveness approach, for example, requires commensuration of all costs and of all benefits but not *between* costs and benefits. For example, health benefits might be measured in units such as life-years saved, while economic costs and benefits are expressed in dollars. The ratio of dollar cost per unit of benefit can then be used as a guide for relative priority setting among alternative safety protection programs without the need for explicit monetization of each separate benefit. Even less aggregation across attributes of outcome is required by the method of *meticulous accounting* (Raiffa *et al.*, 1977), in which impacts are measured in physical units along the outcome attributes of concern (e.g., days of work lost, numbers of lives lost, or life-years lost), but commensuration is not attempted and is left to the implicit judgment of the users of the analysis.

When complete monetarization of benefits is attempted, economists often seek measures of *willingness to pay* for such benefits that reflect the way individuals *would* value these goods if they were traded on markets. For example, the benefit from eliminating a nonfatal case of skin cancer might include the savings of expenditures for medical care that would have been required for its treatment, plus the lost income from days not worked, plus a measure of personal willingness to pay to avoid the discomfort, inconvenience, and cosmetic disfigurement caused by illness.

In all three studies, the principal health benefit considered is the reduction in the incidence of skin cancer. Estimates of the cancer incidence under various CFC emission scenarios are based on quantitative estimates, derived from other studies, of the linkages between CFC emissions and ozone levels, between ozone levels and UV-B penetration, and between UV-B exposure and skin-cancer incidence. D'Arge *et al.* consider only nonfatal cases of skin cancer and measure the cost per case as the sum of two components: the medical care costs required for treatment and the value of earnings lost due to time away from work. SCI adopts the d'Arge *et al.* approach and estimates, apparently without modification. Bailey, in addition to adjusting the d'Arge *et al.* data for inflation, adds a third component corresponding to the hypothesized willingness of an individual to pay to avoid the morbidity, inconvenience, and possible disfigurement associated with a nonfatal case of skin cancer. He also includes estimates of the number of fatalities (9 per 1000 cases) and attributes a willingness to pay of $330,000 per death averted (based on an estimated willingness to pay $330 for a one per thousand reduction in the probability of premature death). This last estimate is based on data on wage premiums for "risky" occupations.

All three studies include, among the other benefits of reduced CFC emissions, reduced weathering of UV-sensitive materials. All three use as a measure of benefit the cost of protective coatings that would have been required to avoid this weathering damage. (This is, of course, an upper bound on the true benefit, since it might be cheaper to let materials weather more rapidly or to substitute other materials.) SCI also includes among the benefits of UV reduction the commercial value of the cattle that would have developed ocular squamous-cell carcinoma ("cancer eye").

D'Arge *et al.* and SCI both include a formal analysis of the costs and benefits anticipated from a possible change in climate. D'Arge *et al.* update and extend the economic analysis from the CIAP study (U.S. Department of Transportation, 1975) to estimate the costs and benefits per 1°C of global warming. Their estimates include increased energy expenditures in urban areas (largely for air conditioning) and impacts on fishery, timber, cotton, and corn production. SCI uses the original CIAP data for estimating the costs per 1°C change but uses estimates of the magnitude of climatic impact from a previous National Academy of Sciences report (Climatic Impact Committee, 1975) as well as from the CIAP study. The data used by d'Arge *et al.* suggest a cost associated with warming, apparently because the original CIAP studies used by SCI did not include the impact of warming on air-conditioning costs.

The data used in the three studies to measure the benefits of CFC emission reduction are summarized in Table K.1 in Appendix K.

Measurement of Control Costs A number of techniques can be utilized to measure the costs of restricting CFC uses. These include, first, measuring the value to a consumer of products that use CFCs and then assuming that no substitutes for CFCs exist. This implies, for example, that the value of the CFC used in a home refrigerator is identical to a consumer's economic value of that refrigerator --termed consumer surplus by the economist--since banning CFCs is assumed to be equivalent to banning home refrigerators. Obviously, this is an upper-bound measure of the value of CFCs. A second approach, termed the derived-demand measure, is to determine the value of CFCs, for example, to the manufacturer of refrigerators--how much the industry is willing to pay for continued CFC use as measured by their demand for CFCs. This technique effectively assumes that good substitutes exist for CFCs. Derived demand yields a lower bound for the value of CFC uses.

Both of these techniques depend on past data on price, quantity, and other economic variables necessary for measuring demand curves and thus have the disadvantage that they are backward looking. New technologies, both for controlling CFC emissions and for producing substitute products, are excluded. A third alternative, which may be superior for the CFC problem, is to examine the engineering costs of each emission-control strategy or best alternative substitute for a good that uses CFCs and to

TABLE 7.9 SCI's Estimates of Cost-Effectiveness of Automobile Air-Conditioning Control Measures[a]

Point of Application of Control Measure	Reduction in Emissions (Pounds per Year)	Cost of Achieving Reduction (Dollars per Year)	Cost-Effectiveness Ratio (Dollars per Pound of CFC Not Emitted)
1. Compressor shaft seal	0.10	0.24	2.40
2. Hose permeation	0.19	7.07	37.21
3. Compressor gaskets	0.09	0.39	4.33
4. Servicing	0.57	1.06	1.86
5. 1, 3, and 4	0.76	1.69	2.22
6. Hermetic seal	0.95	25.00	26.32
7. Collect and reprocess	1.14	1.01	0.89
8. 5 and 7	1.33	2.66	2.00
9. New technology	1.58	11.25	7.12

[a] Based on Table B1 and the accompanying text in SCI (1978), p. B-9.

[b] Costs are averaged over the assumed six-year life of an automobile air conditioner.

estimate the costs of restricting use from these numbers. This alternative requires some knowledge of demand as well, since emission controls on CFCs, or the use of alternative goods that do not use CFCs, may cause price increases resulting in decreased consumption of CFC-related goods and some indirect loss of consumer value.

The d'Arge *et al*. study utilizes the first two techniques described above to obtain upper and lower bounds for the cost of reducing CFC emissions. Demand curves are estimated for commodities that use CFCs (refrigerators, polyurethane foam mattresses, auto air conditioners, mobile refrigeration units, and a number of aerosol products).

The SCI study employs the d'Arge *et al*. demand equations to calculate reductions in CFC product uses if various control strategies are employed but uses the third technique described above to make some preliminary calculations of the costs of alternatives and control measures. Table 7.9 illustrates this by showing SCI's calculated costs per pound of various control options for reducing CFC emissions from auto air conditioners. Increases in costs and consequent reduction in use for three increasingly severe control levels are calculated across a range of uses similar to those considered in the d'Arge *et al.* study.

The Bailey study uses cost estimates taken directly from the d'Arge *et al.* study.

Discounting The argument used by economists to justify discounting the future, i.e., weighting future costs and benefits less than current costs and benefits, can be explained with the following example. Imagine that an individual 50 years from now incurs a nonfatal skin cancer as a direct result of current CFC emissions. An estimate of the approximate costs to that future individual, in today's dollars (i.e., taking inflation into account) might total $2500, including medical care costs, value of lost wages (time off from work), and some compensation for slight disfigurement. The questions then becomes: how much must we deposit in the bank at compound interest to provide $2500 fifty years hence? For example, if we can find an investment or savings account that will earn a 3 percent real rate of return, we need only to invest $558 today to have $2500 in 50 years (in constant dollars). Thus it could be argued that the benefit today of preventing one skin-cancer case 50 years from now is $558, not $2500.

Three principal areas of controversy surround the choice of discount rate. First, the technical determination of the real rate of return appropriate for use in discounting may depend on available investment opportunities, tax distortions, investment risk, and sources of funds. Baumol (1968) has argued that the real rate of return on private investments in the United States is about twice the market rate of return because of the 50 percent corporate income tax. This would imply that a high discount rate (11 percent or more) is appropriate. Alternatively, if public investments spread investment risk (Arrow, 1966) and draw on sources of funds that do not reduce investment in high-yield areas of the economy (Marglin, 1963a), perhaps a low rate of return (for example, 3 percent) is more appropriate.

Second, ethical concerns may affect the choice of discount rate. Page (1977), for example, questions the ethics of discounting future cancer costs when society does not in fact make investments to compensate a future cancer victim. A number of economists have analyzed the consequences of the ethical system put forward by Rawls (1971) in *A Theory of Justice*, which promotes economic equity, generally concluding that where harm to future generations is implied, a low discount rate is appropriate (e.g., Page, 1977). These issues, and the question of whether or to what extent it is appropriate to discount future events of these types are judgmental, dependent to a significant degree on ethical questions--the answers to which are not obtainable from economic market data.

A third argument has been put forward by Marglin (1963b). He argues that the present generation may invest too little in the future because it is difficult for individuals acting now to make investments independently that assure that their own children will live in a better future. Thus, individuals, because of the "public-good" nature of the future--the fact that the quality of the future environment and the future peacefulness of the world as a whole depend in part on actions taken in the present--may not invest enough to meet such ends except through collective action. Thus, Marglin argues that government has the role of increasing total investments (implying a lower discount rate) in activities that will benefit the future. The direct implication of this argument is that a discount rate lower than the private market rate of return is appropriate for the CFC-ozone problem.

The three CFC cost-benefit studies make varying assumptions concerning discount rates consistent with the arguments described above. D'Arge *et al.* use discount rates of 3, 5, and 8 percent to test the sensitivity to discounting in their analysis. Bailey strongly defends the view put forth by Baumol and uses an 11 percent discount rate of return as his median estimate and the basis for his conclusions but also varies the discount rate to test the sensitivity of his assumption. The SCI study uses rather low discount rates of zero and 3 percent, implicitly accepting both ethical arguments and arguments for the public-good nature of the future.

Uncertainty Uncertainty surrounds not only the estimates of the effects of CFC emissions on the ozone layer, the effects of ozone depletion on UV-B increase and its impact on the incidence of skin cancer and on ecosystems, and the effects of ozone depletion and CFC emissions on climate but also the economic costs of CFC reduction (which depend, for example, on the future availability of substitutes for use as refrigerants and foam blowing agents).

There are three major reasons why uncertainty should be reflected in a benefit-cost study of this problem. First, since scientists and economists disagree about the magnitudes of key parameters, it is important to indicate how variations in these parameters can affect the results of the analysis. Second, results corresponding to "most-likely" or average values may not reflect social or individual attitudes toward risk, particularly if small or unknown probabilities of possibly catastrophic consequences are involved. Third, only by considering uncertainty explicitly can an analysis reveal the value of pursuing an adaptive strategy of either delaying regulatory action pending further evidence of, for example, ozone depletion, or of adopting a flexible stance whereby controls are initiated gradually and provision is made for their subsequent tightening, relaxation, or removal.

Uncertainty can be incorporated into the analysis and presentation of a benefit-cost study of this problem in a number of ways.

One approach is to use the best available "point" estimates throughout but to provide ample sensitivity analysis (varying the estimates one or a few at a time to determine to what extent conclusions change). Another approach is to provide upper and lower bounds on each estimated parameter and then to report "best-case" results and "worst-case" results, along with a central result based on the central estimates for each parameter. A variant of this procedure, used by Bailey, was to treat the upper and lower bounds as if they were the fifth and ninety-fifth percentiles of independent probability distributions, thus allowing explicit calculations of the derived fifth and ninety-fifth percentiles for the results. The most explicit approach to uncertainty would be to assign complete, though often judgmental, probability distributions for all uncertain parameters, thus--if these distributions are independent--permitting the calculation of an explicit probability distribution for the result (e.g., net present value).

The latter approach was followed explicitly by SCI, and was approximated by Bailey through the device described just above. Thus, for example, SCI assumes that the percent change in skin-cancer incidence associated with a 2 percent increase in UV-B will be less than 0.5 percent with probability 0.01, less than 0.8 percent with probability 0.25, less than 1.0 percent with probability 0.50 (the median estimate), less than 1.25 percent with probability 0.75, and less than 2.0 percent with probability 0.99. Bailey similarly takes 1.0 percent as his central value of this parameter and sets upper and lower 95 percent (*not* 99 percent) limits at 0.5 percent and 2.0 percent, respectively. D'Arge *et al.* do not explicitly consider uncertainty in the physical and biological effects and use expected values of all parameters. They do, however, recognize the uncertainty in the economic costs of CFC emission reduction by providing a range of estimates corresponding to various assumptions concerning the availability of substitutes for CFCs.

There are several dangers in calculating social benefits and costs of CFC reduction on the basis of "central," or average, parameter estimates. First, there may be nonlinearities in the transfer functions linking CFC emissions and ultimate socioeconomic impact. If this is the case, a result based on "most-likely" estimates for each individual parameter (e.g., the percentage increases in skin-cancer incidence per one percent increase in UV-B levels) may not correspond to the expected, or average, value of the result. This situation arises, for example, if the impacts of successive 1 percent increments in UV-B levels are increasingly severe as the UV-B level increases. It is not impossible then that a 1 percent chance of a 100 percent increase in UV-B could be a more significant risk than a 50 percent chance of 30 percent increase because of nonlinear or threshold effects. Yet this possibility would be ignored unless the full range of uncertainties were carried through the analysis. The methodology of SCI and, to a more limited extent, Bailey, could capture this sort of effect, but the approach of d'Arge *et al.*, using point estimates throughout, cannot. In fact, however, SCI and Bailey fail to capture this effect because they assume a linear relation between UV-B and all measured social costs.

The second danger in using expected, or average, values of social cost is that social preferences may be such that the product of probability of effect times magnitude of effect does not reflect social or individual preferences. That is, the society may want to take a "risk-averse" posture. Arrow (1966) has argued that under certain assumptions, the government as an agent for society should not be risk-averse. He assumes, however, that the range of uncertainty for any single individual is vanishingly small--not a valid assumption in this case in which the full force of any major impact would be felt by an entire population (Smith and d'Arge, 1978). On the other hand, it has been argued that it is appropriate for the government to be risk-neutral with respect to the incidence of mortality and morbidity, provided that the incidence cannot be concentrated enough to produce massive societal trauma (Raiffa *et al.*, 1977). Whether it is possible that the tails of the probability distributions in the CFC problem would encompass such massive societal trauma is a matter of conjecture, but the issue has been avoided in all three studies.

Only the SCI study sets out explicitly to assess the value of a strategy in which regulation is made contingent on information in the form of a detected level of ozone depletion. This strategy is based on the premise that the expected cost of a delay (given the existing assessments of the risks) must be balanced against the expected value of possibly learning that serious ozone depletion is not likely to be occurring, thus saving (i.e., not incurring) the economic costs of CFC reduction. The SCI study finds strategies of this type to be rather appealing in terms of expected net costs, but their attractiveness rests heavily on the assumption that the measured ozone levels over the short term correlate with the actual ozone levels over the long term. They do acknowledge the variability of ozone levels and the imprecision of monitoring techniques, but it is not clear that this variability has been considered adequately. The validity of the assumptions made in this regard should be examined carefully.

Further details of the methodology used in the d'Arge, Bailey, and SCI studies can be found in Appendix K.

Applying Benefit-Cost Analysis to the Ozone Problem

Given these methodological problems, we believe benefit-cost analysis can be helpful to the decision maker trying to select an ozone-protection strategy if great emphasis is placed on identifying assumptions and uncertainties and if a sensitivity analysis is performed showing the extent to which the results depend on the assumptions and choices adopted. At the same time, the analyst should not place too much emphasis on expressing costs and benefits in commensurate terms; such expression may lead to apparent simplicity in the results that is not justified by the underlying information. Even when commensuration of costs and benefits is not possible, benefit-cost analysis can be used for identifying, displaying, and ranking the significant factors that enter into consideration.

Even a limited analysis of this sort, however, requires estimates of the costs and impacts of both the control measures and the ozone depletion that would occur in the absence of controls. Much of the information needed to make such estimates does not yet exist, although this situation may be remedied in the next several years. As our information and understanding grow, and the uncertainties diminish, the range of applicability of formal methods such as benefit-cost analysis may increase somewhat.

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Appendixes

APPENDIX A GLOSSARY

Action spectrum: A graph or mathematical expression indicating the relative effectiveness of radiation at different wavelengths for producing a specified photochemical or photobiological effect.

Azeotrope: A mixture of two or more substances (in the context of this report, two or more CFCs) the relative concentrations of which do not change on transition between the liquid and vapor states. Azeotropes thus retain their identity through changes of phase and can be separated from minor impurities by fractional distillation.

BFC: Bromofluorcarbon.

Bromofluorocarbon: Any chemical compound containing bromine, fluorine, carbon, and possibly hydrogen.

CFC: Chlorofluorocarbon.

CFM: Chlorofluoromethane.

Chlorocarbon: Any chemical compound containing chlorine, carbon, and possibly hydrogen.

Chlorofluorocarbon (CFC): Any chemical compound containing chlorine, fluorine, carbon, and possibly hydrogen.

Chlorofluoromethane (CFM): Any chlorofluorocarbon containing only one carbon atom per molecule.

CIAP: Climatic Impact Assessment Program, a research program carried out by the U.S. Department of Transportation during 1971-1974 to assess the climatic impact of aircraft flights in the stratosphere.

Diethyl ether: $(C_2H_5)_2O$; highly flammable chemical formerly used for presurgical skin cleaning, now replaced by F-113.

Difunctional (bifunctional): Having two chemically reactive groups (i.e., a functionality of two). Exceptions are groups such as the ethylenic group, which is a single functional group in organic chemistry nomenclature but is difunctional in terms of polymerization. In order to make polymers, monomers having a minimum functionality of two are necessary. The resins and isocyanates used to make polyurethanes have a functionality of two, or higher.

DNA: Deoxyribonucleic acid, the cellular "genetic material," carrying information necessary for the cell's construction. Its molecules typically consist of two long, paired strands, each composed of four different kinds of smaller units ("nucleotides") linked together in a linear sequence that encodes the genetic information. The kinds of nucleotides present at corresponding points in the two strands are related, so that the sequence in either strand is determinable from the sequence in the other.

DUV (damaging ultraviolet): A measure of ultraviolet radiation over a range of wavelengths in which the relative effectiveness of each wavelength has been taken into account. Determination of a DUV value requires knowledge of the action spectrum (q.v.) for the biological effect in question.

Elastomeric: The property of rubbery polymers wherein they can be deformed and essentially recover their original dimensions when the stress is released. To be elastomeric, a polymer must be at a temperature above its glass transition temperature (T_g). The elastomeric materials referred to herein include flexible polyurethane and poly(vinyl chloride) foams.

Ethylene oxide: $(CH_2)_2O$; used in combination with F-12 to sterilize medical and pharmaceutical supplies.

Excision repair: One of the major cellular processes by which damaged DNA in cells can be restored to normal structure and function. The damaged region of one strand is removed, and its nucleotide sequence is reconstructed according to the intact information in the other strand (see DNA). This process repairs more than one kind of DNA damage.

Fluorocarbon: Strictly a chemical compound containing only fluorine, carbon, and possibly hydrogen; however, the term has been used to mean any halocarbon containing fluorine, and this may refer to compounds containing chlorine or bromine as well.

Fully halogenated chlorofluorocarbon: A chlorofluorocarbon containing only chlorine, fluorine, and carbon, i.e., containing no hydrogen. Hydrogen-containing CFCs react with other chemicals in the troposphere and are at least partially destroyed there; fully halogenated CFCs do not react, and ultimately reach the stratosphere.

Functionality: The number of reactive groups having the potential to react in an organic compound is its functionality; thus all monomers that when polymerized may join with two, and only two, other monomers have a functionality of two (see difunctional). As used herein, it refers specifically to the number of reactive groups in the resins or isocyanates used to prepare polyurethane foams.

F-11*: $CFCl_3$, extensively used as a refrigerant, blowing agent, and aerosol spray propellant.

F-12: CF_2Cl_2; extensively used as a refrigerant and aerosol spray propellant; also used as a blowing agent, sterilizing agent, and food freezant.

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*The notation used for identifying chlorofluorocarbons is based on that used by DuPont in identifying the CFCs it manufactures under the trade name Freon. (Similar notation is used, with the prefix "R," in the air-conditioning and refrigeration industry to identify refrigerants; thus R-12 is the same chemical as F-12.) Add 90 to the number, and the resulting three digits indicate, in order, the number of carbon, hydrogen, and fluorine atoms per molecule of the CFC; there are as many chlorine atoms as needed to fill out the carbon valence of 4. Modifications of this system have been introduced as needed, such as the suffixes a and b, and the "500" numbers used to denote azeotropes.

F-22: CHF_2Cl; extensively used as a refrigerant in residential air conditioners.

F-113: $CF_2ClCFCl_2$; extensively used as an industrial solvent; also used as a presurgical skin cleaner.

F-114: CF_2ClCF_2Cl; used as a refrigerant and as a blowing agent in certain types of plastic foams.

F-115: CF_3CF_2Cl; used as a stabilizer for whipped toppings and, in the azeotrope F-502, as a refrigerant.

F-134a: CH_2FCF_3; not currently manufactured, but of interest as a substitute for currently used CFCs because it contains no chlorine and appears likely to have desirable physical properties.

F-142b: CH_3CF_2Cl; of interest as a possible substitute for currently used CFCs in manufacturing certain kinds of plastic foam.

F-152a: CH_3CHF_2; used in the azeotrope F-500 as a refrigerant.

F-500: An azeotrope consisting of 73.8% F-12 and 26.2% F-152a.

F-502: An azeotrope consisting of 48.8% F-22 and 51.2% F-115.

GCM (Global Climate Model, or General Circulation Model): Any of a number of three-dimensional numerical (computer) models of the atmosphere used in both research and operations to study and predict weather and climate.

Greenhouse effect: The "trapping" of solar heat within the atmosphere. The atmosphere is transparent to short-wave radiation from the sun, most of which reaches the earth's surface, where it is absorbed and re-radiated as long-wave radiation to which the atmosphere is relatively opaque.

Halocarbon: A chemical compound consisting of one or more of the halogens (fluorine, chlorine, bromine, iodine), carbon, and possibly hydrogen. A fully halogenated halocarbon contains only carbon and halogens.

Halon 1301: CF_3Br; a bromofluorocarbon used in specialized fire-extinguishing applications.

Irradiance: The amount of radiant energy per unit time (i.e., the radiant power) falling on a unit area of a specified reference surface. For each constituent wavelength, the irradiance on a skin surface (the "dose rate") determines the rate at which the radiation produces photochemical damage in underlying cells. Since irradiance changes with the orientation of skin toward a light source, the daylight irradiance on a horizontal surface is often used to represent the general solar radiation environment.

Isocyanate: An organic chemical containing one or more isocyanate groups (-N=C=O). Isocyanates are chemically reactive, especially with active hydrogen compounds. They are generally regarded as toxic intermediates to be handled with care.

Isocyanurate foam: The generic term that designates organic compounds containing the isocyanurate chemical group. The polyisocyanurate foams referred to herein are made by polymerizing isocyanates with very basic amine catalysts in the presence of very small percentages of polyols (to get some urethane linkages for toughness).

Melanoma: A serious, often fatal form of skin cancer the cause of which is not fully understood but is believed to be associated with exposure to ultraviolet radiation.

Methyl chloride: CH_3Cl; a possible substitute for CFCs as an auxiliary pneumatogen (blowing agent) in the manufacture of certain kinds of plastic foam.

Methyl chloroform: CH_3CCl_3 (also called 1,1,1-trichloroethane); used as an industrial solvent.

Methylene chloride: CH_2Cl_2; used as an industrial solvent and as an auxiliary pneumatogen (blowing agent) in the manufacture of some flexible urethane foams. It is potentially suitable for use in making other kinds of foams as well.

Mutagenic: Tending to induce genetic mutation.

Nonmelanoma: Either of two rarely fatal forms of skin cancer, caused primarily by exposure to ultraviolet radiation.

1-D model: A numerical (computer) model in which, to save computer time, the earth's atmosphere is reduced to one significant dimension--the vertical.

Ozone: O_3; a gas whose molecules contain three oxygen atoms. Ozone is unstable and does not persist in the lower atmosphere except as a pollutant in photochemical urban smog; however, it exists as a natural component of the stratosphere at altitudes between 10 and 50 km. Stratospheric ozone absorbs much of the ultraviolet radiation that would otherwise reach the earth's surface.

Ozone layer: The region, within the stratosphere, where ozone is naturally found in significant, although small (a few parts per million), concentrations.

Perchloroethylene: CCl_2CCl_2; used as a solvent in the dry cleaning of clothing.

Photoreactivation: One of the cellular processes by which damaged DNA in cells can be restored to normal structure and function. In this process a special enzyme (which acts in the presence of long-wavelength ultraviolet or short-wavelength visible light) converts one type of ultraviolet-induced damage--the pyrimidine dimer--back to a normal nucleic acid structure.

Pneumatogen (blowing agent): A gas such as air, N_2, CO_2, and Freon, used for inflation. In polymer foam technology, a penumatogen is used to inflate the foam cells to form a low-density structure. If the foam cells remain closed, so that the pneumatogen remains therein, its properties contribute to the overall properties of the foam. Thus a closed-cell foam blown with F-11 is a good insulating material because the F-11 locked in its cells has lower thermal conductivity than air.

Polyester: A resin used in polyurethane production, which contains repeating ester linkages in the polymer chain and reactive hydroxyl or carboxyl groups at the chain ends. The polyesters are formed by reacting an organic acid (e.g., adipic acid, phthalic acid) with a glycol (e.g., ethylene glycol, propylene glycol) to form resin polyols having molecular weights in the 200-5000 range. Polyesters are not so widely used as polyethers in polyurethane production and are hardly used at all in polyurethane foams.

Polyether: A liquid resin of the kind most widely used in manufacturing flexible polyurethane foams. The polyethers contain repeating ether (oxygen) linkages in the polymer chain and hydroxyl groups at the chain ends. The most widely used polyethers are those made by polymerizing ethylene oxide or propylene oxide and have molecular weights ranging from 200 to 5000.

Polyethylene: The high-molecular-weight polymer formed by polymerization of ethylene ($CH_2=CH_2$). These polymers are crystalline to varying degrees, depending on the type of polymerization process and catalyst. The reference in this report is to polyethylene foams.

Polyfunctional: Having a functionality greater than 2. When the monomer functionality is exactly 2, thermoplastic polymers are obtained. When the functionality is greater than 2, vulcanized rubbers and thermosetting polymers can result, as in the polyurethanes. (See thermoplastic and thermosetting.)

Polymer: A material of high molecular weight composed of many (*poly*) repeating units (*mers*) of a simpler (small) compound, arranged in a chainlike structure. Polymers may be organic, semiorganic, or inorganic compositions, derived from either natural or synthetic sources. The polymers referred to in this report are of the organic, synthetic type.

Polymerize: The process wherein reactive low-molecular-weight compounds (monomers) are caused to react and link up to form high-molecular-weight polymers.

Polyol: A "resin" prepolymer in which the active hydrogen is in the form of hydroxyl groups, usually at the chain ends.

Polyolefin: The high-molecular-weight polymer formed by polymerization of unsaturated aliphatic organic (olefin) compounds. Polypropylene, polybutylene, polyisobutylene, and poly-4-methylpentene-1 are all commercially available polyolefins. The polyolefins referred to in this report are polypropylenes and foams made therefrom.

Polypropylene: The high-molecular-weight polymer formed by polymerization of propylene (CH_3-CH=CH_2). As normally made, the commercial polypropylenes are highly crystalline because of a special orderly arrangement of the monomer units along the polymer chain (isotactic).

Polystyrene: The high-molecular-weight polymer formed by polymerization of styrene ($C_6H_5CH=CH_2$). As ordinarily made, the finished polymers are "glassy," brittle, amorphous materials that are thermoplastic. They soften and undergo plastic flow under stress at temperatures above 95°C. Polystyrene has many uses, and the ones referred to in this report are the foam insulation boards and the foam packaging materials.

Polyurethane: The generic term used to describe all the materials that contain urethane linkages as a repeating unit in the polymer chain. Depending on the type of resin and catalyst used, polyurethanes may also contain other related structures including allophanates, ureas, and biurets.

Pyramidine dimer: A photochemically induced structure in DNA or RNA, involving an abnormal extra linkage between certain of the adjacent nucleotides within one strand. It constitutes a common type of ultraviolet damage in DNA that has been exposed to the shortest solar wavelengths reaching the earth's survace (UV-B).

Resin: A relatively high-molecular-weight, natural or synthetic polymer. It may be liquid, semisolid, or solid. In this report, "resin" refers to the liquid, active, hydrogen-containing prepolymers that have molecular weights in the 200-5000 range and react with diisocyanates to form polyurethanes.

RIM: Reaction injection molding, a new technique for the manufacture of high-density urethane foam parts for automobiles, furniture, and building construction.

RNA: Ribonucleic acid, a kind of nucleic acid constructed (like DNA) of nucleotides linked together in long linear sequences, but made from nucleotides differing in significant small details from those in DNA. In cells it does not provide the primary storage of genetic information (a function reserved for DNA), although it is involved in the transfer and readout of this information.

Spectral irradiance: The irradiance per unit wavelength interval (i.e., the irradiance within a very small range of wavelengths, divided by that wavelength range).

Surfactant: A surface-active organic compound having both oil and water-soluble groups that can solubilize, emulsify, or disperse oil in water, or vice versa. In polyurethane foam formulations, surfactants--usually organic silicone compounds--aid in bubble nucleation and produce a finer-celled, more-uniform foam than would otherwise be possible.

Teratogenic: Tending to induce birth defects.

Thermoplastic: Characterizing a polymer or plastic that can be repeatedly softened and made to flow, under heat and pressure, to fill a mold (cavity) wherein it hardens and takes its final shape by cooling. The most common thermoplastics are organic synthetic polymers such as polystyrene, polyethylene, polypropylene, and poly(vinyl chloride).

Thermosetting: Characterizing a polymer or plastic that can only once be softened and made to flow, under heat and pressure, to fill a mold (cavity) wherein it hardens and takes its final shape by a chemical (cross-linking) reaction. The polyurethanes are thermosetting plastics, as are phenol/formaldehyde and urea/formaldehyde polymers.

Toluene diisocyanate: An organic compound of toluene that contains two reactive isocyanate groups and is extensively used to react with polyols and resins to form polyurethanes. The standard commercial product is a liquid mixture of two (or more) isomers and can also be reacted with itself (trimerized) to become the major component of polyisocyanurates. Because of possible toxicity problems, toluene diisocyanate is increasingly used in a high-molecular-weight prepolymer form or replaced with polyfunctional polymeric isocyanates.

1,1,1-Trichloroethane: CH_3CCl_3 (also called methyl chloroform); used as an industrial solvent.

Trichloroethylene: $CHClCCl_2$; used as an industrial solvent.

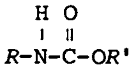
Ultraviolet: An adjective describing electromagnetic radiation with wavelength shorter than that perceived by the human eye but not as short as x rays. This term is also sometimes used as a short substitute for the full adjective-noun combination "ultraviolet radiation."

UV: Ultraviolet.

UV-A: Ultraviolet radiation of wavelength longer than 320 nm.

UV-B: Ultraviolet radiation of wavelength between 290 nm and 320 nm. Because stratospheric ozone absorbs most of the sunlight radiation at wavelengths below 290 nm, the wavelength limits for UV-B conveniently describe the most damaging portion of daylight at the earth's surface.

Urethane: The general term applied to organic compounds containing the urethane



$$R\text{-}\overset{\displaystyle H}{\overset{|}{N}}\text{-}\overset{\displaystyle O}{\overset{\|}{C}}\text{-}OR'$$

group. Urethanes are formed by the reaction of an organic active hydrogen polyol compound with an organic isocyanate. These urethane units are the repeating chemical group in the polyurethane polymer chains.

APPENDIX B ULTRAVIOLET SENSITIVITY OF ORGANISMS

AGRICULTURAL CROPS AND LAND VEGETATION

Higher plants have obvious importance both in agriculture and as the basis of primary production in natural land ecosystems (forests and rangelands, for example). Unlike animals, which can reduce exposure of their living cells to sunlight through protective body coverings and behavioral responses, plants have evolved to expose much of their living tissue to sunlight in order to utilize its energy for photosynthesis--the basic mechanism by which solar energy is captured for use by the entire biosphere. Thus, an atmospheric ozone reduction (with its attendant increase in solar-UV radiation) could be particularly significant for them. Much of the work on biological effects of solar UV during the last few years has dealt with higher plant species, especially crop plants.

Photosynthesis is at least partially inhibited by UV-B radiation in sensitive plants as mentioned above (Brandle *et al.*, 1977; Sisson and Caldwell, 1976, 1977; Van *et al.*, 1976, 1977). Furthermore, UV-B radiation can affect other important processes in plants, such as cell division (Dickson and Caldwell, 1978), which reduces the potential for leaf growth. Additional changes in plant pigments and in growth patterns, such as curling of leaves and changes in the growth of roots compared with growth of leaves and stems, also occur. It is still not clear what mechanisms or radiation receptors cause these changes.

Over 100 species and varieties of agricultural plants, as well as some nonagricultural higher plant species, have now been tested for their comparative sensitivity to UV-B radiation in controlled environment growth chambers. A short-term, but extensive screening program of 82 species and varieties was recently undertaken at the University of Florida in Gainesville (R. H. Biggs and S. V. Kossuth, unpublished BACER report). Approximately 20 percent of the species were classed as highly UV-B-sensitive species. Many exhibited significant reductions in yield when exposed daily to the lowest UV-B dose employed, which is approximately equivalent to the amount of UV-B radiation received in a half day of normal sunshine in the summer in northern Florida. On the other hand, 20 percent of the species suffered no apparent reduction in yield at even the highest daily doses employed, which would correspond to roughly twice the amount of solar UV-B radiation currently received during a summer day in northern Florida. The remaining 60 percent exhibited intermediate degrees of sensitivity to UV-B radiation. Apart from reductions in plant dry weight or yield, UV-B radiation also affected the proportion of plant material represented. in various plant organs such as roots, shoots, and leaves. Although these alterations might not necessarily be detrimental themselves, they could result in undesirable consequences for agricultural utilization of the plants.

The subsequently discovered fact that some plants in the open field are less sensitive to UV radiation than those raised in environmental growth chambers reduces the importance of this extensive study for predicting the consequences of ozone depletion. However, the study does substantiate earlier findings that higher plant species vary considerably in their sensitivity.

It is difficult at present to predict, without testing, which plant species are likely to be more sensitive to UV-B radiation. There is some indication that at least part of the sensitivity difference may be due to pigments or tissues within plant leaves that physically screen the radiation before it reaches physiologically sensitive targets (Van *et al.*, 1977). However, other factors may also be involved. At one point it appeared that plants utilizing a certain photosynthetic pathway known as C_4 photosynthesis might be relatively insensitive (Van *et al.*, 1976), but recent studies show that C_4 plants can also be UV-sensitive (L. H. Allen, U.S. Department of Agriculture, Gainesville, Florida, unpublished BACER report). Some families of plants such as the grasses do seem to be somewhat more resistant than other families such as the mustard family. Still, within these families, and even within the same species, there is a great deal of variation in sensitivity. For example, soybeans tend to be generally sensitive to UV-B radiation, but an examination of 19 varieties indicated substantial differences among them.

Variability in UV sensitivity provides possible breeding stocks for selecting UV-B radiation-resistant varieties in the event that ozone depletion should become a serious problem for these crops. In any such plant breeding program, all the other characteristics that influence the success of a crop species (such as suitability for different climates in terms of pest resistance and length of growing season) would, of course, have to be maintained while the UV resistance was increased. While there is no guarantee that resistant varieties with all the other desired characteristics can be bred, the existence of already resistant plants increases the probability that they can.

It was noted that plants seem more sensitive to UV radiation if grown in greenhouses or controlled-environment chambers, where visible light intensities are much lower than they are in the field. To date only a few experiments have been conducted in the open-field environment, with additional UV-B radiation provided by special lamps. Such experiments are more difficult to carry out successfully than those in controlled environments because the growth variation under field conditions often obscures responses to specific treatments. To date, only some 15 species and varieties of crop plants have been so tested.

Several crop species such as peanuts, southern peas, potatoes, squash, beans, soybeans, and sorghum exhibited no detectable response to UV-B radiation supplements as large as two to three times the present solar DUV for summer conditions at 30° N under field conditions. Other species, such as sugar beets, tomatoes, mustard, and corn did exhibit yield reductions when subjected to these same levels of supplemental UV-B radiation in the field. It appears that the amount of UV-B radiation corresponding to a 16 percent ozone reduction at temperate latitudes in summer might cause an appreciable reduction in yield for at least a few crops. At this point, however, such experiments need to be repeated, with refined and more extensive testing programs.

Virtually nothing is known at present about the interaction of UV sensitivity with common stress factors in the plant environment, such as mild water shortage and nutrient deficiency. They might either tend to accentuate or to reduce the sensitivity of plants to UV radiation in nature.

There is some evidence suggesting that UV preconditioning can significantly affect the UV sensitivity of plants. A particularly vivid example was described by Bogenrieder and Klein (1977), who demonstrated that certain higher plants, when grown in an environment completely free of

UV radiation (UV-B and longer-wavelength UV), were extremely susceptible to normal sunlight UV as occurs in Freiburg, West Germany (50° N). The foliage of several plants was completely destroyed by subsequent exposure to unfiltered sunlight. Plants that were subject to control conditions, where the UV was filtered out of the sunlight, were not affected.

Even though a reduction of atmospheric ozone of the magnitude now envisaged could have significant effects on crop yields in certain plant varieties, the proportion of general agricultural crops in various parts of the world that might be affected, and the degree to which yields might be reduced, cannot be meaningfully surmised at this time.

DOMESTIC AND WILD ANIMALS

Insufficient data precludes accurate assessment of the impact of increased DUV radiation on domestic and wild animals (including insects), but the available information suggests that no serious impact is likely. Given the shade-seeking behavior of most wild animals, and the protective hair, feathers, and pigmented skin, about the only potential vulnerable site for DUV damage is the eye. Soaring birds might be particularly vulnerable. High doses of monochromatic UV-B radiation can cause photokeratitis, and even higher doses can cause cataracts (Pitts and Cullen, 1976). Whether the expected increases in natural DUV doses could cause such effects is unknown. An accumulation of DUV damage to eyes, if it occurs, might shorten the lifetimes of individual animals, thereby removing them from competition with younger survivors.

The most likely impact on agricultural animals is increased incidence of "cancer eye," a carcinoma of the conjunctiva in certain cattle varieties (Macdonald, 1975). A speculative projection based on 1975 data (K. E. Kopeky, E. W. Pugh, Sr., and D. E. Hughes, National Animal Disease Center, USDA, Ames, Iowa, unpublished BACER report) suggests that the 44 percent increase in DNA-damage-weighted DUV radiation expected with 16 percent ozone-layer reduction might increase the number of cattle with parts condemned for carcinoma from approximately 0.38 percent of the total slaughtered each year in the United States to about 0.55 percent.

NONAGRICULTURAL LAND ECOSYSTEMS

The biological world is a dynamic system, composed of both competing and cooperating species, each of which is suited to live in a certain environmental range. Their environment is set by the physical and chemical features of their surroundings, greatly modified by the presence of the organisms themselves. Although the exact numbers and relationships of species normally undergo considerable fluctuations, the dynamic balance of these species over the long run establishes the natural world with which we are familiar. Selection during biological evolution has presumably produced species that are well adapted to their particular niche within it.

Man deliberately manipulates this natural environment in efforts to accomplish his desired ends. These purposeful perturbations (such as, for example, the conduct of agriculture, harvesting of timber, and grazing of livestock) rely for their expected benefits on the remainder of the environment remaining satisfactorily stable. Perturbations that excessively disturb the biological world would change the framework within which man must live and force major readjustments of his activities.

Natural ecosystems are major suppliers of resources. Rangelands contribute over 50 percent of the total food supply in many developing countries. Much of the world's fiber is derived from forests. Nonagricultural ecosystems also control the behavior of important watersheds and are involved in the natural cycling of mineral elements and atmospheric constituents on a global scale. Thus, concern about the effects of increased solar UV on human health or the agricultural systems involved in our food supply should also extend to the forests, rangelands, deserts, tundra, and other areas.

The range of DUV sensitivity of nonagricultural plants does not appear to be different from that of crop plants (S. V. Kossuth and R. H. Biggs, University of Florida, Gainesville, unpublished BACER report; Fox and Caldwell 1978; Sisson and Caldwell, 1977). Thus, reduced productivity of some forest and rangeland species might be expected. However, natural ecosystems are much more complex than agricultural fields. The many-sided interactions between organisms may make the major impact of increased solar UV come in ways other than a reduction of total biomass production. An ecosystem might, for example, show changes in the relative numbers of different species--those having more UV resistance benefiting at the expense of those that are more sensitive (Caldwell, 1977; Fox and Caldwell, 1978). Such changes in competitive balance might amplify rather small sensitivity differences, affecting subtle processes (pollination, relationships between predators and their prey, and biological fixation of nitrogen, for example).

Changes in the competitive balance of plant species have actually been demonstrated, using UV-B-producing lamps to supplement normal sunlight (Fox and Caldwell, 1978). Although these supplements were greater than the UV-B increase that would accompany currently expected decreases in stratospheric ozone, the results indicate some of the processes that may be involved in species replacements. Recently, A. Bogenrieder, B. Bruzek, and S. Kiliani (University of Freiburg, unpublished data) showed that the balance between plant species can also be altered when both UV-B and the longer-wavelength, less biologically active UV-A are filtered out of normal sunlight. This occurred even at 50° N latitude, where the DUV dose rate is considerably smaller than at lower latitudes. Such experiments suggest that changes in nonagricultural ecosystems may accompany small UV-B increases; but because so few nonagricultural plant and animal species have been evaluated, it is impossible at this time to predict which species might benefit at the expense of others.

It is usually not easy to decide whether a specified change in the species balance of an ecosystem should be considered detrimental or beneficial to human welfare. However, the presumed effectiveness of past evolutionary adaptation, and the human need for a stable framework within which to operate, make it prudent to regard any widespread changes as likely to be harmful.

AQUATIC ORGANISMS AND ECOSYSTEMS

Marine and freshwater ecosystems are a vital element in the complex environment that makes life as we know it possible. The finfish and shellfish used for human food, and the organisms on which they feed, are obviously important. In addition, aquatic organisms decompose organic wastes (thus depolluting the waters), and marine algae serve as a source of oxygen and as a sink for carbon dioxide. Amounts of the latter gas in the atmosphere are measurably increasing at this time, because of the very heavy, worldwide combustion of fossil fuels.

Current levels of solar-UV radiation at the water surface can be lethal to marine bacteria, and current surface

UV levels, at wavelengths shorter than the cutoff point for glass or Mylar (below 340 or 315 nm, respectively), significantly reduce photosynthesis in marine algae when these organisms are collected at various depths and brought to the surface (Jitts *et al.*, 1976; Lorenzen, 1975). Laboratory studies on a variety of aquatic organisms support these sunlight studies. Simulated doses of DUV radiation at the water surface, produced by fluorescent sunlamps with filters (see Appendix E), indicate that only a few hours of radiation comparable with that in the near-noon summer sunlight can kill 50 percent of the population in most of the 60 or so species tested (bacteria, algae, protozoa, small invertebrates) (Calkins, 1975; Calkins *et al.*, 1978; Nachtwey, 1976). These studies thus suggest that aquatic ecosystems may be extremely vulnerable to ozone depletion/increased UV-B. However, the dosimetry for these experiments was done with a Robertson-Berger Sunburning Ultraviolet Meter (R-B Meter). As discussed in Appendix E, the use of this meter for comparing DUV from filtered fluorescent sunlamps with that of sunlight may significantly overestimate sunlight sensitivity.

Most recent studies have employed better dosimetry, involving spectroradiometric measurements weighted by either an erythema or DNA-effective weighting function (see Appendix D). Several of these studies provide quantitatively useful data for assessment.

Photosynthesis in a marine diatom (*Chaetoceros didymus*) decreases exponentially with increasing DNA-weighted dose (R. C. Worrest, Oregon State University, unpublished). Recalculations of these data indicates that current summertime daily surface DUV doses at 40° N latitude at the water surface can reduce photosynthesis (carbon dioxide uptake) by 40 percent relative to controls receiving no UV-B. A 44 percent increase in DUV (such as would accompany a 16 percent ozone layer reduction at 40° N latitude) would decrease photosynthesis by 28 percent from that expected in nature with current summertime daily surface doses. These results assumed that the DNA-effective dose is the appropriate one to use, but this may not be the correct weighting function for photosynthetic inhibition. Most important, however, is the protection these organisms receive from being located at some depth in the water.

Similar studies by Thompson *et al.* (1979) examined the effects of simulated solar UV-B on the growth rate (cell divisions/day) in an estuarine chain-forming diatom (*Melosira nummuloides*), which attaches to surfaces and floats in the water column. DUV doses comparable with current summer daily surface doses at 40° N latitude reduced the growth rate by 35 percent relative to controls receiving no UV-B. Any considerable increase in this DUV dose would then be expected to reduce the growth rate for organisms at the water surface.

These two studies indicate that, with current surface doses, these organisms are under UV radiation stress. Yet they thrive in nature. This may mean that they must constantly contend against the UV radiation in order to exist in environments having other advantages and are consequently not producing at the maximum possible rate. The situation could be analogous to that of some terrestrial plants, which show spectacular increases in yield if grown hydroponically under optimum conditions.

In another quantitatively useful study, D. M. Damkaer (NOAA Pacific Marine Environmental Laboratory, Seattle, unpublished BACER report) examined the DUV sensitivity of larval forms of shrimp and crab (two species). These organisms appear to be less sensitive than the bacteria, protozoa, and algae mentioned above, in that several days rather than several hours exposure are required to produce an effect. Moreover, the organisms show a threshold of tolerance to the killing effects of DUV, with no reduction in rates of development at sublethal doses, compared with control organisms. The various tolerance doses (weighted with an *erythemal* weighting function) are plotted in Figure B.1. In this plot, a short, horizontal line is positioned vertically to show the tolerance dose of the organisms (measured at the water surface) and horizontally to show the period of the year during which the larval forms develop. These tolerance doses are superimposed on curves showing the annual DUV cycle of average daily doses at the location of the experimental studies, assuming various ozone-layer reductions.

During most of the reproductive/developmental period, the tolerance threshold daily doses determined for these organisms are greater than the average daily doses experienced at current ozone levels, but there is not much margin, the organisms being near their limits of tolerance. Although daily DUV doses resulting from ozone-layer reductions as large as 40 percent would not exceed the daily tolerance limits for part of reproductive/development period (and would thus leave a window of safety at the beginning of each group's surface dwelling season), this surface-tolerating season could be significantly shortened. There would be some shortening of it even at a 16 percent ozone-layer reduction. Whether or not the populations

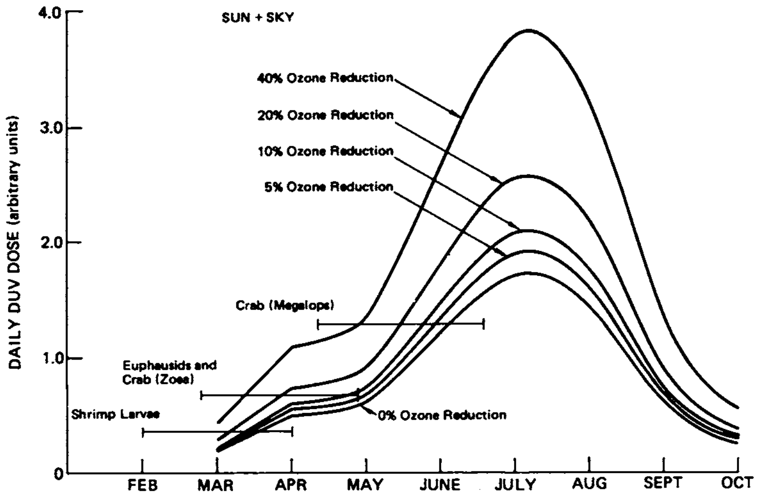


FIGURE B.1 Daily solar DUV dose at the water surface (erythermal action spectrum) in arbitrary units for various ozone thicknesses at Manchester, Washington. Horizontal bars, showing the time of year during which larvae of various species develop, are positioned vertically to indicate the tolerance daily dose.

could endure substantially reduced periods of reproduction/ development is not known. Success of any year's group of larvae (the "year-class") depends on the timing of a great number of factors besides UV-b levels (e.g., weather, food supplies, and predators). Early larvae may do well one year, but only late larvae may survive in a subsequent year. An additional stress like increased UV-B is not likely to be beneficial.

Hunter *et al.* (1979) examined the sensitivity of the eggs and larvae of the northern anchovy and the Pacific mackerel during their embryonic stages when they dwell near the water surface. Using different types of filters they established that the killing effect of UV-B was consistent with a DNA-damage action spectrum. The doses lethal to half the population (LD_{50}'s) for fish embryos irradiated at varying dose rates 7 hours per day for 4 to 5 days were 1150 J m^{-2} (joules per square meter) for anchovy and 1576 J m^{-2} for mackerel weighted for DNA damage effectiveness, as described in Appendix D. Anchovy surviving the lowest dose used (760 J m^{-2}) showed brain and eye lesions and retarded growth and development. These results are compared in Figure B.2 with the DNA-effective radiation penetrating into various natural waters in mid-June at San Diego, California (33° N latitude) (Smith and Baker, 1979). The comparisons indicate that brain and eye damage and retardation of growth should occur in anchovy larvae at the surface in about 4 days in June if the ozone layer were reduced by 25 percent. Since spawning of these creatures occurs mostly over a period (January-June) in which the solar DUV dose rate increases by a large factor, this represents a worst case.

In a subsequent study J. Hunter, J. Taylor, and H. G. Moser (National Marine Fisheries Service, La Jolla, California, unpublished BACER report) have extended their studies with anchovy past the embryonic stage and into the feeding stage. They employed a similar experimental protocol but with lower daily dose rates, expecting that the same total dose given over a longer period of time might allow some repair and thus yield a higher LD_{50}. Surprisingly, they found that exposures over 12 days at 6 h/day at various low dose rates yielded a lower LD_{50}, 675 J m^{-2} (with a DNA damage weighting function). Reference to Figure B.2 indicates that the LD_{50} level is reached at 4 m in clear ocean waters with current irradiances. If a 25 percent ozone-layer reduction were to occur, the LD_{50} level is reached at about 7.5 m. Growth inhibition, which occurs at doses greater than 530 J m^{-2} (DNA-effective) given over 12 days could be expected to occur under present-day irradiances down to 5.5 m, and down to 8.5 m with a 25 percent ozone-layer reduction. Eggs and larvae of anchovy commonly occur at these depths during this period of their development. These calculations, made for a somewhat larger ozone depletion than now envisaged, need to be repeated for the 16 percent depletion figure but give some indication of the general magnitudes of effects that might occur.

At first glance the large effects observed with doses simulating current surface levels seem incompatible with the productivity observed in nature. However, other factors, such as predators or food supply, may so limit the population that UV-B becomes less important. Also, there are reasons why these data may overestimate the UV sensitivity of the organisms tested. An obvious one is that the organisms probably spend part of their time well below the surface, where DUV is attenuated (Figure B.2). Another is that in nature photoreactivating light is available at an intensity more than an order of magnitude above usual laboratory levels, which might increase photorepair of DNA damage.

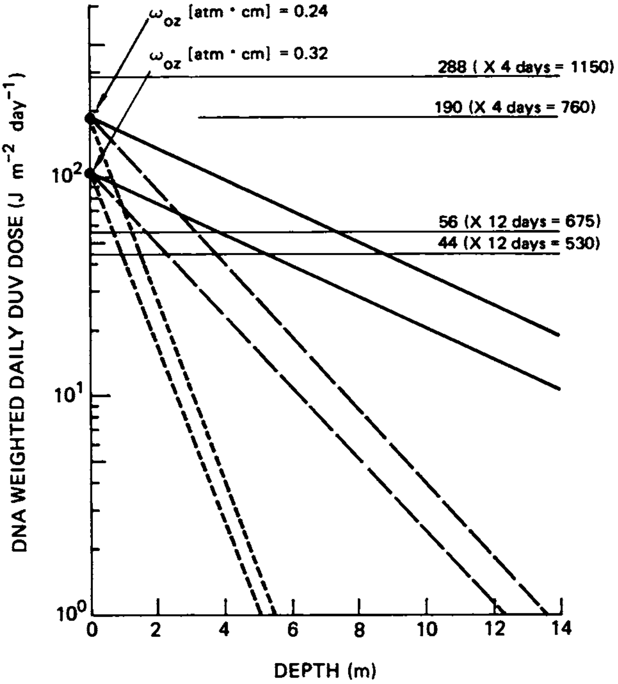


FIGURE B.2 Daily DUV dose (in mid-June at 33° N latitude DNA-damage action spectrum) as a function of water depth in three different types of ocean water. Curves show the dose-depth relation with "standard ozone" thickness (0.32 atm cm) and a 25 percent depletion of this value (0.24 atm cm) in clear open ocean waters of low productivity (i.e., chlorophyll-a content 0.025 mg m^{-3} (———); in moderately productive waters (chlorophyll-a content 0.5 mg m^{-3}) (- - -); and in the latter waters when a high concentration of dissolved organic material is also present (·····). The horizontal line at 288 J m^{-2} day^{-1} shows the daily dose killing half of an anchovy larval population in 4 days (LD_{50} = 1150 J m^{-2}). The horizontal line at 190 J m^{-2} day^{-1} shows a daily dose producing retardation and damage of these larvae in 4 days (760 J m^{-2}). The horizontal line at 56 J m^{-2} day^{-1} shows the daily dose killing half of an anchovy larval population irradiated for 12 days (LD_{50} = 675 J m^{-2}), a time extending beyond the embryonic into the feeding stage. The horizontal line at 44 J m^{-2} day^{-1} shows the daily dose producing significant growth inhibition in 12 days (530 J m^{-2}).

The actual location of organisms in the water column and the amount of penetration of UV-B into natural waters are not well known. In the case of anchovy irradiated for 12 days at current DUV irradiances, 50 percent would die if they remained at a depth of 4 m or less in clear ocean water or if they existed for the same period at 0.8 m or less in the most UV-attenuating waters studied (Figure B.2) Even though the larvae of these animals occur through the upper mixed layer, from the surface to the thermocline, the proportion of the population at various depths is not known, and the effect on the population cannot now be predicted. Moreover, although the calculated irradiances of Smith and Baker (1979) provide some indication of penetration of DUV radiation, their values are based on extrapolations of measurements in only four water types at 310 nm and above, and there have been no measurements in the more effective spectral region for DNA-damage. The biologically important estuarine and near-coast environments have also not been adequately studied. The near-coast measurements, made in moderately productive waters, with a relatively high concentration of dissolved organic material, indicate a very strong attenuation of DUV (dotted lines, Figure B.2). The extent to which this measurement is typical of the productive regions of the globe is not known. Information on the penetration of DUV into the waters where organisms actually exist is critically important to the assessment of the impact of increased DUV on seemingly very sensitive aquatic organisms.

The impacts of ozone depletion on fishery species raise a concern for supplies of human food derived from aquaculture. Half the total protein intake for over 200 million people in Southeast Asia, and additional millions in other regions, is derived from pond-grown fish and shellfish species. These organisms are reared in shallow ponds and are dependent on microscopic plankton for food supply. However, there has not been any experimental work to explore this potential problem.

The effect of more intense photoreactivating light will depend on the degree to which DNA repair is light-limited in the species in question. This is not known at present. Directly determining whether photoreactivating light as it occurs in nature strongly affects the sensitivity to DUV has been difficult. The most practical source of photoreactivating light of solar intensities is the sun itself (full-scale solar simulators being quite expensive both to construct and maintain). Yet experiments in greenhouses or in the field suffer from considerable variability in environmental parameters, particularly temperature. R. C. Worrest, Oregon State University (unpublished) was unable to verify, in a greenhouse study, results obtained in the laboratory, because of the substantial lack of reproducibility from one greenhouse experiment to another, and the question remains open.

In any event, we can say that any ozone-layer reduction will lead to an increase in DUV at all depths in the water column. Moreover, because photosynthetically active radiation (PAR) will not change appreciably with ozone reduction, the ratio of DUV to PAR will also increase at all depths in the water column, with potential consequences to phytoplankton. This would be true even if these organisms could migrate deeper to avoid the increased DUV. Thus, on the basis of current knowledge, we must accept the possibility that ozone depletion could seriously affect the aquatic biosphere.

AVOIDANCE AND ADAPTATION

Most of our quantitative discussion has tacitly assumed that the effects of a long-term depletion of stratospheric ozone on plants and animals would be determined entirely by the average increase in solar UV-B at the earth's surface, i.e., that neither compensating behavioral changes to reduce UV exposure nor adaptations to decrease sensitivity would take place. Clearly, many organisms have evolved strategies that reduce the UV exposure of their sensitive structures. One example is protective outer coverings, such as fur, feathers, or special pigments. Some desert reptiles avoid daylight altogether and are active only in the evening and nighttime hours, but those species that are active by day have melanin accumulations in their outer tissues that can prevent UV-B penetration to physiologically sensitive points (Porter, 1967; 1975). However, it is not clear how rapidly additional protective strategies might emerge.

Aquatic organisms in water of sufficient organic content could readily find a much more protected environment only a few meters deeper (cf. Figure B.2), but increased UV-B radiation may not be directly sensed by these organisms. Instead, they may (like human beings) respond to concomitant visible light or radiant heat and rely on this cue for avoidance of excessive UV exposure in normal sunlight. Since changes in the amount of ozone in the atmosphere would affect essentially only the UV-B radiation, without an accompanying change in the directly perceived cue, behavioral avoidance might be slow to evolve.

Even if such avoidance did occur, changing the time of day that an organism was active (in the case of animals), or changing its location within an ecosystem, would alter its relations with other species and might change the competitive balance of species, the susceptibility of the organism to predators or parasites, or, in the case of plants, the availability of pollinators. Since most species have evolved over millenia to their niche in an ecosystem, such changes in relationships with other species would probably not be advantageous.

Adaptation might occur as either a short-term physiological response or as a longer-term evolutionary change. An example of the former is the tanning of light-skinned humans, in which the aggregation of melanin pigments in outer layers of the skin, in response to a UV stimulus, provides an improved barrier to subsequent UV-B penetration. Such protection is limited, compared with the screening regularly available to dark-skinned races but is nevertheless significant, as increased sunburn resistance after tanning shows. There is limited evidence that some plant species similarly respond to UV radiation by increasing the amounts of certain pigments in their leaves to provide an analogous protection (Robberecht and Caldwell, 1978). The increased physical screening in plants seems to vary considerably from species to species and is also very likely limited (Van *et al.*, 1977; Robberecht and Caldwell, 1978).

Evolutionary Response to Increased UV-B Radiation

Considering that plants and animals have evolved effective and sometimes very intricate mechanisms to cope with present levels of solar UV-B radiation, the possibility exists that some species could evolve an increased resistance. Most natural species of plants and animals carry a certain genetic variability, which provides the background on which natural selection can act in the face of a new stress to evolve a better adapted species. If all circumstances are conducive, a rather rapid evolution of resistance can take place, as in the case of the 250 species of insects and crop pests that have evolved increased tolerance to widely used insecticides--sometimes in periods of a few years (Brown, 1960). Some plants have evolved tolerances toward heavy metals, such as lead in mine tailings (Antonovics, 1975). On the other hand, many species have failed to evolve resistance to new environmental perturbations--

especially where these occurred rapidly--as exemplified by continued sensitivity of falcons and ospreys to DDT. For some organisms, the 35 years in which half the ozone reduction may take place would only span a few generations and is too short for such a mechanism to respond.

The time available for change is a crucial factor (Antonovics, 1975), and in general, a higher probability of evolving resistance is expected for species that are very short-lived, have very large population numbers, and naturally engage in crossbreeding. These characteristics account for the success of insects in increasing their resistance to insecticides, compared with the failure of comparatively long-lived predatory bird species to do this. However, no assured statements can be made beyond these general expressions of probability.

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APPENDIX C SOLAR-ULTRAVIOLET IRRADIANCE AT THE EARTH'S SURFACE

The flux of solar-ultraviolet (UV) radiation reaching the earth's surface on a cloudless day depends on the attenuating components of the atmosphere (variable amounts of stratospheric ozone, of other air molecules, and of aerosol particulates), as well as on the path length of the sunlight in passing through them. The latter parameter varies with the solar zenith angle, which changes with latitude, season, and times of day.

Stratospheric ozone attenuates UV radiation by direct absorption. The amount of this absorption is determined by a wavelength-dependent absorption coefficient, which increases sharply as the wavelength decreases from 350 nm down to 260 nm. Consequently, atmospheric transmission, and the resultant solar-UV irradiance, falls abruptly at shorter wavelengths, as shown in Figure C.1.

At any wavelength, the actual amount of absorption depends, of course, on the total amount of ozone present. The amount in a vertical column over the observer's head is usually expressed in terms of the thickness it would have if isolated and compressed to standard atmospheric pressure (760 nm of mercury) at 0°C. This quantity averages about 0.32 atm · cm for middle latitudes but varies greatly, as indicated below. The increased solar irradiance accompanying a series of reductions in ozone amount below this "standard" level are also shown in Figure C.1. As can be seen, the relative change in transmission is greater at the shorter wavelengths, where the absorption coefficient is greater. However, for sufficiently short wavelengths (say, below 280 nm), the absorption is so effective that even a 50 percent reduction would leave the atmosphere effectively opaque. Any increase in the slant path length of sunlight through the ozone, as the sun moves lower in the sky, increases absorption in the same way as a proportionate increase in the ozone amount.

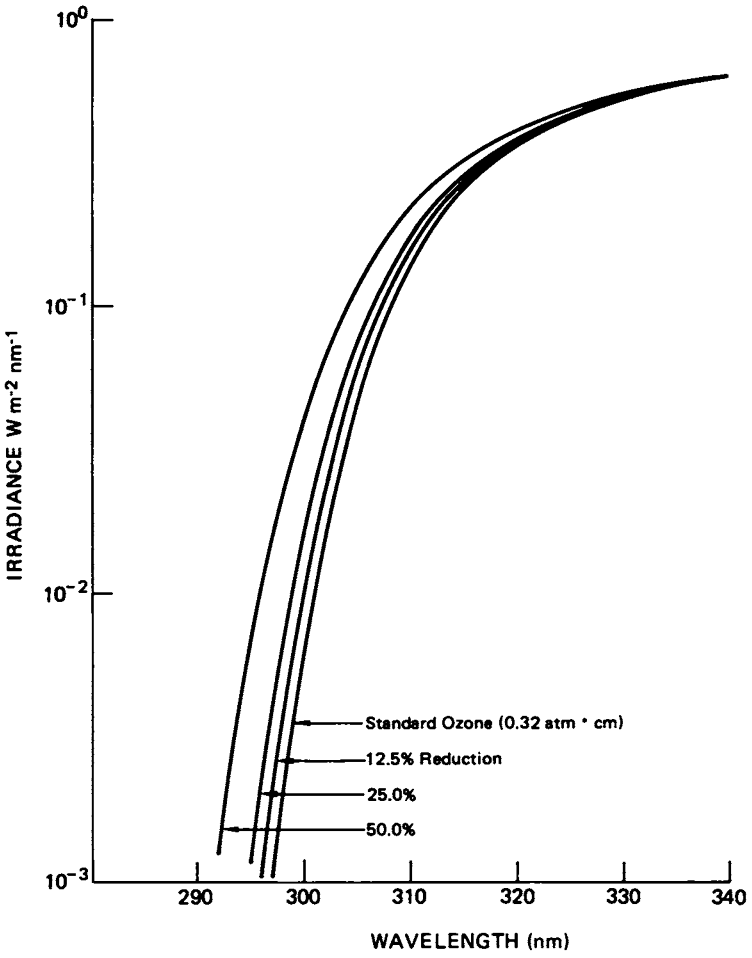

FIGURE C.1 Solar spectral irradiance (on a logarithmic scale) with the sun 30° from the zenith, shown for 0.32 atm • cm of ozone (standard ozone) and 12.5, 25, and 50 percent reductions from this standard.

The attenuation of UV radiation by other air molecules and by aerosol particles results from a wavelength-dependent scattering of sunlight. This process complicates the quantitative details of atmospheric transmission but does not qualitatively change the main features of solar-UV attenuation that we have described.

The natural amount of stratospheric ozone varies substantially with time, as illustrated by Figure C.2, showing the amount measured above Tallahassee, Florida, over a two-year period. Day-by-day variations, as well as seasonal changes from the long-term average, are evident. The amount above one location can change not only within a day (up to 10 percent if a weather front passes) and seasonally (25 percent between spring and fall) but also yearly (5 percent in the course of a decade). Thus the ozone concentration as a function of time constitutes an irregular curve of peaks and valleys. If all else remains equal, a reduction in the average ozone amount will lead to a lowering of the entire curve, making both the average and the valleys lower. The long-term concentration also varies geographically; for example, between Minnesota and Texas it can differ by as much as 30 percent.

The large number of uncontrollable variables determining solar UV-B irradiance makes it impossible to measure this irradiance under all conditions of interest. On the other hand, accurate calculation of the transmission of radiation

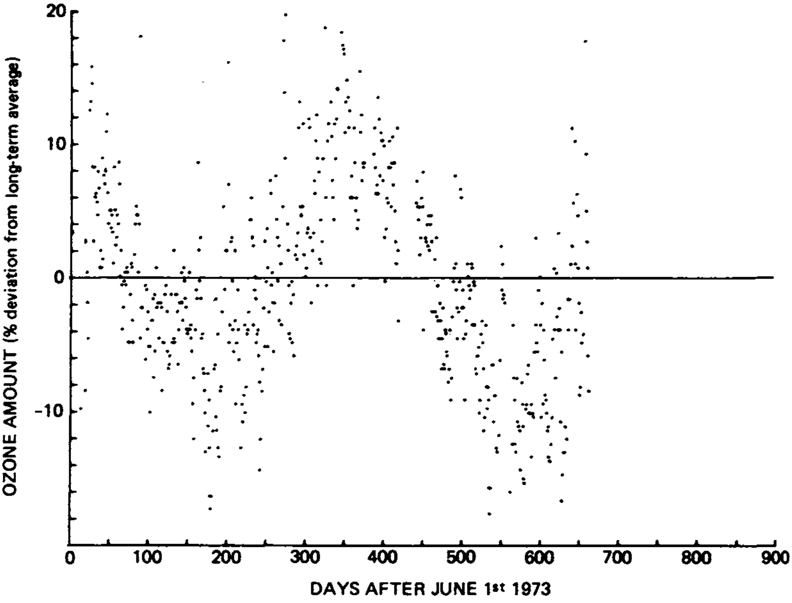

FIGURE C.2 Examples of ozone-layer variability: Daily Dobson meter measurements of ozone amounts above Tallahassee, Florida (30.4° N lat), expressed as percentage deviation from the long-term mean (0.305 atm · cm).

through the atmosphere, taking into account the scattering as well as absorption, is an expensive and time-consuming operation. A. E. S. Green and co-workers at the University of Florida have constructed empirical equations with adjustable parameters, which can be fitted to experimental data or to the results of relatively few detailed, radiative transfer calculations. These can be used to interpolate to any case of interest. Several successively improved attempts at such a procedure have been made by the same group. The most recent version (Green *et al.*, 1979), which is used in this report, eliminates essentially all of those uncertainties about effects of ozone depletion arising from uncertainties in the solar irradiance.

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APPENDIX D THE BIOLOGICALLY EFFECTIVE ULTRAVIOLET RADIATION

The relative effectiveness of different wavelengths (the action spectrum) for most biological ultraviolet (UV) effects increases with decreasing wavelength. For illustrative purposes, Figure D.1 shows a generalized action spectrum of this type, superimposed on the solar spectral irradiances calculated for two ozone thicknesses: the "standard ozone (0.32 atm · cm, indicated as "0 percent reduction") and a large (50 percent) reduction from this level. At any given wavelength λ, the product of the action spectrum (or weighting function) ordinate $E(\lambda)$and the solar irradiance ordinate $I(\lambda)$ gives a value that reflects the number of photons within a small spectral region $d\lambda$, weighted by their biological effectiveness. This product is shown as a function of wavelength for the two illustrative ozone concentrations, and these same curves are replotted with a linear ordinate in Figure D.2. The biologically effective solar irradiance is the sum of the contributions by each small wavelength range: $\int E(\lambda)I(\lambda)d\lambda =$ DUV dose rate. This is, of course, simply the area under each product curve as it is plotted in Figure D.2.

The numerical value of this DUV dose rate depends, of course, on the "normalization wavelength" at which the weighting function $E(\lambda)$ (i.e., the effectiveness of the radiation) has been defined as equal to 1.0. There is no generally agreed on convention for making the choice, which may be made different in different published action spectra (see Figure D.3). DUV dose rates for which the weighting functions happen to have been normalized at different wavelengths are not directly comparable, but the numerical factors by which the dose rates change with a given ozone depletion can be compared.

The biologically effective dose (DUV dose) is the dose rate times the exposure time. (Note that different authors

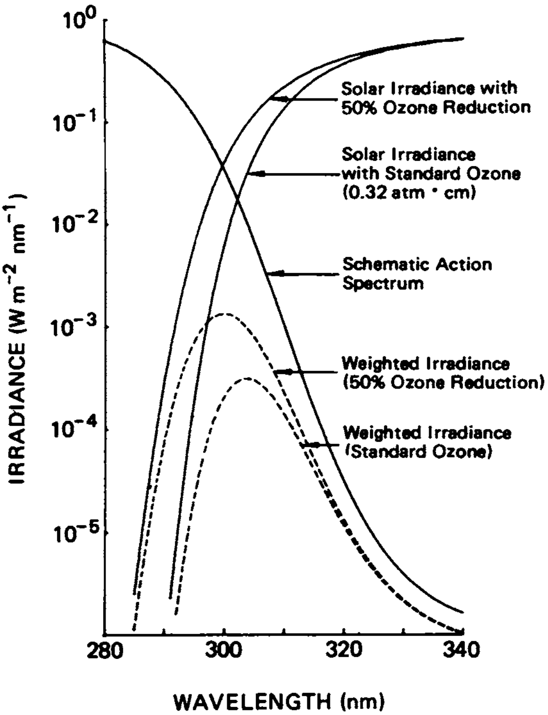

FIGURE D.1 Solar irradiance with standard ozone thickness (0.32 atm · cm), and with a 50 percent ozone reduction, superimposed on a typical biological action spectrum (weighting function). The biologically effective irradiances, represented by the product of the irradiance and weighting function ordinates, are plotted as dotted curves.

use different terms for the biologically effective UV, designated here as DUV). Analogous calculations give the DUV dose rate from any UV source, using the $I(\lambda)$ corresponding to the source in question.

The DUV dose rate changes with the changes in ozone absorption, which are described in Appendix B, and the total DUV dose is accumulated from this continually changing dose rate over the total time of the organism's exposure. The effect of the dose rate itself in determining the impact of a given DUV dose is not known for most of the UV effects of interest here, but may be significant.

Different investigators have used different weighting functions $E(\lambda)$ for calculating the DUV dose. Figure D.3

shows plots of several that have been employed in assessing the biological impact of ozone depletion. Some of these are based on experimentally determined action spectra, while others are contrived "average action spectra." Which one is the most appropriate cannot be readily determined at this time, since for most biological effects studied, the action spectrum is not known.

The research on UV-B biological effects supported by the Climatic Impact Assessment Program (CIAP) of the U.S. Department of Transportation was influenced by the emphasis on human skin cancer, which justified the use of a human erythemal (sunburn) action spectrum for the weighting function (Figure D.3, Curve A). CIAP Monograph 5, Part 1, (Benger, 1975) which reported the CIAP research, included extensive tables of erythemal doses as a function of

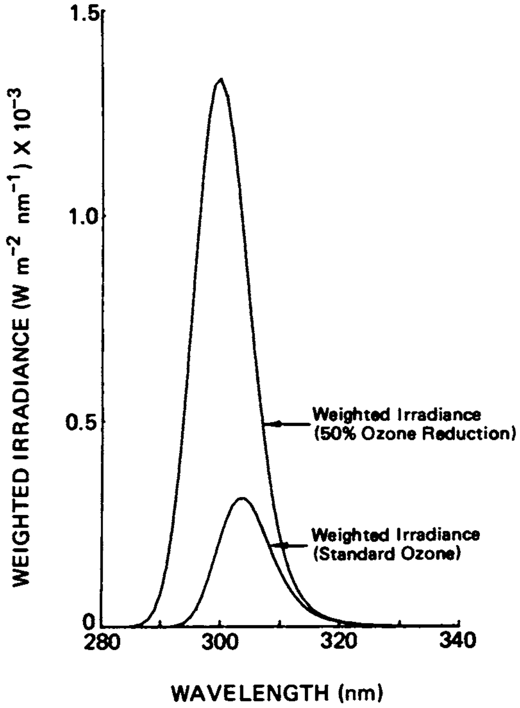

FIGURE D.2 The biologically effective irradiance curves shown dotted in Figure D1, replotted on linear ordinate scales.

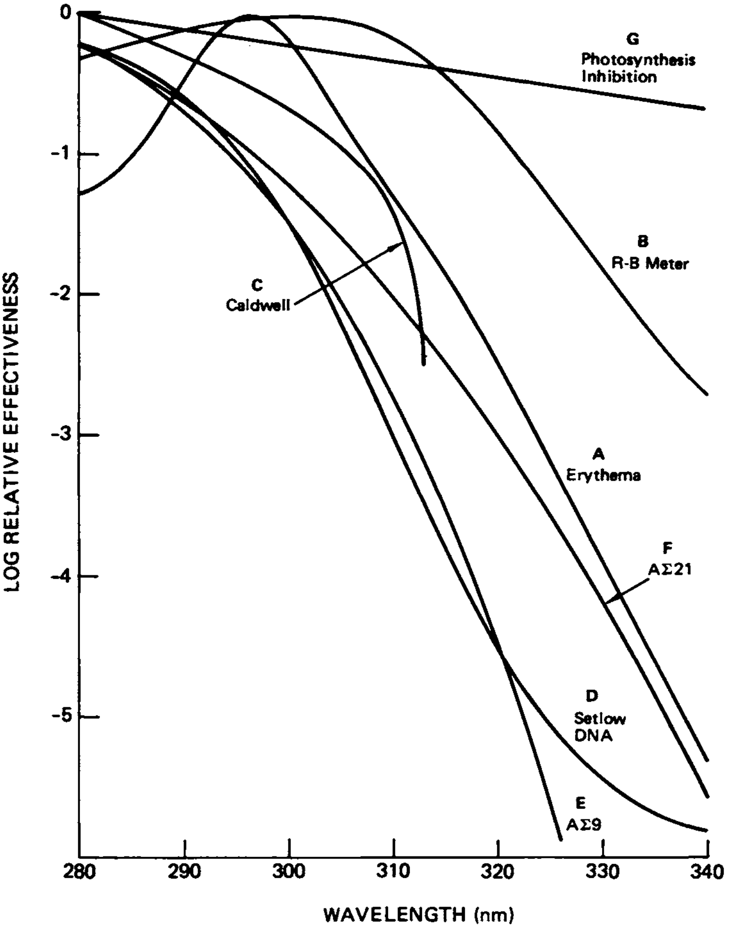

FIGURE D.3 Weighting functions in current use for biological UV effects.

latitude, season, and other factors. These tables became the starting point for various investigations into biological effects other than human skin response. It was believed that, although human sunburn is not itself relevant to effects in other organisms, use of an erythemal weighting function yielded a reasonable, relative DUV radiation measurement for a typical biological effect. This use was reinforced by the availability of the fairly inexpensive

Robertson-Berger Sunburning Ultraviolet Meter, which was reputed at that time to have a response spectrum (Figure D.3, Curve B) sufficiently similar to the erythemal action spectrum to serve as a practical dosimeter. However, as is clear from the figure, the response spectrum of this meter is really somewhat different from the erythemal action spectrum.

Caldwell (1971) developed a generalized plant action spectrum from a number of action spectrum studies with plant material (Figure D.3, Curve C). Setlow (1974) combined the results of action spectrum studies with bacteria and viruses (where injury to DNA is known to be responsible for the effects) to give a generalized DNA-damage action spectrum (Figure D.3, Curve D). In unpublished studies conducted for the EPA-BACER (Biological and Climatic Effects Research) Program, investigators at the USDA Agricultural Research Center, Beltsville, Maryland, employed a simplified weighting function, termed $A\Sigma 9$ (Curve E), which approximates the Setlow DNA-damage action spectrum. Investigators at the University of Florida (R. H. Biggs and S. V. Kossuth, unpublished BACER report) employed an average weighting function, termed $A\Sigma 21$ (Curve F), that falls between the DNA-damage action spectrum and the Caldwell action spectrum in the short-wavelength portion of the UV-B region. Figure D.3 also shows a weighting function (Curve G) for inhibition of part of the photosynthetic process occurring in isolated chloroplasts (Jones and Kok, 1966). This study is the only one known that has critically examined the spectral influence of UV (and visible) radiation on the photosynthetic reaction, independent of influences on cell growth and metabolism. Recent studies by R. C. Smith, K. S. Baker, O. Holm-Hansen, and R. Olson (Scripps Institution of Oceanography, unpublished) have shown that photosynthesis by phytoplankton exposed to solar radiation through various filters is inhibited in a manner consistent with the Jones and Kok action spectrum.

To understand the effect of the weighting-function choice on the calculated DUV dose one may note in Figure D.1 that a given ozone-layer depletion increases the UV-B irradiance by different amounts at different wavelengths. The increase at a short wavelength (like 290 nm), where $I(\lambda)$ is low may be over an order of magnitude more than that at a longer wavelength (like 320 nm), where $I(\lambda)$ is larger. Because of this fact the effect of decreased ozone thickness on the DUV dose rate depends very much on the relative values of $E(\lambda)$ at these longer and shorter wavelengths. For a given ozone change, the calculated change in DUV dose rate will be generally greater with weighting functions that increase more toward the short wavelengths than those that increase less.

Different weighting functions shown in Figure D.3 give very different predictions of the effects of ozone depletion. For example, about 50 percent of the inhibitory effect of UV on the photosynthesis reaction results from radiation greater than 390 nm, and 25 percent from radiation between 340 and 390 nm (Curve G). Thus, 75 percent of the photosynthetic inhibition by solar radiation results from wavelengths that would not change with ozone-layer reduction. Consequently, if this weighting function is applicable to intact plants, a moderate ozone depletion would not be likely to have a serious impact on photosynthesis over that already being experienced. This contrasts greatly with the predictions using an erythemal or a DNA-damage weighting function (Curve A or D), which would predict a much larger effect.

The Robertson-Berger (R-B) meter reading also changes less with a given change in ozone amount than does the DUV dose rate calculated with an erythemal or DNA-damage weighting function. One consequence of this fact is that an R-B meter reading is less sensitive to the latitudinal change of UV-B than is the DUV dose rate calculated with a DNA damage action spectrum. Such a difference in the estimated latitudinal gradient is important because some epidemiological studies correlating human nonmelanoma skin-cancer incidence with DUV have used R-B meter readings at different cities to indicate the local UV environment. From such correlations, projections of increased skin cancer for particular ozone-layer depletions have been made. However, if the DNA-damage weighting function is more appropriate for skin cancer than the R-B meter response, and there is preliminary evidence that this is so for skin-cancer induction in hairless mice (P. D. Forbes, F. Urbach, and R. E. Davies, Temple University Skin and Cancer Hospital; R. D. Rundle and D. S. Nachtwey, NASA Johnson Space Center, unpublished), the latitudinal DUV dose gradient is actually much steeper than the value measured. This would change the estimated increase in skin-cancer incidence accompanying a given ozone-layer depletion.

As shown in Figure D.4, a rather different latitude dependence of solar-DUV dose rates is calculated with different action spectra, using the average values of ozone-layer thickness appropriate for the season (the summer solstice) and latitude. (To facilitate comparison, all these curves are normalized to 30° N latitude, corresponding

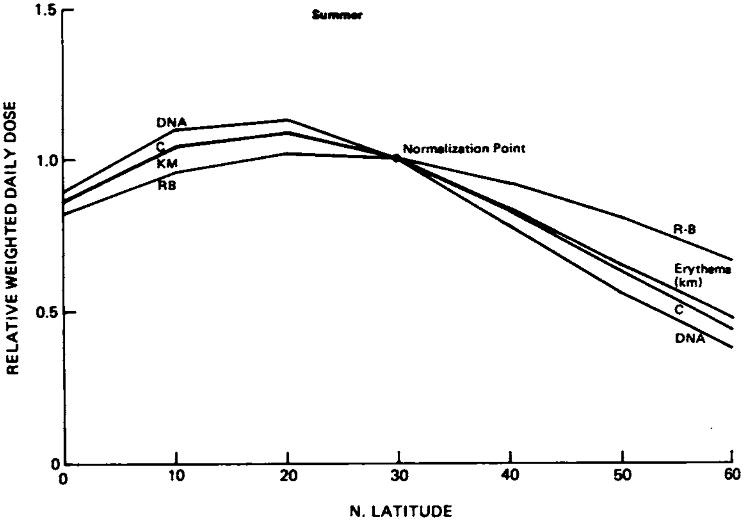

FIGURE D.4 Relative daily doses at different northern latitudes at the summer solstice, calculated with different weighting functions. Values have been normalized to the daily dose at 30° N latitude.

to the most southerly parts of continental United States.) This fact constrains some convenient ways of communicating experimental information. Investigators have often chosen the DUV dose delivered by sunlight during a typical experimental day (at the season and latitude of the experiment) as a unit for expressing supplementary UV doses delivered by lamps. However, if this is done at one latitude, the result will not hold at other latitudes unless the correct weighting function is employed.

The change in the relative daily DUV dose produced by a change in the ozone-layer thickness [(Δ% daily DUV dose)/(-Δ% ozone layer thickness) = Radiation Amplification Factor (RAF)] is a complex function of initial ozone-layer thickness, percentage ozone-layer reduction, latitude, season, and weighting function. Table D.1 shows latitudinal and seasonal RAF values for 1 percent ozone-layer reductions from initial ozone thicknesses appropriate for the latitude and season. Table D.2 summarizes the range and the percentage spread of these RAF (1 percent) values in moving between 0° and 60° N latitude. The statement sometimes heard that "a 1 percent ozone-layer reduction leads to a 2 percent increase in DUV" is obviously only a very rough rule-of-thumb;

the variation of RAF from the "folklore" value of 2 can be noted for each of the weighting functions used. The higher RAF values in Table D.1 occur at higher latitudes, where the current DUV doses are lower, and the current and potentially increased biospheric impacts from DUV radiation (both now and with future ozone depletion) are presumably less. On the other hand, near the equator, where the greatest current DUV irradiation occurs, the RAF values are lower, and the DUV doses will show smaller percentage increases for a given percentage ozone-layer reduction, even though the increase in absolute DUV dose will still be high.

The change in DUV dose per day accompanying a change in ozone-layer thickness greater than 1 percent is shown in Figure D.5 for one fixed latitude and season and several different weighting functions. The daily DUV dose for 30° N latitude at the summer solstice has been set equal to unity to facilitate comparison. The predictions obviously diverge nonlinearly with increasing ozone depletion. High-percentage ozone-layer reductions yield much higher percentage increases in DUV than expected from the RAF calculated for a 1 percent ozone-layer reduction [RAF (1%)] using any particular weighting function. For example, with the DNA-damaging weighting function, a 16 percent ozone-layer reduction leads to about a 46.5 percent increase in DUV; i.e., the RAF (16 percent) is 2.91, in contrast to the RAF (1 percent) of 2.27.

The complex relationships between RAF and latitude, season, percentage ozone-layer reduction, and weighting function create considerable uncertainty in any simple statement about the DUV dose change expected for any particular ozone depletion. This uncertainty is compounded with the uncertainty in the relationship of the biological response to the DUV dose in assessing the ultimate biospheric impact.

In addition to the remarks about action spectra in Part II, Chapter 2, of this report, the following points may be noted:

1. Action spectra have usually not been determined to ascertain a weighting function for polychromatic radiation but rather to clarify the nature of the molecule involved in a photobiological effect. Emphasis has therefore been on the shape and position of peaks and high valleys for comparison with known absorption spectra, with little attention to the "tail" that falls off toward longer wavelengths. Since such a tail contributed significantly to

TABLE D.1 RAF (1%) Values

Latitude/ Season	Setlow DNA	Caldwell	R-B Meter	Erythema	AΣ21	AΣ9
0° Spr	2.21	1.61	0.73	1.61	1.28	1.93
Sum	2.23	1.66	0.75	1.63	1.28	1.95
F	2.18	1.56	0.71	1.58	1.26	1.90
W	2.21	1.61	0.73	1.60	1.27	1.92
Annual	2.21	1.61	0.73	1.60	1.27	1.92
10 Spr	2.23	1.65	0.75	1.63	1.29	1.95
Sum	2.23	1.63	0.74	1.62	1.28	1.94
F	2.21	1.60	0.73	1.60	1.27	1.92
W	2.25	1.69	0.76	1.64	1.28	1.97
Annual	2.23	1.63	0.74	1.62	1.28	1.94
20 Sp	2.28	1.74	0.78	1.67	1.31	2.00
Su	2.24	1.65	0.75	1.63	1.29	1.95
F	2.24	1.66	0.75	1.63	1.28	1.95
W	2.30	1.85	0.80	1.69	1.31	2.03
Annual	2.25	1.70	0.76	1.65	1.29	1.97
30 Sp	2.33	1.89	0.83	1.72	1.34	2.07
Su	2.27	1.72	0.77	1.66	1.30	1.99
F	2.27	1.75	0.78	1.68	1.30	2.00
W	2.33	2.11	0.87	1.72	1.34	2.12
Annual	2.29	1.79	0.80	1.68	1.31	2.02

40 Sp	2.39	2.14	0.90	1.76	1.38	2.17
Su	2.31	1.81	0.81	1.70	1.33	2.04
F	2.32	1.88	0.82	1.70	1.32	2.05
W	2.26	2.50	0.94	1.70	1.36	2.21
Annual	2.32	1.90	0.84	1.71	1.34	2.07
50 Sp	2.38	2.48	0.97	1.78	1.42	2.28
Su	2.35	1.93	0.84	1.73	1.35	2.09
F	2.35	2.10	0.87	1.73	1.35	2.13
W	1.94	2.76	0.98	1.61	1.32	2.17
Annual	2.35	2.04	0.88	1.74	1.36	2.12
60 Sp	2.28	2.84	1.03	1.76	1.43	2.35
Su	2.38	2.08	0.88	1.75	1.37	2.15
F	2.30	2.36	0.92	1.71	1.36	2.19
W	1.44	2.09	0.89	1.37	1.13	1.82
Annual	2.36	2.17	0.91	1.75	1.37	2.17

TABLE D.2 Ranges and Percentage Spread of RAF (1%) Values in the Latitudinal Range 0-60° N Latitude

	Setlow DNA Damage	Caldwell	R-B Meter	Erythema	AΣ21	AΣ9
Total range	1.44-2.39	1.56-2.84	0.71-1.03	1.37-1.78	1.13-1.43	1.82-2.35
% Spread[a]	66	82	45	30	26	29
Spring range	2.21-2.39	1.61-2.84	0.73-1.03	1.61-1.78	1.28-1.43	1.93-2.35
% Spread	8	76	41	11	12	22
Summer range	2.23-2.38	1.63-2.08	0.74- .88	1.62-1.75	1.28-1.37	1.94-2.15
% Spread	8	28	19	8	7	11
Fall range	2.18-2.35	1.56-2.36	0.71- .92	1.58-1.73	1.26-1.36	1.90-2.19
% Spread	8	51	30	9	8	15
Winter range	1.44-2.33	1.61-2.76	0.73- .98	1.37-1.72	1.13-1.36	1.82-2.21
% Spread	62	71	34	25	20	21
Fall range	2.18-2.39	1.61-2.36	0.71-1.03	1.61-1.78	1.26-1.43	1.90-2.35
% Spread	10	47	45	11	13	24

[a] $\frac{\text{MAX - MIN}}{\text{MIN}} \times 100.$

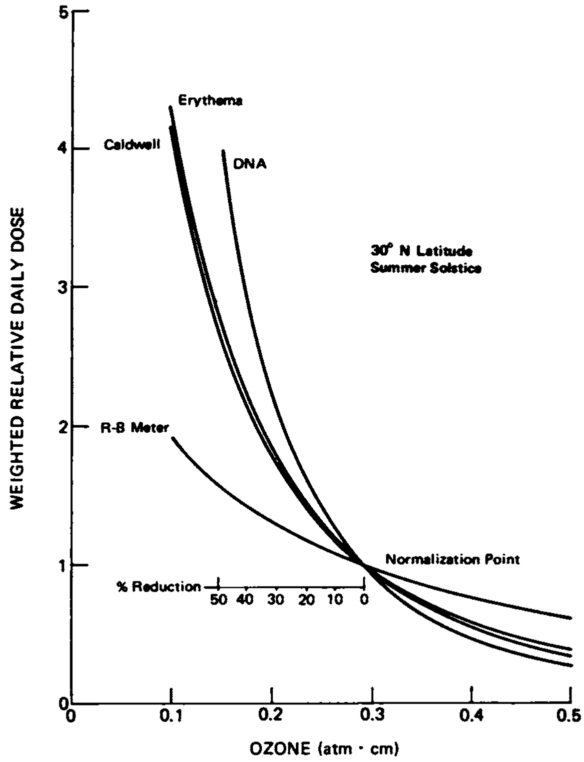

FIGURE D.5 Relative daily DUV doses calculated with different weighting functions as a function of ozone-layer thickness. Values have been normalized to the doses at 30° N latitude on the summer solstice, with an ozone-layer thickness of 0.292 atm · cm. Percentage reductions from this value are also indicated on the inset scale.

the solar-DUV dose, because of the very high irradiance at longer wavelengths, action spectra must extend far enough if they are to serve dosimetric needs. (Setlow, 1974, is a notable exception, in following UV action on DNA down about six orders of magnitude from its peak effectiveness.)

2. Even when a DNA-action spectrum is plausibly correct as a basis for a weighting function, some modification from the Setlow form may occur, either from filtering by overlying structures and pigments or some other factor. For example, Rothman and Setlow (1979) found that the action spectra for killing of V-79 Chinese hamster cells and induction of

pyrimidine dimers (the most common UV-induced damage in DNA) had a shape similar to, but not identical with, that for bacterial and viral inactivation. The mammalian cells were about twice as sensitive to radiation at wavelengths greater than 290 nm relative to the peak sensitivity at 265 nm than were the bacteria and viruses.

3. There are examples of sensitizing molecules of unknown structure, normally present in the cell, which absorb more at longer wavelengths than do DNA molecules and apparently lead to photooxidation of DNA, mutation, and death of bacterial cells (Webb, 1977). The numbers and types of such sensitizing molecules could be different in different cell types, yielding different action spectra.

4. Action spectrum studies usually employ monochromatic radiation and would not detect synergistic effects of different wavelength regions, such as are present in the radiation from a polychromatic source like the sun or fluorescent sun lamps. There is some evidence for such effects. For example, Rothman and Setlow (1979) with monochromatic radiation found an excellent correlation between pyrimidine dimer formation in DNA and cell killing as a function of wavelength and concluded that dimer formation is the most important type of damage in cell killing over a broad range of UV wavelengths. On the other hand, Elkind *et al.* (1978), in a comparative study of the killing of three mammalian cell types with monochromatic 254-nm UV and polychromatic UV from unfiltered fluorescent sunlamps (FS20), found distinct differences in the shapes of the survival curves, indicating at least partially different modes of killing by the two types of radiation. From their analysis they conclude that if the pyrimidine dimer is the principal lethal lesion following 254-nm UV irradiation, it is not the only, or perhaps even the principal, lesion following sunlight-like radiation.

It is possible that the sunlamp UV produces additional photochemical damage that interferes with repair of nearby pyrimidine dimers. Alternatively, broadband sunlamp UV (and, by extension, solar UV) may inhibit enzymatic repair systems, in addition to producing DNA damage. Tyrrell and Webb (1973) and Tyrrell *et al.* (1973) have demonstrated that very high, but nonlethal, doses of 365-nm UV radiation to bacteria can inhibit repair of 254-nm UV-induced pyrimidine dimers in DNA. The action spectrum for this effect has not been determined. Although the effective doses of 365-nm UV are in the range of megajoules per square meter, this amount of UV-A radiation is the same order of magnitude as found in nature. (The daily dose of UV-A radiation between 320 and 380 nm in summer is 1 - 2 MJ m^{-2} day^{-1} at all latitudes up to 60°). Moreover, Nachtwey (1975) has demonstrated that irradiation of an alga (*Chlamydomonas reinhardi*) with UV-B and UV-A from fluorescent sunlamps with nonlethal doses comparable with those in sunlight can inhibit the photoreactivation repair process.

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APPENDIX E UNCERTAINTIES IN SOLAR SIMULATION

In addition to the problems associated with estimating the biologically effective UV dose (the DUV), as outlined in Appendix D, related uncertainties arise from the difficulties in simulating solar irradiances adequately. These are of several kinds.

Fluorescent sunlamps (filtered to remove the shortest wavelengths) are widely used to augment solar-UV-B exposure of organisms. The spectral qualities of this source do not closely match the solar irradiance for any combination of solar zenith angle and ozone level. Figure E.1 shows the spectral irradiance from six fluorescent sunlamps filtered with cellulose acetate, superimposed on the solar irradiances expected when the sun is 30° from zenith, and the ozone-layer thickness ranges from 0.1 to 0.5 atm · cm. As can be seen, there is too little irradiance above 300 nm and too much below this wavelength for all ozone thicknesses greater than about 0.1 atm · cm (which would represent an extreme depletion). To relate the additional daily dose from the sunlamps to that expected from the sun under the relevant ozone-layer thickness, the DUV doses must be determined, using the proper weighting function. As discussed in Appendix D, the validity of extrapolating from sunlamp-DUV responses to the expected solar-DUV responses is strongly dependent on the validity of the weighting function used.

An example of the problems this creates can be provided using the data of R. H. Biggs and S. V. Kossuth (University of Florida, unpublished BACER report). These workers found that the total yield of advanced mature Walter tomatoes from field-grown plants, under natural solar radiation supplemented with radiation from cellulose-acetate-filtered fluorescent sunlamps, declined in a linear manner with increasing added UV-B irradiance. In Table E.1 their data

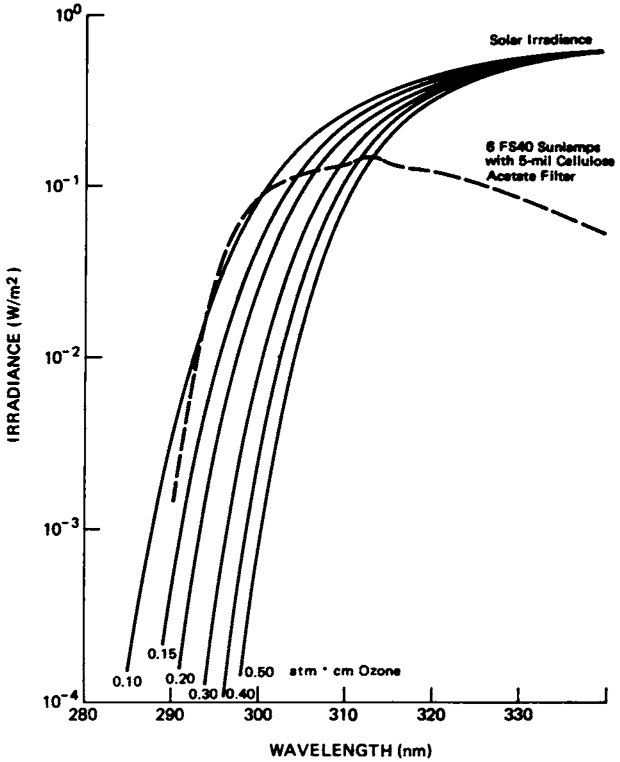

FIGURE E.1 Spectral irradiance at a distance of 16.5 cm from six FS40 sunlamps, filtered with 5-mil cellulose acetate, superimposed on the solar spectral irradiance (sun 30° from zenith) with different ozone thicknesses.

are reanalyzed, using three different weighting functions (DNA-damage, $A\Sigma 21$, and Caldwell), to obtain the percentage reductions in yield as a function of the added daily DUV doses.

The experimentally determined percentage reduction per unit DUV dose is given in Column 2. To determine the reduction in yield that might result from, say, a 15 percent ozone depletion, one must multiply these figures by the increase in the appropriately weighted daily DUV dose in joules per square meter per day ($J \cdot m^{-2}$ day^{-1}), which would accompany this ozone reduction. Column 3 shows the current daily DUV dose rates in $J \cdot m^{-2}$ day^{-1}, obtained with the three weighting functions for the summer solstice

TABLE E.1 Comparison of Percentage Reductions in Tomato Yield for a 15% Ozone Reduction Using Three Weighting Functions

(1) Weighting Function	(2) % Yield Reduction per Unit DUV Dose Rate (J m^{-2} day^{-1})[a]	(3) Calculated Current DUV Dose Rate (J m^{-2} day^{-1})[b]	(4) % Increase in DUV for 15% O_3 Depletion	(5) Increased DUV Dose Rate with 15% O_3 Depletion (J m^{-2} day^{-1})	(6) % Yield Reduction for 15% O_3 Depletion
DNA damage	0.33 (1.00)[c]	141 (1.00)	40 (1.00)	56.5 (1.00)	19.0 (1.00)
AΣ21	0.16 (0.48)	791 (5.61)	23 (0.58)	181.5 (3.21)	29.0 (1.56)
Caldwell	0.05 (0.15)	2099 (14.9)	30 (0.75)	637 (11.3)	32.0 (1.72)

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[a] The ratio of the slope/intercept × 100 taken from the linear regression of experimentally determined yield of Walter tomato (advanced mature) in grams versus added daily dose of DUV determined by weighting the output of filtered fluorescent sunlamps with the weighting functions listed in Column (1). Data of R. H. Biggs and S. V. Kossuth, University of Florida (unpublished EPA-BACER report).

[b] For summer solstice, 30° N latitude, $O_3 = 0.292$, GCS model.

[c] The numbers in parentheses are the ratios of the values in every column to the value for DNA damage.

at the approximate latitude (30° N) of Gainesville, Florida, where the experiments were performed.* Column 4 shows the percentage increase in this dose rate, with a 15 percent ozone reduction. Column 5 shows the corresponding increase in weighted daily DUV dose rate in $J \cdot m^{-2} \cdot day^{-1}$ (the product of the values in Columns 3 and 4), and Column 6, the percentage reduction in yield for a 15 percent ozone-layer reduction (the product of Columns 5 and 2).

It may be noted (Column 4) that the percentage increase in DUV is lower with the Caldwell weighting function than with the DNA-damage function, and still lower with the $A\Sigma21$ function. However, the yield reductions expected with 15 percent ozone depletion (Column 6) are *higher* with the $A\Sigma21$ and Caldwell weighting functions than with the DNA-damage function. This seemingly paradoxical situation arises because weighting functions like $A\Sigma21$ and Caldwell, which give more emphasis to the longer UV-B wavelengths, make the DUV dose rates for sunlamp radiation considerably lower, relative to sunlight, than those calculated with a DNA-damage weighting function. Consequently, in order to simulate a certain increase in solar-DUV dose rate on the basis of these weighting functions, more actual sunlamp exposure is required than if the DNA-damage function were employed. Hence the larger biological effect. Use of the photosynthesis inhibition weighting function (Curve G of Figure D.3, Appendix D), instead of the Caldwell curve, would make even a larger difference. The question is, of course, which of these Column 6 numbers is correct (i.e., what weighting function should be used)?

An analogous problem arises when a dosimeter, such as the Robertson-Berger meter, is used to compare sunlight with UV from sunlamps in an experimental setup. If the DUV dose rate from sunlight (say, at noontime on the summer solstice, at 30° N latitude, with 0.29 atm · cm of ozone overhead) were the same as that from a particular set of filtered sunlamps, according to the R-B meter reading, it would then be about sixfold less than the lamp dose rate if recalculated on the basis of a DNA-damage weighting function. That is, the sunlamp radiation would actually contain six times the DNA-damaging UV of sunlight

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*Note that, for the reasons explained at the beginning of Appendix D, the raw DUV doses for different action spectra in Column 3 cannot be directly compared (although the final numbers in Column 6 can be).

when adjusted to make the two give the same R-B meter reading. This creates a large uncertainty in how experiments should be set up and interpreted, which cannot be eliminated until the correct weighting functions are known.

The instantaneous DUV dose rate may be an important parameter in determining the biological effect, since high rates of UV damage may overwhelm repair processes. Nachtwey (1975) has demonstrated a strong dependence on dose rate of the effectiveness of filtered sunlamp radiation for killing the alga *Chlamydomonas reinhardi* (Figure E.2). These experiments employed a range of R-B meter readings (expressed in "Sunburn Units," or SU) corresponding to sunlight with present to moderately depleted ozone levels. However, if the DNA-damage weighting function (rather than the R-B meter response spectrum) is actually the appropriate one for killing of this organism, almost all of the dose rates studied were greatly in excess of those given by the sun, even with extreme ozone-layer reductions. Only the points around 1 SU · h^{-1} are close to current noontime

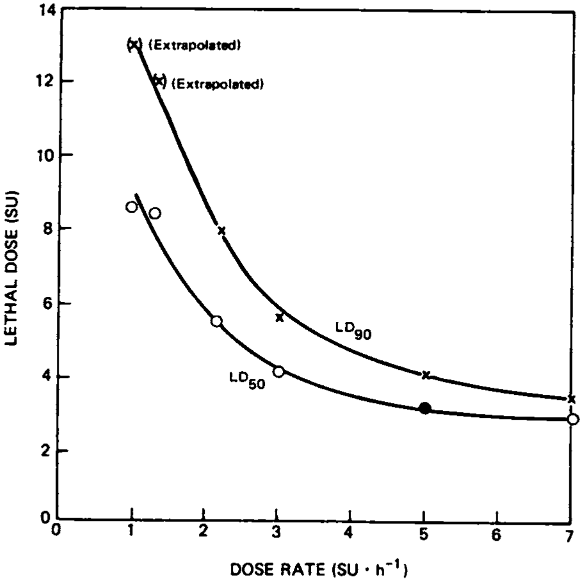

FIGURE E.2 Lethal doses for 50 percent killing (LD_{50}) and 90 percent killing (LD_{90}) of *Chlamydomonas reinhardi* exposed to filtered fluorescent sunlamp radiation at different dose rates. Doses and dose rates are given in terms of R-B meter readings ("Sunburn Units," or SU).

irradiances on a DNA-damaging dose-rate basis, and at this rate the time required for 90 percent kill amounts to a full daylight period at noontime dose rates--i.e., it exceeds the daily dose naturally available. Since irradiation protracted over a period of days might well give a different dose response because of the better opportunity afforded for repair, reports of biological effects resulting from a few SU delivered by fluorescent sunlamps must be reevaluated with better information about the weighting function. The conclusion that the organisms can be killed by a few hours of summer sunlight under current irradiances may or may not be valid.

An additional complication in experimental studies is that, in most situations, the sunlamps are turned on for from 4-6 h to obtain a given daily dose comparable with that from the sun. This is obviously unnatural and subjects the organisms to much higher intensities than the sun delivers at some times of day (e.g., in midmorning and midafternoon) but to lower intensities than the sun delivers at noon. Only a few investigators have used the more natural upward and downward stepping of irradiance, which is a better practice.

Another problem is that the UV-A and visible components, even with supplemental white fluorescent lamps, are generally more than an order of magnitude less intense than that in sunlight. This unnatural situation may eliminate some significant synergisms, positive or negative, between radiations of different wavelength that are present in sunlight.

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APPENDIX F

FACTORS IN ULTRAVIOLET DOSE-RESPONSE OF NONMELANOMA SKIN CANCER AND MELANOMA SKIN CANCER

As can be seen in Table F.1, nonmelanoma skin cancer appears to correlate best with cumulative lifetime UV-B exposure, therefore older persons will have more cumulative effects. Melanoma does not so correlate, which suggests that intermittency of exposures may be important. Personal dosimeters could be utilized to demonstrate the effect of winter travel to sunny climates for indoor workers in northern latitudes or of a two-week summer beach vacation, contrasted with the total UV-B exposure in the remainder of the year. A vacation UV-B-to-total UV-B ratio might be used as an index of the rate of UV-B exposure contrasted with total dose. A recent epidemiologic study from Norway suggests that travel to sunny climates may be a risk factor associated with malignant melanoma.[30] The role of traumatic sunburns remains to be evaluated.

Israeli data suggest that the duration spent in a low latitude correlates with the melanoma incidence. More-recent European immigrants have a lower age specific rate than do individuals who are native Israeli born.[31]

TABLE F.1 Factors Underlying UV Dose-Response of Nonmelanoma Skin Cancer and Melanoma Skin Cancer[a,b]

		Nonmelanoma Skin Cancer	Melanoma Skin Cancer
ULTRAVIOLET DOSE	Age (cumulative exposure)	Strong relationship to UV-B	Strong relationship for LMM[c] Not strong for other types (mid-age peak) Individuals of the same age born in successively more recent decades have high age-specific rates (Lee)[1,2]
	Cohort	No data	Strong cohort effect since 1900[1,2]
	Sex	Male greater than female	Equal incidence[3]
	Latitude gradient	Strong[4]	Strong[4]
	Occupation	Outdoor[4]	Indoor white collar[5] Outdoor before college[6] Highly educated, high-income men[7]
	Life style	Data not available	Data not available
RESPONSE	Distribution Over body[I]	Direct sun-exposed areas (face, neck, arms, and hands) > 90%[4]	Light-skin Caucasians: face, neck, back of both sexes; anterior torso of males, legs of females[3] Blacks, Orientals, and dark-skinned Caucasians: palms, soles, nailbeds, and mucous membranes[8-11]
	Skin color[II]	Increased risk in Caucasians[27] Greatly increased risk in Albinos[14] Decreased risk in Blacks,[24,25] Orientals, and dark-skinned Caucasians	Increased in light-skinned Caucasians,[12] especially Australians, Celtics, and Scandinavians[13] Albinos, few melanomas reported--tumors are nonpigmented and many need EM for recognition Rare in Blacks,[8] Orientals,[11] and dark-skinned Caucasians[10]

	Skin reaction type	II and III	II and III primarily
	Sensitive skin cells[III]	Xeroderma pigmentosum ? Celtics Basal-cell nevus syndrome	Xeroderma pigmentosum Celtics[12]
	Abnormal DNA repair[IV]	Xeroderma pigmentosum Actinic keratoses surrounding skin[26]	Xeroderma pigmentosa
	Precursor lesion[V]	Solar keratosis	BK mole syndrome[16]
	Congenital[V]	Epithelial nevi	Congential melanocyte nevi
	Chemical exposure	Arsenic	? Oral contraceptives ? *levo*-Dopa ? Polychlorinate biphenyls
	Physical exposure	X ray Grenz ray Thermal burn scars	
	Human model	Albinism Basal-cell nevus syndrome	BK mole syndrome[VI,16]
	Animal model[VI]	UV-B in mice → squamous-cell carcinoma	Dimethylbenzanthracene application on guinea pigs[21] Ultraviolet exposed mice[22]
MAGNITUDE OF PROBLEM	Most common type of skin cancer[23] >300,000 cases/yr		1% of all cancer (excluding non-melanoma skin cancer), 13,600 new cases estimated for 1979[23]
SEVERITY OF PROBLEM	1600 deaths/yr[23] substantial disfigurement, and potential morbidity with advanced cases		4000 deaths/yr[23]

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[a] Notes to this table, indicated by roman numerals, appear on the following pages.

[b] References, indicated by arabic numbers, appear at the end of this appendix.

[c] Lentigo maligua melanoma.

NOTES FOR TABLE F.1

I. Distribution of Malignant Melanoma by Body Site for Each Sex[a]

Site	Male Cases	Female Cases
Scalp	17	4
Head and neck	48	44
Back	132	86
Buttocks	1	5
Anterior torso	79	24
Upper extremity	60	60
Hand	7	8
Thigh	19	36
Leg	17	72
Foot	13	25
Genitalia	2	2
TOTAL	395	366

[a] Number of patients equals 761.

II. EFFECT OF SKIN COLOR

The effect of the degree of skin melanization on melanoma incidence is dramatic. In the United States, the incidence rate in Blacks is 1/6 to 1/7 of that of white Caucasians (Third National Cancer Survey). When melanoma does occur in Blacks, the sites of predilection are those that are less heavily melanized, such as the palms, soles, nailbeds, and mucous membranes (Krementz). Dark-skinned Caucasians such as residents of India (Reddy) have very low rates of development of melanoma. The incidence rates in Orientals are also substantially lower than among Caucasians, with sites or predilection similar to those found in Blacks (Seiji). Light-skinned Caucasians have the highest rates (see Tables II.A and II.B). The individuals domiciled at high northern latitudes (Irish, Scandinavian) have high rates, perhaps in part from high susceptibility and perhaps in part from vacation travel to more sunny southern latitudes. In Australia, in which a susceptible population is located at a latitude of high UV-B flux, the highest rates of melanoma incidence in the world are noted. In the United States over a 25-year period from 1950 to 1975, the melanoma death rate per million population more than doubled

TABLE II.A. Age-Adjusted Death Rates for Melanoma per 100,000 Population for Males[a]

Country	Rank among Countries	Rate
Australia	1	4.5
New Zealand	2	4.5
Norway	3	3.0
Switzerland	4	2.9
Finland	5	2.8
United States	10	2.4
El Salvador[b]	40	0.3
Panama[b]	41	0.3
Honduras[b]	42	0.2
Thailand[b]	43	0.1
Mauritius[b]	44	0.0

[a] Reference 23.

[b] In these countries the low death rate may in part reflect the less-complete case findings.

TABLE II.B. Age-Adjusted Death Rates for Melanoma per 100,000 Population for Females[a]

Country	Rank among Countries	Rate
Australia	1	2.6
New Zealand	2	2.2
Iceland	3	2.0
Hungary	4	2.0
Denmark	5	1.9
United States	18	1.4
Mauritius[b]	40	0.3
Panama[b]	41	0.2
El Salvador[b]	42	0.2
Honduras[b]	43	0.1
Thailand[b]	44	0.0

[a] Reference 23.

[b] In these countries the low death rate may in part reflect the less-complete case findings.

from 8 to 18.* Studies in New Mexico further support the greater susceptibility of lighter-skinned individuals for the development of melanoma.[28] The rates of Hispanics and Indians was 1/7 and 1/12, respectively, of fair-skinned "Anglos."

III. SUSCEPTIBLE POPULATIONS

Prolonged redness in response to a quantified amount of UV-B exposure has been noted in a higher proportion of individuals with nonmelanoma skin cancer than in a group of age-matched controls.[32,33] A similar but less pronounced response was also noted in melanoma patients (Jung). If confirmed, this approach may be of use in screening individuals to select those at greatest risk.

IV. DNA-REPAIR PROBLEMS IN SUSCEPTIBLE POPULATIONS

In the rare genetic disorder xeroderma pigmentosum, in which defects in DNA repair exist, susceptibility to ultraviolet-induced, nonmelanoma skin cancer and malignant melanoma is extraordinarily high. On a more limited basis, DNA repair defects have been found in the sun-damaged skin adjacent to actinic keratosis.[33]

V. PRECURSOR LESIONS

Melanocytic lesions at an increased risk for development into malignant melanoma have been noted in two distinct situations:

1. Giant congential melanocytic nevi have been noted to develop melanomas in 2 to 40 percent of individuals bearing these lesions.
2. Certain families in which there has been observed an increased frequency of melanoma bear multiple large odd-appearing nevi (B-K mole), which has the tendency to develop into malignant melanoma.[35] The factors that trigger the malignant change of such nevi are at present unknown (spontaneous, UV-B, etc.).

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*Source: Vital Statistics of the United States.

VI. UV-A-INDUCED CARCENOGENESIS

IV-A-induced skin cancer has been reported at various meetings since 1973 (see below), but only in the recent work of P. D. Forbes was the light source only UV-A. It should be noted that UV-B is 1600 times more carcinogenic than UV-A.

P. D. Forbes: Influence of longwave UV on photocarcinogenesis. First Annual Meeting of the American Society for Photobiology, Sarasota, Florida, 1973.

> Two groups of hairless mice--both exposed to same dose of UV-B radiation daily.
>
> Group A: FS40 bulbs delivering 13 mJ/cm^2/day of UV-A radiation
> Group B: Xenon arc delivering 120 mJ/cm^2/day of UV-A radiation
>
> Group B developed tumors earlier (17 versus 25 weeks) and in greater numbers (1.0 versus 0.14 at 31 weeks) as compared with Group A.
>
> Comment: Forbes has partially retracted these results as he has been unable to repeat the study.

G. Mahrle, H. Berger, and K. Külmel: Stages of connective tissue alteration and tumor development under UV-A radiation in mice skin. Joint Meeting of the European Society for Dermatological Research and the Society for Investigative Dermatology, Amsterdam, 1979.

> Hairless albino mice were exposed to Philips TL40/09 bulbs. 38 of 50 developed tumors.
>
> Comment: Lamps were unfiltered and therefore the UV-B radiation (4 percent of output) could be responsible for the tumors.

P. D. Forbes: Personal communication, October 1979.

> Hairless mice exposed to glass-filtered BL bulbs 24 h/day develop tumors after approximately 40 weeks. This can be compared with the same mice exposed to FS40 bulbs for 10 minutes/day, which results in tumors by 20 weeks.
>
> Very approximate calculations indicate that 72.5×10^3 J/cm^2 of UV-A radiated is as carcinogenic as 45 J/cm^2 of UV-B radiation.

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APPENDIX G FURTHER DETAIL ON MALIGNANT MELANOMA

U.S. RATES OF INCIDENCE

The best available estimates of current incidence rates of melanoma come from the Third National Cancer Survey (1975), based on counts during the years 1969-1971. Table G.1 gives both crude and age-adjusted rates for the entire population and for sex-color groups.

TABLE G.1 Average Annual Incidence Rates per 100,000, U.S. 1969-1971

Population	Rate Crude	Age Adjusted (1970)
Total	4.1	4.2
White Males	4.4	4.6
White Females	4.6	4.4
Black Males	0.7	0.9
Black Females	0.6	0.7

U.S. FIVE-YEAR SURVIVAL

According to the National Cancer Institute's *End Results in Cancer* (Report No. 4, and *Recent Trends in Survival of Cancer Patients 1960-1971*, published in 1974, the 5-year adjusted survival rate is 67 percent for malignant melanoma patients diagnosed between 1965 and 1969.

PERCENTAGE OF ALL CANCERS

Melanomas make up approximately 2 percent of all cases of cancer to be diagnosed in 1979 and will account for 1 percent of all cancer deaths in 1979. These figures came from the American Cancer Society, Cancer Statistics, 1979.

Applied to a current estimated population of 200 million, the results of this survey would indicate 13,600 new cases for 1979. The survival rates quoted above suggest that 4300 of these new patients will die within 5 years.

OTHER SITES OF COMPARABLE INCIDENCE

Melanomas can be viewed from the perspective of other cancers found with similar frequency. The estimated total number of new cases and deaths from cancers at that site for 1979 are presented in Table G.2.

TABLE G.2 Cancer Sites with Comparable Incidence[a]

Site	Estimated New Cases at that Site for 1979	Estimated current Deaths from Cancer at that Site for 1979
Melanoma (skin)	13,600	4,300
L.R.C.S.[b]	15,000	5,200
Brain	11,600	9,500
Larynx	10,400	3,500
Thyroid	9,000	1,000
Multiple myeloma	8,800	6,100
Esophagus	8,400	7,500

[a] From E. Silverberg, 1979. Cancer Statistics, 1979, *CA--A Cancer J. for Clinicians* 29:6-21.

[b] Lymphosarcoma and reticulum-cell sarcoma.

COHORT EXPERIENCE

Lee and his colleagues (Lee, 1973, 1975; Elwood and Lee, 1979) have shown definite changes in melanoma incidence and mortality in the United Kingdom and Canada. Persons born in more recent years have high incidence and mortality at all ages than those born earlier. Lee and Elwood (1975) thus describe a "generation" effect implication on etiologic factors that operates from an early age. People born between 1900 and 1920 in England and Wales were the first group to experience higher rates. Similarly, in Canada, later born cohorts have higher melanoma mortality at all ages.

GEOGRAPHIC VARIATION

Within the United States, incidence doubled for each 10° decrease in latitude (Climatic Impact Committee, 1975). Similar latitude gradients have been observed in Australia and Norway. Worldwide plots of latitude data support a latitude effect on both incidence and death rate, but some deviations exist in certain countries and at some locations within countries. These deviations may result from the effects of microclimate, differences in fraction of susceptible population, difference in exposure practices, or differences in completeness of registry data collection. These factors make comparisons between countries difficult.

TYPES OF MELANOMA

Malignant melanoma arising in the skin is not one but at least four different specific types of cancer of pigment cells (see Table G.3). The differences are related to the age of onset, the clinical appearance, the cellular pattern (histology), the rate and manner of growth in the skin, and the survival rate.

The relative occurrence of the four types, as seen in different kinds of hospitals, appears to be quite different, with superficial spreading melanoma as high as 80 percent in general hospitals and reported to be as low as 10 percent in specialized cancer hospitals. Because three of the four types of melanoma may be present as an identifiable cancer for several years before invading deeply in the skin, it is possible to remove these early lesions surgically before deep invasion occurs and by this treatment have a chance of curing the disease. This, of course, depends on early detection of primary melanoma by patient or physician, which might reasonably be achieved by an intensive public educational program, perhaps even by as simple a program as adequate publicity for the following paragraph.

TABLE G.3 Primary Melanoma of Skin (in White Persons)

Type of Melanoma	Median Age (yr)	Specific Sites[a]	Rate of Development	Appearance
Lentigomaligna	70	Face, neck, and hands	Slow: 5-20 yr	Predominantly flat spot 2-20 cm in size, with irregular borders and pigment pattern. Raised areas indicate areas of invasive tumor
Superficial spreading melanoma	47	Face, neck, upper trunk, and lower legs (in females)	Moderately slow: 1-7 yr	Predominantly a slightly raised lesion with a raised distinct irregular border that may be notched. The brown and black color is admixed with blue, white, red, or their half tones gray and pink
Nodular	50		Rapid: months	Isolated small (3.0-cm) nodule with smooth borders; color uniform blue-black
Acrolentiginous[b]		Palms, soles, nail beds, mucous membrane		Predominantly flat spot with irregular borders. Raised areas indicate invasive tumor

[a] The first three types occur either on the exposed parts of the face, neck, and hands or on the relatively exposed areas of the chest, back, and legs. Only a few lesions are seen on covered areas such as the breasts of females, bathing trunk areas of males, and bathing suit areas of females.

[b] This type predominates in blacks and orientals.

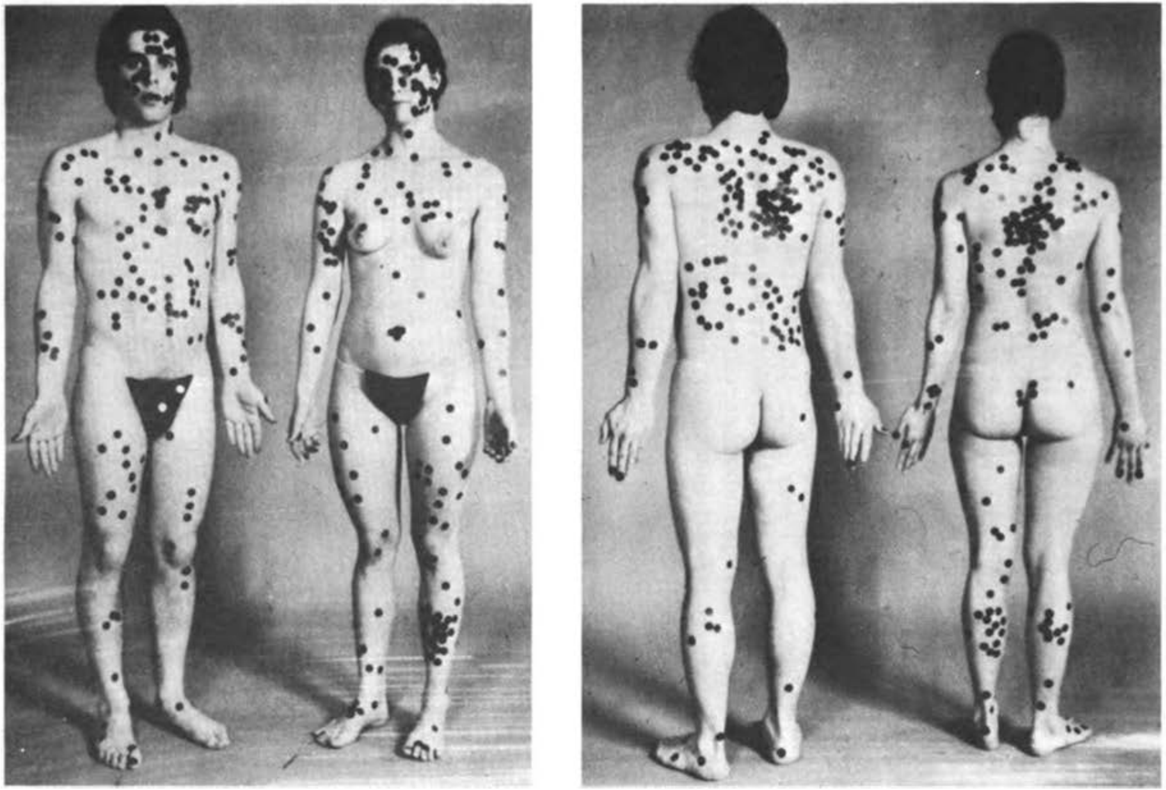

FIGURE G.1 Exhibit of localization of melanoma skin cancer in 761 males and females.

Examination of the human body for early stages of superficial spreading melanomas, the most common type, is very easy and can be conducted effectively by almost everyone. One has only to examine moles carefully, noting whether (a) the mole's edges are rough and contain a notch or (b) the color is speckled and contains red, white, or, particularly, blue. If either of these conditions is found, examination by a specialist is urgent (very few moles with either of these characteristics are noncancerous).

Figure G.1 shows the specific sites of origin of primary melanoma. (Data from Malignant Melanoma Clinical Cooperative Group comprising four centers: Massachusetts General Hospital; New York University Hospital; Temple University Hospital; and University of California, San Francisco Hospital.) Note the predominant localization of sites of origins to areas of skin that are constantly exposed to sunlight (face and lower legs in females) or to body areas that are intermittently exposed (trunk and legs of males). Also note the virtual absence of melanomas in body areas that are covered (bathing trunk area of males, bathing suit area of females).

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APPENDIX H PREVENTIVE MEASURES RELATED TO MELANOMA

PREVENTIVE MEASURES

With melanomas at present providing about 1 percent of all cancer deaths, and with a relatively clearer understanding of both causation and prevention, it would not be appropriate to discuss the possible increase in risk from increased DUV without discussing the possible decrease in risk that an effective practice of preventive measures could contribute. Since most of the effective measures require active cooperation by the persons involved, there are real difficulties in the way of an effective program, but the potential--and even the plausible--reductions in unnecessary deaths make the outlining and consideration of a program or preventive measures essential.

Such a program would involve three phases:

- Identification of persons of higher susceptibility.
- Adequate protective measures, continued through life, by these more sensitive individuals.
- Regular educated self-examination of these individuals, in order to discover skin cancers in their earlier stages, when treatment (surgery) is effective. (The amount of potential benefit is still a controversial issue. There is no information from well-designed observational or experimental studies to justify a definitive conclusion that early detection and treatment changes the natural history of disease. However, medical oncologists believe that clinical experience points to prolonged survival with early detection and treatment. The major point of debate is the proportion of melanomas whose consequences can be effected by such measures.)

Sun damage to skin is often equated with acute sunburn, but sun-induced skin damage is cumulative and irreversible, and repetitive short exposures with no visible sunburn can lead to skin damage. The following points are important:

1. DUV is most intense between 11:00 a.m. and 3:00 p.m. (daylight time), accordingly susceptibles will do well to schedule exposures before 11 a.m. or after 3 p.m.
2. Some clothing transmits more than 20 percent of DUV.
3. Because of reflection, DUV intensities in the shade are sometimes 50 percent or more of those in the bright sun.
4. Seventy to 80 percent of the bright-sun DUV reaches the ground on bright but hazy days with clouds.
5. A sand background increases the DUV by 25 percent; snow by 100 percent.

That a significant fraction--conceivably as much as one third--of the U.S. population should have to plan to protect themselves, throughout their whole lives, from the ill effects of excessive sunlight will be surprising to many--and shocking to some. Yet, until and unless we find better ways to focus on a smaller group of susceptibles, nothing less can do very much to reduce skin-cancer incidence.

The measures that need to be taken include

- Avoidance and reduction of exposure, particularly between 11:00 a.m. and 3:00 p.m.
- Daily use of effective sun-screen preparations (most widely advertised *suntan* preparations are ineffective for necessary exposures, e.g., occupational).

Currently effective sunscreens block UV-B predominantly. Effectiveness is measured by the ability to prevent sunburn. If the action spectrum for melanoma is greatly different from the UV-B spectrum, then these sunscreens may be of limited usefulness. At present, it has not been demonstrated that regular use of sunscreens by susceptible individuals will reduce their risk for development of either melanoma or nonmelanoma skin cancer. Environmental and health hazards of chronic sunscreen use in large populations have also not been assessed.

Most people who are more highly susceptible are likely to need to use effective sunscreens, although some may be able to reduce their exposure so drastically that sunscreens are not essential.

TABLE H.1 Working Classification of Sun-Reactive Skin Types Used in Clinical Practice[a]

Skin Type[b]	Skin Reactions[c] to First 30-Minute Exposure of the Summer
I	Always burn, never tan
II	Usually burn, tan below average (with difficulty)
III	Sometimes mild burn, tan about average
IV	Rarely burn, tan above average (with ease)

[a] More precise and sensitive classification will be needed as knowledge evolves.

[b] Type I and Type II persons often have light skin color, blue eyes, may have red scalp hair, and may or may not have freckling. However, some persons with dark brown hair and blue or green eyes have Type I and Type II sun reactions.

[c] At age 12-40 years.

SKIN TYPES

Different persons are very differently susceptible to sun-induced skin damage. Personal history of sunburning and/or suntanning following the first 30-minute exposure to the summer sun (at northern latitudes) is ordinarily sufficient to classify whites in four types of grades of reactivity (see Table H.1).

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APPENDIX I TECHNOLOGICAL POSSIBILITIES FOR REDUCING CFC EMISSIONS FROM MOBILE AIR CONDITIONING

There appear to be three basic technical approaches to reducing emissions or losses of CFC refrigerants to the atmosphere from automobile air-conditioning systems. They are to:

1. Continue to use the current F-12 refrigerant, but reduce losses to the atmosphere through controls during manufacture, testing, servicing, and disposal as well as through system design improvements to reduce leaks during routine use;
2. Develop alternative (either non-CFC or hydrogen-containing CFC) refrigerants to use in vapor-compression systems basically similar to those currently used with F-12; and
3. Develop alternative refrigeration systems that would not require the use of CFC refrigerant materials.

The control of losses from currrent F-12 systems could be accomplished in the near future, while the development of satisfactory alternative refrigerants or systems are longer-term solutions.

REDUCTION OF LOSSES FROM CURRENT F-12 SYSTEMS

This approach is being addressed in detail in the Rand study, which estimates possible reductions in F-12 loss approaching 70 percent if all suggested improvements are made.

The potential reductions are grouped by Rand in three categories: manufacture and testing, service and disposal, and technical changes (system design improvements). The feasibility of reducing CFC losses in each of these areas is discussed below.

Manufacture and Testing

Approximately 11 percent loss reduction is anticipated by Rand during manufacture and testing. Some of this is already being attained by recovery and recycling of F-12 within manufacturing facilities and by using either dilute mixtures of F-12 and nitrogen or other materials such as helium (with a mass-spectrometer detector) as substitutes for F-12 in component leak testing. Substitute materials such as dry air or nitrogen could also be used for functional testing of compressors if suitable equipment and procedures are developed.

An additional factor related to the manufacturing process is the capability of the system assembly sequence for avoiding leaks due to misassembly of components. The potential improvement in this area is difficult to estimate. Manufacturers continuously strive to improve assembly quality in order to reduce cost and to maximize customer satisfaction.

Service and Disposal

Present mobile air-conditioning service procedures recommend that the F-12 refrigerant be vented to the atmosphere whenever system service or repair is required. The same venting process occurs inadvertently on the eventual scrapping or disposal of the vehicle. These F-12 losses could be largely eliminated through the use of recovery equipment and procedures at the time of service or disposal.

Chemical destruction of the refrigerant at the service or disposal site is not practical because there is no currently known procedure for effectively destroying F-12. The major by-products of F-12 incineration, for example, are corrosive HCl and HF acids. F-12 recovered from mobile air-conditioning systems would therefore have to be reprocessed and recycled, either on-site for immediate reuse in recharging the system or off-site at a centralized bulk reprocessing facility.

Prototype on-site recovery equipment has been built and demonstrated by industry, but no satisfactory on-site processing equipment is known at this time. Commercial off-site reprocessing of CFC refrigerants is being carried out in a few locations for large commercial users. However, federal regulations* relating to the shipment of compressed

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*Department of Transportation, Materials Transportation Bureau, 49 CFR, Sec. 100-199.

gases could have a major adverse effect on the cost of transporting used CFC refrigerant to centralized reprocessing locations.

Quality and cleanliness specifications for reprocessed refrigerant would have to be established and controlled for either on-site or off-site reprocessing of used refrigerant. Moisture, noncondensable gases, dirt, products of decomposition, and other factors affecting CFC purity must be controlled to assure satisfactory reliable performance of air-conditioning systems recharged with used, reprocessed refrigerant.

There are approximately 140,000 to 230,000 air-conditioning service outlets in the United States and approximately 800 major salvage yards. Control of a CFC refrigerant recovery, reprocessing, and reuse program at this large number of individual, privately owned establishments would be very difficult. At present, there is no economic incentive for a small business to recover and reprocess CFC refrigerant. Total investment for this type of equipment is estimated to be approximately $2000 per unit, or as much as $450 million if all outlets acquired the equipment.

Leakage Reduction

System design factors that might be improved to reduce F-12 losses are permeability of hose material; length of hoses used in the system; reliability and leak rate of gaskets, fittings, and connections; and reliability and leak rate of compressor shaft seals. Reduced leakage through these components will reduce the frequency of service recharging required and thus further reduce losses. Many of these potential improvements are already being partially or fully implemented by the automobile manufacturers.

The complete redesign of mobile air-conditioning systems to utilize hermetic sealing similar to household refrigerators has been proposed by many as a means of minimizing refrigerant loss. This would not only reduce direct losses from leaks during use but might also reduce losses during servicing by reducing the frequency with which system servicing is required. There are three primary reasons why this has not yet been accomplished.

1. An electrical or hydraulic compressor drive motor that could be hermetically sealed inside the unit requires a matching power "generator." The combined efficiency of the generator and the motor is approximately half that of

the conventional mechanical belt-type drive in use today. (Over the normal vehicle operating speed range the overall efficiency of each unit might be approximately 70 percent; therefore the combined efficiency would be 0.70 (generator) × 0.70 (motor) = 0.49 or approximately 50 percent as compared with a 95-percent-efficient belt drive.) System power requirement would be approximately double that of current belt-drive systems, and the weight of the power transmission elements would be more than double that of a belt-drive system.

2. Effective, efficient, mechanical seals allowing a hermetic mechanical "through-the-wall" drive for a compressor do not exist today. Such a seal would not only have to be totally durable over the life span of the automobile but would have to be capable of performing hermetically leak-free over a temperature range from -40°F to 300°F, over a range of pressures varying from vacuum conditions as low as 1 mm Hg to pressures as high as 500 psi and over an operating speed range from prolonged static periods to 8500 rpm.

3. Mobile air-conditioning systems require isolation of the vibration and noise generated by the vehicle engine and/or the air-conditioning compressor from the body structure and passenger compartment. Hermetic metal refrigerant lines are not currently available that will reliably withstand these vibrations along with normal road-transmitted vibrations and at the same time provide the needed passenger-compartment isolation. Alternative systems involving the use of glycol-water, for example, as an intermediate heat-transfer fluid (so that no flexible refrigerant lines would be required) could be developed but would introduce further cost, performance, and energy penalties.

Reduced Initial Charge

Reduction of initial refrigerant charge in the system is another potential means of reducing losses to the atmosphere. Such a reduction in initial charge can be accomplished through the use of smaller-internal-volume components but will result in higher internal flow rates, greater pressure drop in the components, and reduced tolerance to loss of charge before cooling performance is impaired. Changes in the basic design of evaporators or condensers such as suggested by the Rand study may adversely affect system size, weight, and cooling performance. Projected reductions in refrigerant losses due to reduced system initial charge may also be partially offset by increased frequency of service recharging due to lower refrigerant reserve.

A complicating factor related to assessing the effect of possible system design improvements is that no satisfactory test procedures exist at present to measure accurately the "base-case" system loss rates or the effect of any design improvements that might be made by industry. The Society of Automotive Engineers is currently gathering data to develop a suitable F-12 emission test procedure for air-conditioned vehicles. Other industrial groups, including the American Society of Heating, Refrigerating, and Air-Conditioning Engineers; the International Mobile Air-Conditioning Association; the Motor Vehicle Manufacturers Association; and the Air-Conditioning and Refrigeration Institute also have under way studies of alternatives to present air-conditioning practices.

Evaluation

Even in view of these difficulties, improvement in the manufacture, testing, design, service, and salvage of F-12 refrigeration systems appears to be the only feasible short-term means of significantly reducing F-12 losses into the atmosphere from automobile air-conditioning systems. Improvements in service and salvage procedures will affect all vehicle systems currently in use--not just new vehicles. Containment, recovery, and reuse of F-12 also represent a prudent approach to the long-range conservation of a depletable resource (fluorspar).

Losses due to system damage in cases of severe accident or component failure are largely uncontrollable.

DEVELOPMENT OF ALTERNATIVE REFRIGERANTS

A variety of materials have been considered[1] for development as alternative refrigerants to replace F-12 in the vapor-compression refrigeration system for mobile air conditioning. These have included both organic and inorganic compounds, but most potential candidates are some form of fluorocarbon.

Examples are

propane	C_3H_8
cyclo-propane	C_3H_6

ammonia	NH_3
sulfur dioxide	SO_2
carbon dioxide	CO_2
methyl chloride	CH_3Cl
perfluoropropene	CF_3CFCF_2
perfluoropropane	C_3F_8
perfluorocyclopropane	$c\text{-}C_3F_6$
F-22	$CHClF_2$
F-124	$CHClFCF_3$
F-134a	CH_2FCF_3

and mixtures

F-22/F-124
F-22/F-142b

In considering these alternatives, it is important to recognize that the current F-12 refrigerant represents the culmination of approximately a century of research and development to find a refrigerant that best meets the requirements of physical-thermodynamic properties, chemical inertness, low toxicity, nonflammability, availability, manufacturability, and cost. Some of these alternative materials, such as ammonia, sulfur dioxide, propane, and methyl chloride have been used as refrigerants in the past but have been replaced because of excessive toxicity, flammability, and corrosiveness.[2]

The new dimension of environmental acceptability from the viewpoint of potential stratospheric ozone depletion and/or atmospheric greenhouse effect must be added to the list of needed characteristics. If potential atmospheric acceptability is considered in addition to the above requirements, only a few candidates remain as practical alternative refrigerants for mobile air conditioning:

F-22

Mixtures: F-22/F-124 and F-22/F-142b

F-134a

Of these remaining candidates, only F-134a is chlorine-free. F-22, F-124, and F-142b, with only one chlorine atom per molecule, contain less chlorine than F-12. (Chlorine percentages by weight are F-12, 59 percent; F-22, 41 percent; F-124, 26 percent; F-142b, 35 percent.) In addition, F-22, 124, and 142b contain hydrogen, which results in much shorter tropospheric life, with less of the CFC, and consequently less of the chlorine, reaching the stratosphere. Note that F-22 is currently used extensively in residential air conditioning and is also used in some commercial air-conditioning systems, and in a few mobile applications such as buses. F-22, however, is not well suited for automobile air conditioning because of considerably higher operating pressures, greatly reduced oil solubility for compressor lubrication, and considerably greater permeation rate through elastomeric hoses with resultant greater loss to the atmosphere. It would require a complete redesign, and development of completely new components for automobile air-conditioning systems, to accommodate the use of F-22 as a refrigerant. Such a redesign, development, and retooling program could take as long as five to seven years and could require new industry-wide investment on the order of $500 million. Manufacturing cost could also be somewhat higher; F-22 material cost is currently approximately twice that of F-12.

Of the mixtures, F-22/F-142b shows greatest promise because of its thermodynamic properties, lower cost, and current availability. However, F-142b is somewhat flammable by itself (not in the mixture) and has been found to be possibly mutagenic in preliminary screening tests. Mixtures of refrigerants such as this do not perform as a single compound but tend to separate into the two base materials during the evaporation and condensing stages. This results in significant cooling performance loss in current systems when compared with F-12. Required system redesign would be less than for F-22 alone.

F-134a has the greatest theoretical potential as a long-range replacement for F-12 in mobile air conditioning, but it also presents the greatest number of unknowns at this time. There is currently no known method of commercial manufacture for F-134a. The physical properties of F-134a closely resemble those of F-12, and it contains no chlorine to disrupt the ozone layer; however, its insolubility with oil may cause compressor-lubrication problems, its toxicity characteristics have not been established, and only small quantities have been available for limited laboratory testing. Development of F-134a as a mobile air-conditioning refrigerant, if successful, could require a 10- to 20-year development program.

Evaluation

Overall, the potential development of alternative refrigerants for use in vapor-compression systems similar to today's F-12 system must be regarded as a long-term, costly program possibly requiring major redesign of mobile-air-conditioning systems. Since CFC emission would be reduced only in new systems produced for use with the new refrigerant, full effectiveness of an alternative refrigerant would not be reached until 7-10 years after introduction.

DEVELOPMENT OF ALTERNATIVE REFRIGERATION SYSTEMS

The third approach to the reduction of CFC emissions is the development of alternative refrigeration systems that would not use CFC vapor-phase refrigerants.

Thermodynamics of Alternative Fluids or Cycles

Air-conditioning and refrigeration units are reversed heat engines, which means that, as shown schematically in Figure I.1, a mechanical power input (Wk) is required for a quantity of heat (Q_1) to be absorbed at a low temperature (T_1) and for this quantity of heat, plus that equal to the mechanical power input, to be rejected at a higher temperature (T_2).

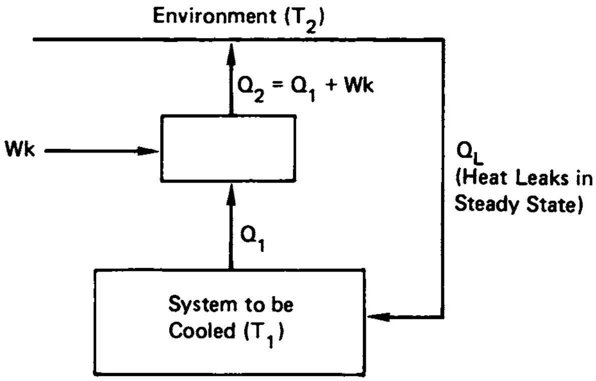

FIGURE I.1 Schematic illustration of the cooling cycle.

The coefficient of performance (COP) is defined in terms of the energy flows shown in Figure I.1 as

$$\mathrm{COP} = Q_1/Wk.$$

The maximum possible COP is given by a corollary of the second law of thermodynamics in terms of the temperatures at which the heat flows are absorbed and rejected:

$$\mathrm{COP}_{\mathrm{max}} = T_1/(T_2 - T_1).$$

The maximum possible COP for a given unit is then set by the specified input and output temperature levels (i.e., for mobile air conditioning, the passenger compartment temperature, and the surrounding ambient temperature).

There are two primariy factors through which alternative fluids and cycles will show thermodynamic advantages and disadvantages: (1) the energy efficiency of the compressor and expanders and (2) the degree to which the temperatures at which heat is actually absorbed and rejected approach the ideal temperatures. Compression efficiency is affected little by either the cycle or the fluid employed. Expansion efficiency is zero for the throttling process in liquid-vapor cycles, but the loss of availability, or the drop in COP, is very small. Gas cycles must employ work-producing expanders to recover energy because they expand a gas rather than depressurizing and partially expanding a small-volume liquid, as in a liquid-vapor cycle.

The heat-transfer temperature difference is affected by cycle and fluid choices in several significant ways. Vapor cycles employ condensation and evaporation, which are highly efficient because the heat-transfer coefficients of the fluid side are very high, leading to small temperature differences. Moreover, the heat is transferred at constant temperature, so that no additional unnecessary temperature differences need occur during the process.

In air cycles (reversed Brayton cycle), the refrigerant side of the heat exchangers has single-phase air, which has a relatively low thermal conductivity and a low heat-transfer coefficient and, therefore, changes temperature considerably while exchanging heat. The COP suffers greatly. In contrast, a Stirling cycle using hydrogen as the working fluid has a high heat-transfer coefficient because of the high thermal conductivity of hydrogen, so that the temperature differences can be small. In addition, the engine mechanism allows the fluid space to be expanded while heat is being absorbed, and to be compressed while heat is being rejected, so that heat exchange occurs at approximately constant temperature. Accordingly, a Stirling-cycle refrigerator is conceptually capable of relatively high COP values.

These observations concerning temperature differences in the heat-transfer process presuppose heat exchangers of fixed size. The temperature difference could be reduced by making the heat exchangers larger. But even heat exchangers of infinite size cannot reduce the excess temperature difference resulting from constant-pressure cooling of a single-phase gas, as in the reversed Brayton cycle.

The inference from this thermodynamic argument is that the only viable, efficient alternatives to vapor-compression cycles using F-12 are vapor-compression cycles using other fluids having two-phase properties in the appropriate temperature and pressure range (such as those discussed above) or theoretical gas cycles with Carnot ideal efficiencies (such as Stirling and Ericsson cycles) using hydrogen.

In the paragraphs below we discuss the reversed Stirling cycle along with other alternative refrigeration systems or cycles that have been considered for mobile air conditioning. Any alternative system considered for use should not significantly penalize vehicle weight, fuel economy, or the safety of employees of the manufacturer or the service station, or the vehicle passenger.

Absorption Refrigeration Systems

Absorption refrigeration systems have been in use for commercial-residential air conditioning for many years. Two types have been most commonly used: ammonia-water and water-lithium bromide. They are best suited for large installations where waste heat is readily available as an inexpensive energy source.

Even though engine exhaust heat could be utilized in vehicle applications, this source of energy is inadequate and these systems would require an auxiliary heat source as well as very large, heavy heat exchangers for heat rejection (10 times that for an F-12 system) because of their very low COP. Coefficients of performance for these absorption systems are typically in the range of 1/4 to 1/8 that of vapor-compression systems.[3]

The use of water as either the refrigerant or the absorbent material makes these systems unsuitable for use or storage below freezing temperatures. Air-cooled absorbers are unsatisfactory for lithium bromide above 110°F ambient temperature because of crystallization of the lithium bromide. Ammonia, on the other hand, is a highly toxic material and could not be used inside the passenger compartment of a vehicle with reasonable safety.

Because of these major disadvantages, absorption refrigeration systems are not considered to be suitable candidates for use in mobile air conditioning.

Air-Cycle Refrigeration

During the past few years, air-cycle refrigeration has been widely publicized as a candidate for use in mobile air-conditioning systems. The air-cycle concept has been known for many years and was used commercially as early as 1850. It is currently the primary air-conditioning system used for aircraft. Lightweight turbine-type compressors and expanders along with easy availability of large quantities of high-pressure air from the engine compressor make this application desirable in spite of low overall efficiency.

Application of air-cycle refrigeration to vehicle air-conditioning systems, however, has not been as successful. Even though a performance equivalent to current F-12 systems has been claimed, actual evaluation of mobile air-conditioning systems using the air-cycle principle have shown that cooling capacity is considerably lower, size and weight are significantly greater, noise level is high, and power requirement is approximately 3 to 10 times greater (for a given capacity) than current F-12 systems.[4,5]

The use of moist air as a working fluid has been proposed as a means of improving the COP; however, experience has shown very little improvement and the sure risk of damaging corrosion within the internal parts of the system and mechanisms. A recent proposal to develop a more complex system using an air/vapor refrigerant mixture indicates an effort to revise the system to partially utilize the higher efficiency provided by conventional vapor-compression refrigeration.

Air-cycle refrigeration, even with further development, shows little or no prospect of approaching the current F-12 system levels of weight, size, cost, reliability, and efficiency.

Reversed Stirling Cycle

Within the past 25 years, considerable development work has been done on the reversed Stirling cycle, particularly by Philips Research Laboratories in The Netherlands. This cycle has been successful for cryogenic applications in the range of -100°F to -330°F using helium or hydrogen as the working fluid.

There is considerable diversity of opinion about the potential use of the Stirling cycle for mobile air-conditioning refrigeration, ranging from predictions of its having no potential to considerable optimism about its future success.

Heat exchangers seem likely to be more complex and expensive for the Stirling-cycle system, and a regenerator is required. No Stirling-cycle air-conditioning systems have been demonstrated up to this time. A long-range research and development program will be needed to evaluate the potential of the reversed Stirling cycle for possible application to mobile air conditioning.

Other Systems

Thermoelectric cooling is most easily described as a reversed thermocouple. If certain dissimilar metals are joined forming a closed circuit and a voltage is applied, one junction absorbs heat and the other rejects heat, thereby producing a cooling effect at the "cold" junction. This is the thermoelectric effect.

Even though a thermoelectric system would involve no CFC refrigerant, there is little prospect of adapting this principle for mobile air conditioning[6,7] because current thermoelectric material technology results in approximately 7 to 11 times the energy requirement that would be needed for an F-12 system of the same capacity. Materials are extremely fragile and expensive, and total heat dissipation is difficult because of system inefficiency and the resulting large amount of heat to be rejected.

Steam-jet refrigeration utilizing water as the refrigerant has been used in large systems where abundant sources of high-pressure steam are available.

This system is not suited for automotive use because large, heavy components are required, a source of high-pressure steam is needed, water used as a refrigerant will freeze at low ambient temperatures, and overall system efficiency is very low, on the order of one fifth that of an F-12 system. The steam jet also tends to be quite noisy.

Stored cold: Cooling cycles could be omitted entirely, and vehicles could carry well-insulated tanks of, for example, an ice-water slurry. These tanks would be replenished at gasoline stations, which would have installed cooling cycles (presumably conventional vapor compression), which would use and emit much lower amounts of CFC than would the displaced systems in the automobiles serviced.

Such an arrangement has obvious user disadvantages and has not been evaluated.

Magnetic refrigeration: The application of ferromagnetic cooling, previously used to attain temperatures near absolute zero, to near-room temperature uses has recently been proposed.[8,9] High thermodynamic performance has been claimed. Further long-range research is needed to investigate the potential applicability of such an approach to mobile air conditioning.

Evaluation

At the present state of technology, there appears to be no suitable alternative refrigeration cycle that could be adopted within the next 5 to 10 years for mobile air-conditioning use without excessive penalities in size, weight, efficiency, reliability, cost, and safety.

This Appendix draws largely on the Rand study and the DuPont submission to EPA[10] and on information provided to the CARCE Panel on Industrial Technology in spoken or written form by the following organizations:

Air-Conditioning and Refrigeration Institute
Air Force Flight Dynamics Laboratory
Chrysler Corporation
E. I. du Pont de Nemours and Company
Ford Motor Company
General Motors Corporation
International Mobile Air Conditioning Association
ROVAC Corporation
Sunpower, Inc.
York Division, Borg-Warner Corporation

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APPENDIX J TECHNOLOGICAL POSSIBILITIES FOR REDUCING CFC EMISSIONS FROM PLASTIC FOAMS

Four major types of plastic foam--flexible urethane foam, rigid urethane foam, reaction injection molding, and non-urethane foam--will be discussed in turn. In each case, the technological alternatives are described in four categories:

- Recovery and recycling of CFC blowing agents,
- Partial or complete substitution of non-ozone-depleting blowing agents for the CFCs,
- Restricting production of that class of plastic foam,
- Developing new foam-production technology.

FLEXIBLE URETHANE FOAM

Flexible urethane foams are made by reacting long-chain polyols (polyethers and polyesters) with difunctional isocyanates to form the product polyurethane. The most common raw materials are the polyols derived from propylene and ethylene oxide and toluene diisocyanate. Depending on the exact chemical composition, molecular weight, and functionality of the polyol and isocyanate, a variety of semirigid to rubbery products can be formed. The reaction, once started, proceeds with the evolution of considerable heat. If it is desired to produce foams, then pneumatogens and surfactants are incorporated into the formulation. The pneumatogen or blowing agent can be one or more of the following:

- CO_2 from the reaction of excess isocyanate with water;
- Low-boiling liquid pneumatogens and frothing agents (methylene chloride, F-11, F-12);
- Thermally decomposing chemicals (Porofor N, Nitrosan, for example).

Open-cell foams are produced by the continued evolution of pneumatogen during and after the foam rises, forming interconnecting or open cells. By this means, the thin plates of the dodecahedral cell walls are literally blown out, leaving behind the coarser struts that make up the intersecting edges of adjacent cells.

The plant production of flexible urethane foams can be done continuously on moving belts (slabstock--large buns--for use in mattresses and other items) or batchwise in closed molds (e.g., car bucket seats). The plant equipment is capital intensive and requires expensive precision metering and mixing machines. One of the prime raw materials, the isocyanates, is known to be toxic, and rigid control of emissions of this chemical is necessary to ensure the health of workers.

In addition to the chemical composition of the polyurethane polymer, the physical properties of flexible foams are strongly controlled by foam density, cell size, cell uniformity, and the percentage of open and closed cells. Typical flexible foams will have densities of about 1-3 lb/ft^3 (0.02-0.05 g/cc), 20-50 cells/lineal inch, and "good" cell size uniformity. There are also semirigid (or semiflexible) foams, often referred to as microcellular foams, with densities from 5 to 60 lb/cu ft. In this category fall also self-skinned or "integral skin" foams (e.g., for automotive arm rests and other automotive interior components). The use of F-11 in these applications provides the molded foam products with a pinhole-free, cosmetic surface.

Reducing CFC emissions from flexible urethane foam production is a more viable, near-term option than achieving reductions in the manufacture of rigid urethane foams and in other foam applications that also use CFCs. The primary reasons for this are the following:

- The total annual level of CFC emissions from flexible urethane foam production is high and is projected to increase (although there is some difference of opinion on the projected growth rate since one of the potential alternatives, methylene chloride, is lower in cost than the CFCs and may be used in their place). Steps to reduce emissions can therefore have significant impact on overall domestic emissions.
- Emissions from each production unit are both large and prompt. Unlike rigid closed-cell foams, practically all the CFC used in flexible urethane foams is emitted either immediately on the foam production line or soon thereafter in curing-storage in the plant.

- There is at least one alternate blowing agent, methylene chloride, which is being used in some current applications, is available in large quantities, is lower in cost, and is presumably acceptable from the point of view of toxicity.
- The costs to industry resulting from government actions restricting CFC use are likely to be low since the alternate--where applicable--is significantly lower in cost than the currently used F-11.
- Since the CFC pneumatogen is emitted promptly, it does not (and cannot) serve any functional use in the finished foam. It is used in manufacturing because it contributes to better foam quality and therefore to improved performance of the finished product in cushions and mattresses, for example, and substitution of other blowing agents may result in a performance penalty. In contrast, the CFC used in production of rigid foam is retained for a long time, and its presence improves the insulation capability of the product, which is essential to satisfactory product performance.

A number of technical alternatives for effecting a reduction in chlorofluorocarbon emissions from flexible-urethane-foam production deserve consideration.

Recovery and Recycling of CFC Blowing Agents

Very large quantities of air are blown through the tunnels in which foam slab stock is produced. This extensive air flushing is required in order to dilute and vent relatively high concentrations of isocyanates from the work area. Toluene diisocyanate is toxic, and there are strict limits set by the Occupational Safety and Health Administration on the quantities of this reactant to which workers can be exposed.

Recovery of the CFC from the air stream is possible using activated charcoal or other absorbers, and some brief experiments have shown that recovery of a significant fraction of CFC by this means is feasible. However, the recovered CFC would be contaminated with toluene diisocyanates and other reaction products. Separation of these components from the CFC would also have to be provided for. The Rand study estimates the potential for recovery to be between 30 and 80 percent. The capital costs of modifying existing plants to permit CFC recovery would be very high, since both the processing air and the vented air from the entire plant would have to go through the CFC scrubbing/recovery process. For these reasons, recovery and recycling of CFCs does not appear to be a promising approach.

Partial or Complete Substitution of Non-Ozone-Depleting Blowing Agents for CFCs

Flexible urethane foams are normally blown with a combination of CO_2 (produced by a reaction involving water and isocyanate) and a liquid vaporizing pneumatogen such as F-11 or methylene chloride (CH_2Cl_2). Because methylene chloride is lower in cost than F-11, this pneumatogen is already being used for economic reasons in a major fraction of flexible-urethane-foam applications. Use of methylene chloride is highest in slabstock, lower in molded foams, and lowest in the supersoft (1.2 lb/ft^3 density) foams.

A number of problems involving processing, discoloration of product, toxicity of pneumatogen, and odor, that have slowed or prevented widespread conversion to the lower-cost methylene chloride, now appear to have been resolved. Processing problems have been eliminated by reformulation. Stabilizers have been incorporated that minimize discoloration. Recent reports from Dow[1] and Eastman Kodak[2] suggest that toxicity is minimal. There remains only the objectionable odor of CH_2Cl_2, and that is a problem only in the processing plant--not in the product--and can be overcome by proper ventilation. As a result, optimistic industry forecasts are that 85 percent of total flexible urethane production could utilize CH_2Cl_2 within a relatively short period of time (2-5 years), and the remainder (certain molded and supersoft foams) could be converted to CH_2Cl_2 use in a longer time period. It is the supersoft foams, however, that now use the largest quantities of CFC.

Hydrocarbon blowing agents can also be used in urethane-foam production but have been little developed in industry because of the attendant fire hazard. Hydrocarbon blowing agents might nonetheless be used alone (under appropriate processing conditions) or in combination with CO_2, which may provide a noncombustible atmosphere.

Thermally decomposing blowing agents such as Porofor N, Nitrosan, or other similar chemical blowing agents are capable of releasing nitrogen or carbon dioxide and can be used to supply at least part of the pneumatogen system for flexible foams, but at a very high cost.

Alternate fluorocarbon blowing agents that presumably do not contribute to ozone depletion are also available and could be developed for use in flexible urethane foams. However, the cost of these alternates is very high (compared with that of F-11), and processes for producing them in quantity are perhaps 7-10 years away.

Reducing the Quantity of High-CFC Foams Produced

This method of achieving reduction in use and emissions of CFCs from flexible urethane foams is addressed in the Rand study. Since the higher percentages of CFCs are used in the supersoft foams, it follows that reducing output of these products will be more effective than an equivalent reduction in output of slabstock. A variation on this approach is to downgrade (increase the density of) supersoft foam and thereby use less CFC.

Changes in Foam Technology

Mechanical frothing using an Oakes-type mechanical mixer could be used to introduce air or inert gas into the polymerizing urethane components to produce a fine-celled foam. This technique is now being used in the urethane industry to a very limited extent for the production of shoe interlining and similar applications. Presumably the density of these foams could be further reduced by auxiliary blowing agents such as methylene chloride. Another approach would be to inject air or an inert gas such as N_2 or CO_2 into a mass of the reacting flexible-foam components in a manner analogous to those used in the production of elastomeric PVC foams (Fallalay Elastomer Process). A third possibility would be the use of bead materials, such as expandable polystyrene foam beads or low-density glass beads, as additive components in the flexible urethane process. A final alternate technology would be frothing of appropriate urethane/urea emulsions (in a manner similar to those used for production of foam rubber).

Except for mechanical frothing, these alternate processes should be considered long-range possibilities that would have to be explored for both technical and economic feasibility. They all have the advantage that they eliminate the requirement for CFCs in the production process.

Activated charcoal has been tested on a plant scale for removing CFCs from urethane foam manufacturing plant air. New technology might be developed wherein the CFC-containing air is passed through a "spheropore" filter composed of interlocked chains of lightly crosslinked polymer beads (spheres) in which the CFC is readily soluble. Such absorption columns could be charged and discharged in a sequential manner and could be more efficient scrubbers than activated charcoal.

RIGID URETHANE FOAM

The chemical reactions of isocyanates with polyfunctional polyols to produce closed-cell rigid polyurethane foams are similar but not identical to those involved in flexible urethane foam production. The polyols or resin components have more reactive groups (higher functionality) and are initially lower in molecular weight. Further, the resins may be based on either polyols or other compounds containing active hydrogen atoms including phenols, amines, organic acids, and water. The isocyanates used in rigid-urethane-foam production will also usually have a higher functionality than those used in flexible foams. All of these factors contribute to a high rate of reaction, a large temperature increase, and concurrent production of a highly crosslinked thermosetting product. Because of the large amount of heat generated, the vaporization of the low-boiling pneumatogen serves as an effective heat sink to moderate the reaction.

Another type of chemically modified rigid polyurethane foam is the isocyanurate foams, which are made from a large excess of polymeric isocyanate and smaller amounts of polyols and employ special types of catalysts. These isocyanurate foams are characterized by higher heat resistance than conventional rigid urethane foams. They also use F-11 and in some cases F-12 (for froth foams). Isocyanurate foams are used primarily in the construction industry either in the form of continuous board stock, building panels, or sprayed foam. The proportion of isocyanurate to conventional rigid polyurethane foams is increasing steadily.

The blowing agents used in rigid-foam production can be the same ones used for flexible foams (CO_2, vaporizing liquids, thermally decomposing chemicals). However, if the foams are to be used for insulation, then F-11 is required in order to obtain products with better insulating capability than glass wool or other insulating materials. There are other organic compounds whose gases have thermal conductivity equal to that of F-11, but none of the currently known ones combine this feature with the other desirable properties of F-11 (low toxicity, nonflammability, boiling point near room temperature, low rate of permeation, for example).

The plant production of rigid urethane foams utilizes the same type of complex mixing and dispensing equipment used for producing flexible foams. The foaming can be done continuously or batchwise. One important process difference, attributable to the faster reaction rate of the rigid products, is that the foams can also be applied by spray procedures. The latter is growing in importance for many foam-in-place insulation applications.

As with the flexible foams, the physical properties of the rigid polyurethane foams are strongly influenced by the chemical composition and functionality of the isocyanate and resin (polyol) selected to make the product. Fire retardance, for example, can be markedly improved by selection of highly aromatic isocyanates and resins as well as incorporation of suitable flame retardants, either in the form of additives or as reactive components. Thus a wide range of chemical compositions is used to achieve specific properties.

In rigid foams, the strength properties are also highly (exponentially) dependent on foam density. Strength decreases and open-cell percentage increases as densities are brought below 2 lb/ft^3. The rate of diffusion (permeation) of the pneumatogen out of the foam depends strongly on both the chemical composition and the density of the foam product, even when density is sufficiently high to produce dimensionally stable closed-cell foams. However, too high a density detracts from the insulation quality of the foam.

It appears that reducing CFC emissions from the production of rigid urethane foams cannot be readily accomplished without excessive economic or performance penalty. There are several notable differences from flexible foams in both the function of the CFC and in the size and number of emission sites.

- In contrast to flexible urethane foams, which are prompt emitters, the CFC emissions from rigid urethane foams occur slowly over a long period of time at a multiplicity of small sites. Depending on whether the foams have metal foil or other impermeable surface skins, e.g., gypsum boards and metals, the half-life retention time may be 10 to 20 years or even longer. Thus, emissions of

CFC from rigid urethane foams occur at many separate sites with no one source supplying a significant quantity of CFC.

- Because of the long-term retention of the CFCs in rigid urethane foam, they add little immediate increase to the concentration of potentially ozone-depleting chlorofluorocarbons in the atmosphere. However, since recovery does not appear practical, in the long run all of this banked CFC will eventually appear in the stratosphere and will contribute at that time to further ozone depletion. Thus, in contrast to flexible-urethane-foam emissions, strategies that bring about short-term reductions in emissions from rigid foams (e.g., foam cladding, reduced manufacturing losses) only increase the amount that will be banked and emitted later. The Rand study estimates that for the rigid urethane foams produced in 1977, about 32 percent of the total CFC emissions occurred during manufacture, 54 percent will occur during normal use, and 14 percent will occur on disposal.
- Because of the large number and small size of the emission sources, recovery and recycling of the CFC from rigid insulating foams appears to be completely impractical unless refrigerators and buildings that use foam insulation are redesigned to permit ready recovery, and such recovery is mandated.

There are only a limited number of ways to reduce emissions from rigid urethane foams while continuing their production and use in essential insulation applications. Several of these alternatives are described below. None of them is attractive as either an immediate or a longer-term measure, and all involve large economic or other penalties.

Recovery and Recycling of CFC Blowing Agents

Emissions of CFCs from rigid polyurethane foams occur at three different stages: manufacturing, normal use, and disposal.

Manufacturing: Losses of CFC in manufacturing occur only to a minor extent in the polymerization process since the product has a high percentage of closed cells with the CFC liquid and vapor trapped therein. Especially where the foam is foil clad during production, the polymerization losses are minimal. The principal manufacturing losses in slab or board stock for insulation take place during finishing operations such as sawing and trimming. There are differences of opinion concerning the amount of CFC loss that occurs.

Rigid-urethane foam-in-place and other unfaced foam will probably have higher initial manufacturing losses than will foil-faced foam. Requiring CFC recovery and recycling by the foam manufacturer could probably reduce early (prompt) emissions to 50 percent of present levels. This may indeed be desirable; moreover, the fact that the number of emitting sites is small and the total emissions per site relatively large makes it practical to implement. There are also potential economic incentives for recycling that may make this approach relatively palatable. However if the reduction is achieved by preventing CFC escape from the foam, rather than by recycling the CFC that does escape, it would serve only to increase the CFC bank, i.e., the amount that will be emitted later.

Normal use: The only known means of reducing emissions from rigid urethane foams during normal use are

(a) make the urethane less permeable to CFC (i.e., less soluble);
(b) require foil or other impermeable skins on all urethane rigid foam.

The first of these alternatives is incompatible with other processing requirements that the pneumatogen be soluble in the urethane precursors. However, the effects of systematic changes in chemical composition to determine to what extent permeation of CFC can be reduced has not been extensively explored. Increasing the foam density will reduce the rate of permeation but if carried too far detracts from insulation quality. Both of these approaches are worth study as long-range methods to reduce in-use emissions.

The second alternative--requiring foil or other impermeable facings on all rigid CFC-blown polyurethane closed-cell foam for insulation and other applications--could have immediate short-range benefits. Further, the technology to implement this strategy is already available and is being applied to a significant extent. Present building code regulations already require the use of a facing, e.g., gypsum board, cementitious coating, or metal, on rigid foams for building use. There should be only a small economic penalty for this process modification. However, the long-range effect of decreasing the in-use CFC emissions will be to increase emissions at disposal.

Disposal: Reducing emissions at disposal would be a challenging task, hard to implement and difficult to enforce. The difficulty stems largely from the large number of sites (literally millions) and small amount of emissions per site.

As a start, implementation of this alternative would require redesign of, for example, refrigerators, houses, and trucks--wherever this foam insulation is used--to permit it to be recovered intact when its useful life is completed. Further economic incentives and policing would be required to ensure recovery and recycling of the CFC at disposal time. Cost of recovery and purification for recycling is also likely to be high.

On an overall basis, elimination of disposal emissions does not appear to be economically or practically feasible.

Partial or Complete Substitution of Non-Ozone-Depleting Blowing Agents for CFCs

There is no currently known substitute for the CFCs in rigid foam that will allow their excellent insulating properties to be maintained. Development of a suitable alternate is expected to require extensive research efforts over an extended period of time.

Methylene chloride, which is a viable substitute for flexible foams, is too strong a solvent for the polymer, destroys the closed-cell structure, causes swelling, and results in foams with inferior strength and poorer insulating properties. All attempts thus far to substitute CH_2Cl_2 for F-11 have been singularly unsuccessful. Major producers say that use of CH_2Cl_2 in rigid, closed-cell urethane foams is not foreseeable.

Good-quality closed-cell polyurethanes can be produced by non-CFC pneumatogens such as CO_2, and early urethane foams were all made this way. However, the major current use of rigid urethane foam is in insulation, where the lower thermal conductivity obtained with F-11 is a vital factor in the cost performance of this product relative to competitive materials such as glass wool.

Certain other low-boiling-point organic compounds (e.g., cyclopentane/acetone azeotrope) have also been evaluated with a limited degree of success in rigid-urethane-foam preparation. These solvents could present a fire hazard, and the insulation (K-factor) is not so good as in F-11 blown foams.

Restricting Production of Rigid Polyurethane Foam Produced with CFCs

Restricting or rationing the use of CFC in rigid-urethane insulation foam carries with it a heavy economic and energy penalty, especially with energy costs for heating and cooling of homes rising rapidly. A limited reduction in CFC emissions could be obtained by restricting use of F-11 blowing exclusively to closed-cell rigid foams used for insulation.

Changes in Foam Technology

There are four long-range, technically possible changes in rigid-urethane-foam technology that, with sufficient research, might lead to means for replacing the currently used F-11.

- Further intensive research effort might uncover an environmentally safe, economic substitute for F-11. The likelihood of finding such a material soon is remote, since much effort has already been expended in this direction by industry in attempts to avoid the original Frost patent (which discloses the use of CFC as blowing agents in foams).
- Frothing foam techniques might be further developed to enable low-density rigid foams to be developed with an inert low-thermal-conductivity gas such as argon. This approach could work but would undoubtedly be more expensive than current pneumatogens.
- It may be possible to tailor a urethane rigid-foam composition that could use methylene chloride. Urethane technology is versatile, and by selecting and using appropriate polyols and isocyanates it should be possible to change the solubility parameter of a polymer so that it would not be excessively solvated (i.e., softened or plasticized) by methylene chloride. Alternatively, solvent swelling could be reduced by higher crosslink density in the polyurethane. It should be possible to determine the technical and economic feasibility of this approach within 3-5 years. Again, however, the new raw materials are likely to be more expensive than the present ones.
- A final long-range technical approach would be to make open-cell rigid-urethane foams, apply impermeable surface skins, and produce a reasonably good vacuum inside the package. This approach may be very feasible for

refrigerators and similar insulation where the vacuum could be periodically renewed. The approach should be economic and completely safe environmentally. It would be difficult to apply to insulation used in housing, however. Nonetheless, this may be the most feasible of the long-range alternate technologies.

REACTION INJECTION MOLDING

Reaction injection molding (RIM) is a new and rapidly growing sector of the urethane industry. The chemistry involves the rapid reaction of pneumatogen-containing polyols and isocyanates, similar to those used in flexible foams, to form semirigid and rigid polyurethane moldings for use in motor vehicles and buildings. In a recent modification, reinforcing materials such as "milled" glass fibers and other fibers are being used to both lower cost and increase the modulus of the product in new types of machinery to produce reinforced RIM (RRIM) parts (side panels, doors, and other body components).

In this process the pneumatogen-containing monomers (1-10 percent F-11) are impingement mixed and precisely metered into a closed, vented mold so as to fill it initially to 80-85 percent of volumetric capacity. In the mold the F-11 vaporizes to complete the filling of the mold at low pressure. By this means it is possible to produce very large-area, relatively thin moldings, directly from monomeric precursors on short cycles in inexpensive molding equipment. The products made in the RIM process are very high-density closed-cell foams (30-60 $\mathrm{lb/ft^3}$) that can be used in structural applications. The largest present use of RIM is for fabricating strong light front facia (shells around headlights and radiator areas) and other parts (e.g., fenders) for automobiles. The major automobile manufacturers all have RIM parts on current model cars and have plans for expanding RIM use, applying this technology to further reduce car weight and cost. There is also increasing use of this technology by the construction industry for doors, window frames, and other parts, as well as by the appliance and furniture industries.

The total 1978 U.S. production of RIM urethanes is estimated at 60,000,000 lb, with projected 1990 production of 150,000,000-300,000,000 lb. Since the product contains 2.5-5 percent F-11 (at 3.5 percent average), this 1978 production utilized about 2,000,000 lb of F-11. The use and growth of RIM technology in the United States is being paralleled in Western Europe, especially Germany, and to a lesser extent in Japan.

RIM technology represents a new use for high-density urethane foams whose growth is projected to be rapid. RIM moldings are very slow emitters (even slower than rigid foams) because of the closed-cell structure, the high density of the product, and the presence of surface skins. Manufacturing emissions are small, and almost no emissions occur during normal use. Nearly all of the emissions will occur at disposal. Thus, although the quantity of F-11 used per pound is small, the total amount of CFC entering the "bank" between now and 1990 could be substantial.

The prospect for reducing CFC emissions from RIM urethanes parallels that for the rigid urethane foams used for insulation, and the alternatives are essentially the same. As with rigid foam, strategies that would tend to reduce the already small manufacturing and normal use emissions will increase the amount of emissions that will be encountered on disposal.

Recovery and Recycling of CFC Blowing Agents

Because of the large number and relatively small size of the individual RIM emitting sources (e.g., auto facia), recovery and recycling of CFC-containing automobile parts on disposal would be difficult but not impossible. Such recovery would, however, be uneconomic and would require legal mandates, tax incentives, and vigorous policing to implement. The use of RIM in construction applications presents even greater challenge to any CFC recovery-recycling strategy. Since recovery/recycling does not seem practical, substitution of the CFC in RIM products may be a more workable alternative.

Partial or Complete Substitution of Non-Ozone-Depleting Blowing Agents for CFCs

The CFC used in RIM production contributes several process advantages and significantly improves the quality of the finished part as well. It facilitates mold filling, reduces the total clamping pressure required to keep the mold closed, and reduces the large temperature increases that would otherwise occur. It yields a part whose surface finish is smoother, more paintable, and free of "sink marks." Since there is no requirement for very low density (as in foam cushioning) or low thermal conductivity (as in insulation) the list of possible substitute pneumatogens is broader than for the flexible and rigid urethane foams. However, substitution of other blowing agents may require extensive reformulation of products.

Methylene chloride: A major portion of current RIM production consists of flexible urethane compositions that are reasonably compatible with CH_2Cl_2. However, the high boiling point of CH_2Cl_2, compared with F-11, presents processing problems. Changes in the chemistry of the system to modify the reaction rates, along with other reformulations, will be required. The prospects for success in substituting CH_2Cl_2 for F-11 are fair to good if industry is given the incentive and some time to implement the change. The lower cost of CH_2Cl_2 will also encourage development of this alternative.

Air, N_2, CO_2, and other blowing agents: Because the amount of foaming in RIM moldings is so low, other foaming processes such as frothing may be applicable. In frothing, a gaseous pneumatogen is dissolved or dispersed in the urethane reactants under pressure, and frothing (foaming) takes place on release of the pressure.

Possible candidates for RIM frothing include air, N_2, and CO_2, all of which are plentiful, low cost, and innocuous to the environment. Low-boiling-point organic compounds (non-CFC) may also be used as either liquid or gaseous pneumatogens. Since the quantity used is small, fire hazards, if present, may be small.

Restricting RIM Polyurethane Production

Restricting the production of RIM moldings involves a substantial economic and energy penalty and would stifle the growth of this new and promising technology. The substitution of RIM plastic parts for metal in automobiles is energy efficient in that these parts require less energy to produce than the metal parts they replace. Further, because the RIM parts are significantly lighter than metal parts, application of this technology in the automobile industry contributes to lower weight and attendant fuel saving.

Reducing CFC emissions via lower RIM production does not appear to be necessary since prospects for eliminating the use of CFCs in RIM appear good.

Changes in RIM Foam Technology

No major breakthrough in foam technology is required to reduce CFC emissions from RIM production. As already noted, alternate foaming agents such as CH_2Cl_2 and techniques such as frothing are foreseeable for near-term development to enable production of RIM parts without CFC use or emissions.

NONURETHANE FOAMS (OPEN AND CLOSED CELL)

A wide variety of nonurethane foams are produced in the United States. These foams may be thermosetting or thermoplastic, flexible or rigid, and open or closed cell. However, of these nonurethane foams, the only ones that use and emit significant quantities of CFC pneumatogens are those made from thermoplastic polystyrene and polyolefin (polyethylene and polypropylene).

The most important applications of these polystyrene and polyolefin foams are the following:

- Extruded polystyrene sheet and polyolefin packaging materials;
- Extruded polystyrene board (Styrofoam) for insulation;
- Expanded polystyrene bead foam for food containers, packaging, flotation, and other purposes.

There are important differences between the extrusion and bead-molding processes. In the extrusion of sheets and boards of polystyrene, granules are fed to a heated thermoplastic screw-type extruder, where they are melted to become a high-viscosity liquid. The granules may or may not contain CFC blowing agent. If they do not contain CFC, this ingredient is injected into the melt, along the barrel of the extruder, and mixed thoroughly in the polymer, which expands and foams on exit from the extruder. If the pneumatogen has been incorporated into the beads by the raw material supplier, the melt injection is unnecessary, and the granules are simply melted (thermally plasticized) as they go through the extruder, and foaming takes place as the melt exits the die. Polyolefin foams can be produced by a similar process.

Bead foam molding is quite different. Small polystyrene beads that contain the required quantity of pneumatogen are prepared by the raw material supplier. These beads are first pre-expanded, "rested," then further expanded in a closed, steam-heated, vented mold to produce low-density foam products in which bead boundaries are readily seen.

Originally, much of the nonurethane foam industry used pentane hydrocarbon as the blowing agent. However, for both fire safety and better foam quality, most of the current pneumatogen is F-12, with significant quantities of F-114 and some F-11 also being used.

Most of the CFCs that are used in the polystyrene and polyolefin foams are emitted quickly, that is, in the processing plant or soon thereafter. Certainly this is true for extruded polystyrene sheets, polyolefin foams, and expanded polystyrene bead foam. The Rand study suggests that most emissions take place in the first year of product use. However, a recent Dow report[3] maintains that at least in their extruded polystyrene insulation boards, the emission time is significantly longer. It is fair to conclude that rigid polystyrene insulation foam boards retain their CFC much longer than do the flexible urethane foams but perhaps not so long as the closed-cell rigid urethane. Thus for three of the four categories of nonurethane foam, losses will be greatest during processing and soon thereafter; comparatively much lower in normal use; and little or none at disposal. CFC emissions from polystyrene foam insulation boards will be similar to those from rigid urethane insulating foams--small during manufacture and larger throughout normal use and on disposal.

Most of the extruded polystyrene foam sheet is used in convenience-food packaging applications and in institutional food service. For these uses it is essential that the blowing agent be nontoxic and leave no residual odor or taste.

The technical and economic feasibility of alternatives for reducing CFC emissions from nonurethane foams varies with the specific process and application. The promptness of the pneumatogen emissions also varies with the process and product.

Polyolefin foams blown with F-12 or F-114 will emit 50 percent of their CFC within one week. The extruded polystyrene insulation foam may lose up to 15 percent in manufacture, with continuing emissions during normal use and a significant residual of CFC at the time of disposal.

Recovery and Recycling of CFC Blowing Agents

Polyolefin foams: Most of the emission from polyolefin foams takes place during manufacture or immediately thereafter. Therefore, recovery and recycling is technically possible. However, recovery of the F-12 would be fraught with the same problems as cited for CFC recovery from flexible urethanes. The problem is further amplified since F-12 boils at a considerably lower temperature than F-11 and would therefore be more difficult to condense and recover. Recovery does not appear to be economical or practical. Large capital investments would be required, and the likely outcome is that the industry would effectively vanish.

Extruded polystyrene foam sheet: Extruded polystyrene foam sheet constitutes a major fraction of nonurethane foam production and CFC emissions. Almost all of the CFCs (F-11 and F-12) used as blowing agents are emitted promptly during manufacture or soon thereafter. The problems of recovery and recycling are very similar to those of flexible urethane foams and polyolefins. Absorption on beds of activated charcoal is possible but not likely to be economic or to provide a high percentage of CFC recovery.

Polystyrene foam insulation board (Styrofoam): Styrofoam is blown primarily with low-boiling F-12. Losses at the manufacturing plant are low, and diffusion of the pneumatogen from either clad or unclad boards later on is very slow, with clad board having the slowest emissions.

Recovery of in-plant CFC emissions would confront the same problems and unfavorable economics listed for rigid polyurethane foam. The percent of recovery would still be low since most of the CFC goes out of the plant with the product.

Recovery and recycling during normal use and on disposal does not appear to be any more feasible than for rigid polyurethane foams. Cladding will reduce emissions during the early part of the use life (if it is not too long) and increase emissions at disposal. Recovery at disposal has the problem of many small sites and would require collection of the used product to a central station for effective recovery.

No satisfactory substitute blowing agents are known, and considerable time and research would be required to develop one. Currently available alternatives invoke large penalties either in insulating performance or in terms of safety hazards.

Pelaspan-Pac: This product is an F-11-blown loose-fill material used primarily for packaging applications. The foaming is done at each customer's site. Emissions are prompt and 90 percent complete by the time the foamed product leaves the foam fabricator's plant.

Recovery and recycling appears to be impractical for this product for the same reasons as cited for recovery of F-11 from flexible-urethane foam manufacture.

Bead polystyrene foam: At one time all the pneumatogen used in bead-foam production was pentane. This hydrocarbon blowing agent presents strong fire hazards in the production plant and in the foam molder's shop.

Recovery and recycling of F-11 from any bead-foam product of this type would be impractical for the reasons already cited.

Partial or Complete Substitution of Non-Ozone-Depleting Blowing Agents for the CFCs

The prospects for substituting other chemicals for the F-12 used in polystyrene closed-cell insulation foam are no better or worse than those cited for rigid-urethane foams. It may be possible to find a suitable replacement eventually but not immediately. The requirement for proper compatibility and long-term retention (slow diffusion) greatly limits the choice of substitute blowing agents.

In the other uses where the pneumatogen is fugitive (polyolefin foams, extruded polystyrene sheet foams, and Pelaspan packaging foams), substitute pneumatogens may be somewhat easier to find. However, there will again be strong economic or safety (e.g., fire hazard) penalties attached to any foreseeable replacements.

Restricting the Production of Nonurethane Foams

As with the rigid polyurethane foams, reducing the production of the rigid nonurethane foams used for insulation appears likely to carry a heavy economic penalty. Reducing the production of nonurethane foams used in packaging might stimulate increased use of other packaging materials such as paper.

New Foam Technology

The possibilities associated with new technology are the same as those applying to rigid urethane foams. This is not a near-term alternative.

This Appendix draws largely on the Rand study and on information provided to the CARCE Panel on Industrial

Technology in oral or written form by the following organizations:

Dow Chemical Company
E. I. du Pont de Nemours & Company
Jim Walter Corporation
Single Service Institute
Society of the Plastics Industry
Sweetheart Plastics Division, Maryland Cup Corporation
Tenneco, Inc.

REFERENCES

1. Dow Chemical Company, "Health Evaluation of Fiber Production Workers With and Without Occupational Exposure to Methylene Chloride," to be published, 1979.
2. B. R. Friedlander, T. Harne, and S. Hall, "Epidemiologic investigations of employees chronically exposed to methylene chloride," *J. Occup. Med.* 20(10), Oct. 1978.
3. Dow Chemical Company, "Comments on Non-Aerosol Propellant Uses of Fully Halogenated Halocarbons," submitted to EPA, October 1977.

APPENDIX K SUMMARY OF THREE BENEFIT-COST STUDIES

Each of the three studies--Bailey (1978), d'Arge *et al.* (1976), and Systems Control, Inc. (1978)--is reviewed with respect to (a) policy alternatives considered, (b) data and assumptions used, and (c) results and policy implications. The data and assumptions used as bases for estimating benefits in the three studies are summarized in Table K.1. All three studies predate the U.S. ban on nonessential aerosol uses of CFCs, so that a 50 percent reduction in emissions corresponds roughly to action that has since been taken.

BAILEY: "COSTS AND BENEFITS OF CHLOROFLUOROMETHANE CONTROL" (1978)

Policy Alternatives

Three emission scenarios are considered: the status quo (continued growth in CFM emissions at 10 percent per year until 2020, when emissions would cease); a freeze on growth of emissions in 1974; and a total ban on emissions in 1978. The net benefits of a 1974 freeze and the 1978 ban are measured relative to the status quo.

Data and Assumptions

The effect of CFM emissions on ozone was based on reports of the Committee on Impacts of Stratospheric Change (1976a; 1976b; 1977) and on a paper by Wofsy *et al.* (1975). Under unrestricted growth of CFM production, it was estimated that ozone depletion would be 47 percent by 2020 and would approach a limit of 75 percent after 2050; with a

TABLE K.1 Bases for Estimation of Benefits in Three Benefit-Cost Studies of CFC Emission Reduction

	Study		
Component of benefit	Bailey (1978)	d'Arge *et al.* (1976)	SCI (1978)
UV effects			
Skin cancer	$4400/case	$325-1292/case	$325-1292/case
Morbidity			
Medical costs and wages	$850/case	$325-1292/case[a]	$325-1292/case[a]
Willingness to pay	$550/case	--	--
Mortality	$3000/case[b]	--	--
Materials weathering	Cost of additives[a] to avoid damage	Cost of additives[a] to avoid damage	Cost of additives[a] to avoid damage
Cancer eye in cattle	--	--	$70 million to $350 million per year per 1% increase in UV-B
Temperature effects			Considered insignificant[f] (detail not given)
Urban resources			
Fossil-fuel demand	--	Difference in energy for heating[c,e]	[f]
Electricity demand	--	Change in electricity demand, including air conditioning[d,e]	[f]
Clothing and housing	--	Difference in expenditures[c,e]	[f]
Highway maintenance	--	Cost required to maintain roads in equivalent state[c,e]	[f]
Forest products	--	Change in output[c,e]	[f]
Marine resources	--	Change in output[c,e]	[f]
Cotton	--	Change in output[c,e]	[f]
Corn	--	Change in output[d,e]	[f]

[a] From CIAP study (U.S. Department of Transportation, 1976).

[b] $330,000 per fatality × 0.009 fatalities/cancer.

[c] Net benefit from warming.

[d] Net cost from warming.

[e] Derived using methodology from CIAP study.

[f] Estimates taken directly from CIAP study. The cause of the apparent discrepancy between the d'Arge *et al.* and SCI estimates of economic impact of temperature change is unclear, given that both are based on the same source. Apparently, d'Arge *et al.*, in updating and modifying the original CIAP analyses, derived more substantial adverse effects of warming because of air-conditioning requirements.

freeze at 1974 emission levels, there would be an estimated 10 percent depletion by 2020 and 20 percent by 2120; a ban in 1978 would lead to an estimated 3 percent depletion in 1990, dropping to 1 percent after 2080. Effects of ozone on UV-B and of UV-B on skin cancer were estimated from the IMOS (1975) report and incorporated a 20-year lag of cancer incidence behind increased UV-B flux.

Methods used for estimating economic costs and benefits were described in Chapter 7 of this report. The benefits considered were reduced skin-cancer incidence and reduced expenditures to prevent weathering of materials.

Costs of CFM emission reduction were estimated as the loss in consumer surplus according to the method of derived demand. A discount rate of 11 percent was used throughout. Uncertainty was handled by defining, around the central estimate of each parameter, a 95 percent probability range. By convolving these distributions, upper- and lower-bound estimates of benefit and cost were derived.

Results and Implications

The results of the study are summarized in Table K.2. Expected costs exceed expected benefits for both control options; the ratio of benefits to costs is 0.42 for a 1978 ban and 0.47 for a 1974 freeze. Benefits from materials weathering exceed health (cancer) benefits in all cases. The results are undoubtedly sensitive to the choice of an 11 percent discount rate, but unfortunately no sensitivity analysis is presented.

An informal analysis of a partial ban strategy is also provided. The expected present value social cost per pound of CFM emissions is calculated to be about 25¢. The derived demand curve for CFMs indicates that if this cost were charged to producers, the market would respond by cutting back production by about 50 percent (mainly aerosols). Further reductions would not be justified, according to this model.

D'ARGE, EUBANKS, AND BARRINGTON: "BENEFIT-COST ANALYSES FOR REGULATING EMISSIONS OF FLUOROCARBONS 11 AND 12" (1976)

Policy Alternatives

Two separate sets of policy alternatives are considered. First, a "steady-state" analysis evaluates the costs and benefits of complete or product-specific partial bans on F-11 and F-12 relative to 1973 production levels. The status quo scenario, in this analysis, corresponds to continuation of 1973 production levels into the indefinite future, with no growth considered. Second, a set of six "international restrictive strategies" are considered and compared with the baseline scenario of continued emissions at 1973 levels. The six consist of three degrees of international cooperation (the United States unilaterally,

TABLE K.2 Results of Bailey (1978) Study

	1978 Ban			1974 Freeze		
	Upper-Limit Value[a]	Central Value	Lower-Limit Value[b]	Upper-Limit Value[a]	Central Value	Lower-Limit Value[b]
Benefits of Control ($$10^6$)						
Cancer	6,900	1,100	180	5,200	820	130
Materials	10,700	2,300	500	7,000	1,500	320
Total[c]	15,000	3,400	770	10,000	2,320	530
Cost of Control ($$10^6$)						
Total	22,000	8,000	3,000	13,000	4,900	1,800

[a] True value assessed to exceed this value with probability 0.05.

[b] True value assessed to lie below this value with probability 0.05.

[c] Totals for upper- and lower-limit values differ from sum of above two rows because of the handling of uncertainty through independent probability distributions.

the United States and OECD,* and the entire world), each with two scenarios for the phasing in of controls. For example, one worldwide control scenario provides that world production drops to 75 percent of 1973 levels in 1977, to 50 percent in 1978, to 45 percent in 1979, to 35 percent in 1980, and 20 percent in 1981 and thereafter; the U.S. unilateral control scenario provides that U.S. production drops to 50 percent of 1973 levels in 1977, to 30 percent in 1979, and to 10 percent in 1981 and thereafter.

Data and Assumptions

Estimates of ozone depletion were based on the then unpublished work by Crutzen and Isaksen. Under continued emissions at 1973 levels, estimated ozone depletion in the long run would be 9 percent (compared with Bailey's estimate of 20 percent). Effects of ozone on UV-B, and of UV-B on skin cancer, were estimated to lead to a 2 percent increase in skin-cancer incidence per 1 percent decrease in ozone, but the dose-response effect was assumed to be delayed according to estimates of Cutchis (1975). Effects of ozone reduction on temperature and climate were estimated using two different climatic models, those of Coakley and Ramanathan.†

Benefits of CFM emission reduction include (1) skin-cancer reduction (savings in medical expenditures and lost earnings), (2) material weathering reduction (savings in expenditures for protective materials), and (3) preventing the net U.S. costs of a temperature increase. These are summarized in Table K.1. The temperature/climate benefits include primarily savings in energy costs for air conditioning and cooling. Effects on marine resources, forest resources, other urban resources, corn, and cotton were included. For all of these (except corn) the effect of warming was found to be a benefit, but not enough to compensate for the air-conditioning effect. Because of the controversial nature of the climate estimates, most results were presented both including and excluding these benefits.

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*OECD is the 25-nation Organization for Economic Cooperation and Development.

†Ramanathan's model estimates an increase of 0.02°C for each 100 parts per trillion of CFM in the upper atmosphere; Coakley's model estimates an increase of 0.01°C for each 1 percent ozone reduction.

Costs of CFM emission reduction were estimated by three methods corresponding roughly to three assumptions about the availability of substitutes for CFMs: (1) total consumer surplus lost (assuming no substitutes); (2) derived demand surplus (allowing for substitutes) for all products except refrigerants, with substitutes for refrigerants becoming available after 10 years; and (3) derived demand surplus for all products. Most results are presented under each of these economic assumptions.

Discount rates of 3 percent, 5 percent, and 8 percent per annum were used for purposes of comparison.

Uncertainty was not considered explicitly, and point estimates were used. No sensitivity analysis was provided with respect to the uncertain physical or biological parameters. Uncertainty in the cost estimates was acknowledged by presenting all results under each of the three economic demand assumptions described above (no substitutes; no substitutes except, after 10 years, for refrigerants; substitutes).

Results and Implications

The analysis addressed (1) the economic feasibility of a complete ban; (2) the optimal percentage level of steady-state reduction in U.S. use of F-11 and F-12 from 1973 levels; and (3) the economic feasibility of seven international strategies.

Table K.3 shows that the benefit-cost ratio for a complete ban varied from 0.16 to more than 5.8, depending critically on the assumptions used for costs of control (derived or consumer surplus measures) and for benefits (inclusion or exclusion of climate effects). Thus, a ban is most feasible (benefit-cost ratio far exceeds unity) when derived surplus (lower bound) is used for costs and climatic effects are included in the benefit measures (upper bound).

"Optimal" steady-state reductions in use of F-11 and F-12 are also highly dependent on the assumptions employed, including the discount rate. The "optimal" level is the point at which the sum of environmental costs and control costs, as measured by lost derived demand or consumer surplus, is minimized. Table K.4 presents the control cost functions, and Table K.5 the environmental cost functions used in the analysis. Conclusions were that

> "Given that adequate substitutes are found or are available for F-11 and F-12 and given the validity

TABLE K.3 Simple Benefit-Cost Comparisons for a Ban on Production of Fluorocarbons-11 and -12, United States, 5 Percent Discount Rate, Present Value 1974[a] (Millions of U.S. 1971 Dollars)

Measure of Costs and Benefits	Benefit[b] Estimates	Cost[c] Estimates	Benefit-Cost Ratio
Derived surplus	16,978-17,132	2,942	5.8
Final product consumer surplus[d]	16,978-17,132	107,234	0.16
Derived surplus (plus omission of temperature impacts)	621-775	2,942	0.21-0.26
Final product consumer surplus (refrigerators, mobile refrigeration systems, and automobile air conditioning uses excluded)	9,508-9,594	27,685	0.34-0.35

[a] From d'Arge *et al.*, page 6, Table 1.

[b] Measured by savings in environmental costs of 1973 level production of F-11 and F-12 in present value terms.

[c] Loss in consumer or derived surplus at 1973 use rates in present value terms.

[d] Includes consumer surplus loss for refrigerators, auto air conditioners, mobile refrigeration systems, polyurethane foam mattresses, aerosol deodorants and antiperspirants, hairsprays and care products, insecticides, pharmaceuticals, cosmetics, perfumes, deodorizers, and shaving products.

of the hypothesis that fluorocarbon emissions influence global temperature, then a reduction in U.S. production of at least 75 percent appears to be optimal. If these hypotheses are not valid, then a 0-16 percent reduction in long-run production may be optimal from the standpoint of minimizing costs to the United States."

TABLE K.4 Estimated Surplus Loss Functions[a,b,c]

A. Derived Surplus

$S(Q) = 147.004 - 2.935Q + 0.0146Q^2$

$S'(Q) = -2.935 + 0.029Q$

$S''(Q) = 0.029$

B. Consumer Surplus

$S(Q) = 5{,}647.362 - 114.724Q + 0.577Q^2$

$S'(Q) = -114.724 + 1.154Q$

$S''(Q) = 1.154$

C. Consumer Surplus with Substitution Assumption[d]

$S(Q) = 3{,}977.708 - 79.550Q + 0.398Q^2$

$S'(Q) = -79.55 + 0.796Q$

$S''(Q) = 0.796$

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[a] From d'Arge *et al.*, page 7, Table 3.

[b] Q = percentage 1973 production of F-11 and F-12. $S(Q)$ = surplus loss function.

[c] Q is defined only over the range [0,100].

[d] The assumption about substitution is that there are immediate substitutes for foams and propellants and substitutes for refrigerants after 10 years.

In interpreting these conclusions, it should be noted that the d'Arge results refer to 1973 U.S. production of F-11 and F-12, which was nearly double the present production.

In analyzing the range of multilateral and unilateral strategies, the measures of control costs, benefits, and discount rate again play an important role. Unilateral action is justified only for low discount rates, when climate impacts are included in the benefit measures, or when good substitutes are assumed to exist for CFCs.

SYSTEMS CONTROL, INC.: "TECHNOLOGY ASSESSMENT OF THE FLUOROCARBON/OZONE DEPLETION PROBLEM" (1978)

Policy Alternatives

The SCI study only examines strategies involving a complete ban on use of CFCs in the United States. However, the "optimal" timing and nature of the presumed phaseout of CFCs is explored in some detail. Thus, options considered range from immediate initiation of a 20-year

TABLE K.5 Estimated Environmental Cost Functions[a,b]

Discount Rate	Intercept	Slope	r^2
Total Environmental Cost			
3%	184.94	15.87	0.98
	(55.36)	(1.04)	
5%	96.08	7.81	0.96
	(36.57)	(0.68)	
8%	23.23	1.96	0.81
	(22.77)	(0.43)	
Skin Cancer and Materials Weathering Costs			
3%	6.29	0.46	0.99
	(0.78)	(.015)	
5%	5.89	0.33	0.99
	(0.46)	(.01)	
8%	3.88	0.16	0.99
	(0.20)	(.01)	

[a] From d'Arge *et al.*, page 10, Table 4.

[b] The estimated equation was $y = a + bx$, where y equaled annual costs commencing in 1973 in millions of 1971 U.S. dollars and x equaled the percentage of 1973 U.S. production of F-11 and F-12. Note that x is defined only over the interval [0,100].

phaseout to a phaseout that begins only when an ozone reduction of a certain level (2½ or 5 percent) is detected.* Each strategy is evaluated in terms of damages--which they term external costs--and costs of control--which they term internal costs. The best strategy in their terminology is then the one that has the least external and internal costs. This criterion is precisely the same as that of benefit-cost analysis since benefits are defined--to use SCI's term--as reduced external costs, and benefit-cost analysis suggests that the best strategy is the one where benefits exceed costs to the greatest extent.

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*The report *Stratospheric Ozone Depletion by Halocarbons: Chemistry and Transport* (National Academy of Sciences, Washington, D.C., 1979) points out the difficulties of detecting such ozone reduction.

Data and Assumptions

Benefits of CFC control include (1) reduced skin-cancer morbidity and mortality, (2) reduced materials weathering, (3) reduced inhibition of photosynthesis, (4) reduced cancer eye in cattle, and (5) reduced global warming.

Control costs include those resulting from emission controls and decreased use of CFC products during the phaseout. However, it should be noted that the study assumes that perfect substitutes will eventually be found for CFCs, so these costs "decay" to zero about 50 years after a phaseout is initiated.

Results and Implications

Figure K.1 shows the time profile of internal (control) and external (damage) costs for a strategy that assumes that a CFC phaseout is triggered at 5 percent ozone depletion. Note that without the imposition of a CFC phaseout just before the year 2000, the external cost profile would, given the SCI model, be much higher. Thus, the heart of the analysis is trading off reduced or lowered external costs (benefits) for increased internal costs (cost of control).

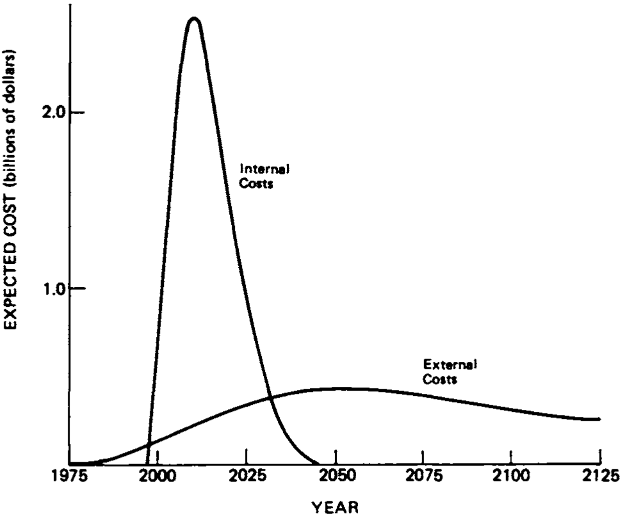

FIGURE K.1 Comparison of internal and external cost profiles (from SCI, 1978, pp. 3-20, Figure 3.13).

One possible criticism arises from the assumptions used in the analysis. The discount rates used are quite low. Since, from Figure K.1, benefits of control (reduced external costs) extend much further into the future than cost of control (internal costs), low discount rates obviously favor control. This fact, along with the assumption that control costs decay as substitutes for CFCs are found, biases the study so that a ban on CFCs is always economically feasible at some point in time. Thus the only questions for analysis relate to the timing and form that a possible phaseout might take. These are useful questions. However, the study is not structured to evaluate the appropriateness of various levels of action in controlling CFCs.

In contrast, the treatment of uncertainty in the SCI study is quite sophisticated and adds much to the analysis. For example, the probabilities of various types of climate change are identified. These probabilities are then used to calculate expected damages (the probability of level of damage times the damage). Summing expected damages over possible climate changes is technically a more appropriate way of including uncertainty in decision analysis than the usual procedure of giving a range of estimates (although it may fail to give proper weight to extreme consequences having low probability). The SCI study thus gives unique estimates of *expected* damages and control costs.

The SCI study uses an assumption for ozone depletion consistent with the projections described in Chapter 1 of this report, but considers a range for the effect from zero to five times this level. The relationships between CFC emissions, ozone depletion, and skin cancer used in the cost calculations for the previous figure are shown in Figure K.2. Here, again, a CFC phaseout is triggered at the 5 percent depletion level that occurs in 1995. Damages and control costs are only calculated for the United States, but the phaseout of CFCs is taken to be worldwide. Note the long lag of almost 70 years between peak CFC emissions and the peak skin-cancer increase.

The principal conclusion of the study is that the "wait-and-see" strategies generally perform better than an immediate (1980) phaseout. Only in the case of a zero discount rate does an immediate phaseout appear superior to waiting until ozone depletion reaches the 5 percent level. However, even for a zero discount rate, waiting for 2½ percent ozone depletion before a phaseout begins is superior to immediate action. Again, it is important to

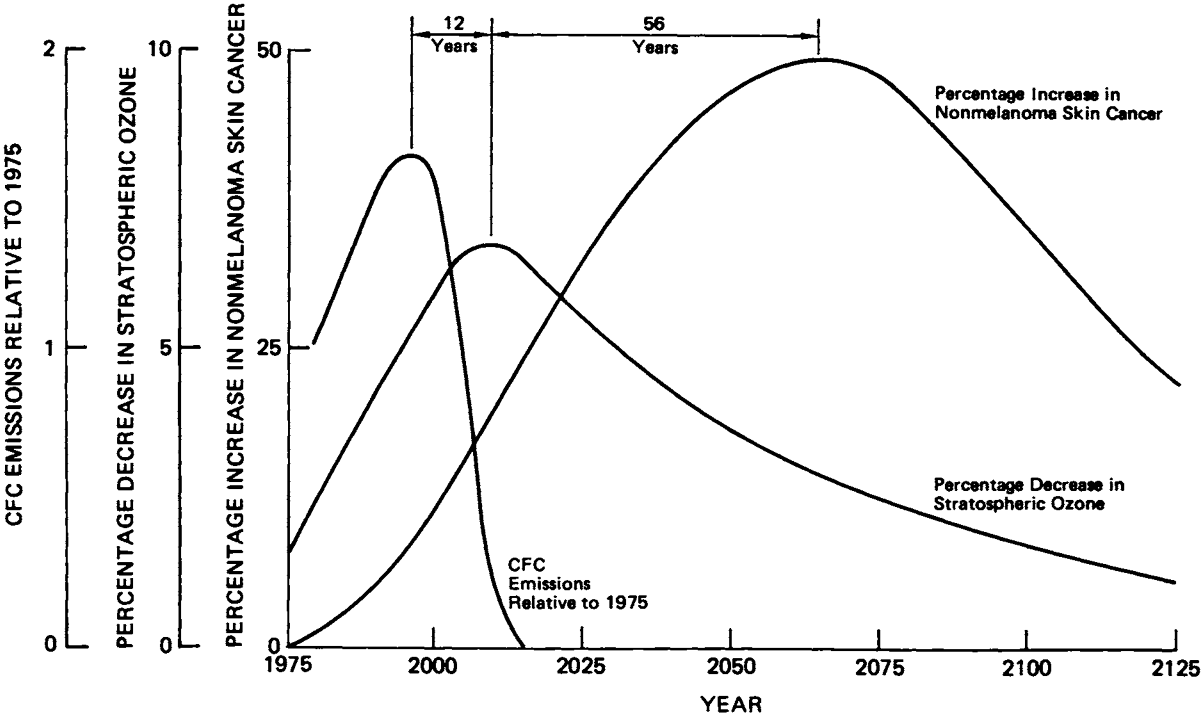

FIGURE K.2 The phase relationships among variables (from SCI, 1978, p. 3-4, Figure 3.2).

note that this analysis assumes that the phaseout of CFCs is worldwide. A unilateral U.S. phaseout of CFCs is also considered, but the overall ozone depletion profile turns out to be hardly affected by unilateral action. Control costs exceed benefits in this case.

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APPENDIX L

SOURCES OF INFORMATION - CARCE

In preparing Part III of this report, the Committee on Alternatives for the Reduction of Chlorofluorocarbon Emissions drew on information from the sources listed below. In some instances information was provided to the committee by oral presentations or written submissions, in other cases in the form of documents provided by the sponsor, EPA, and in still other instances through reference to existing documents.

Air Conditioning and Refrigeration Institute
Air Force Flight Dynamics Laboratory, Wright-Patterson AFB
American Frozen Food Institute
American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc.
Arthur D. Little, Inc.
Bureau of Business and Economic Research, University of Maryland
Chemical Manufacturers Association
Chrysler Corporation
Cook Paint and Varnish Company
Dow Chemical Company
Environmental Protection Agency
Ford Motor Company
Freon Products Division, E. I. Du Pont de Nemours & Company
General Motors Corporation
Government Research Corporation
Green Giant Company
International Mobile Air Conditioning Association
International Research and Technology Corporation
The Jim Walter Corporation
Lear Siegler, Inc.

Lockheed Missiles and Space Company, Inc.
Midwest Research Institute
Natural Resources Defense Council
Organization for Economic Cooperation and Development
Pennsylvania Engineering Company
Putnam, Hayes & Bartlett
Rand Corporation
Rockwell International
ROVAC Corporation
Single Service Institute
Society of the Plastics Industry
SRI International
Sunpower, Inc.
Sweetheart Plastics Division, Maryland Cup Corporation
Systems Control, Inc.
Tenneco, Inc.
The Trane Company
Vilter Manufacturing Corporation
York Division, Borg-Warner Corporation