Timing Regulations to Prevent Stratospheric-Ozone Depletion

James K. Hammitt
The research described in this report was supported by The RAND Corporation as part of its program of public service. Publication of the report was funded by a grant from the John M. Olin Foundation.


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Published by The RAND Corporation
1700 Main Street, P.O. Box 2138, Santa Monica, CA 90406-2138
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April 1987

RAND
PREFACE

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

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

The present report analyzes the desirability, from a global economic perspective, of immediately adopting additional regulations to limit emissions of potential ozone depleting chemicals, or delaying a decision for several years to benefit from expected improvement in scientific understanding of ozone depletion and its possible consequences.

Other papers in the series include:


Preliminary results of the research described in this report were presented at the September 1986 United Nations Environment Programme Workshop on the Control of Chlorofluorocarbons, held at Lynchburg, Virginia. The research was sponsored by The RAND Corporation, as part of its program of public service, using funds earned from its endowment and fee income. Publication of the report was funded by a grant from the John M. Olin Foundation.
SUMMARY

Emission of chlorofluorocarbons and related chemicals to the atmosphere may promote chemical reactions that reduce the concentration of stratospheric ozone and contribute to global warming (the "greenhouse effect"). Depletion of stratospheric ozone could increase the quantity of ultraviolet radiation penetrating to the earth's surface, which could have significant adverse consequences for human, animal, and plant life. However, the extent of ozone depletion and the severity of the consequences of projected emission levels are extremely uncertain. Future ozone concentrations are calculated using complex atmospheric models that have not been completely reconciled with the limited available atmospheric measurements of ozone and other trace-gas concentrations. Moreover, there are believed to be substantial lags between production and emission of potential ozone depleting chemicals, and between emissions and effects on ozone concentrations. As a result, by the time it becomes clear whether ozone depletion is an important threat to global welfare, it may be too late to prevent serious adverse consequences.

Because of current uncertainty about the likely extent of future ozone depletion and its effects in the biosphere, it is not possible to determine the appropriate level of regulations at present. Instead, this report addresses the central question for current policy: whether to adopt interim regulations to reduce potential ozone depleter emissions now, or to wait several years for improved information before deciding whether to regulate. Regulating immediately creates the risk of incurring economic costs that later prove to have been unnecessary. Waiting for better information creates the risk that emission reductions, should they be necessary, will be more costly.

The analysis takes a global economic perspective. It abstracts from issues related to international coordination of emission-limiting regulations. It is based on the following simplified decision problem: We face the choice of whether to impose emission-limiting regulations now or await better information. Regardless of the decision taken, we will learn whether emission reductions are necessary in several years. At that time additional regulations may be implemented or abandoned if necessary. The problem is structured so that both strategies impose equivalent environmental risks. The only risk to waiting for better information is that regulations, if needed, may be more costly. Thus, the analysis abstracts from the possibilities that it is already too late to
prevent significant ozone depletion, or that it will be too late to
prevent it before we learn whether ozone depletion is a serious threat.

Either strategy can impose smaller expected costs, depending on the
probability that emission-limiting regulations will be required. The
results of the analysis are characterized by a "critical probability"
deﬁned so that immediate regulations will have lower expected cost if
and only if the probability that regulations will be necessary exceeds
this value. Thus, immediate regulations are cost-justiﬁed if and only if
policymakers' estimate of the probability that emission reductions will
be necessary exceeds the critical probability. The report does not
address the question of how policymakers should estimate this proba-
bility: However, they should consider the best available scientiﬁc evi-
dence concerning likely future ozone depletion and its consequences
and currently observed trends in ozone and other trace-gas concentra-
tions.

The critical probability is calculated using a model that incorporates
detailed information on the cost of reducing emissions and the likely
growth of demand for potential ozone depleters, based on earlier
RAND work. It depends primarily on the quantity of emission reduc-
tions that may be required and the discount rate used to compare
present and future costs. For a wide range of assumptions about the
likely growth and elasticity of demand for potential ozone depleters,
the possibility that technological innovation will reduce the cost of
emission reductions, the date at which improved information will
become available, and the horizon used for limiting emissions and cal-
culating costs, the critical probability is remarkably consistent. More-
over, it is a nearly dichotomous function of the extent of emission
reductions that may be required. If the effects of projected future
emissions are not important, immediate regulations cannot be cost-
effective and the critical probability is one. However, if emission
reductions may be necessary, the critical probability is between about
0.3 and 0.5 and is not sensitive to the exact extent of reduction or to
variations in most of the parameters. The critical probability is sen-
sitive to the discount rate used to compare current and future costs and
to the possibility that demand for potential ozone depleters becomes
substantially more elastic at elevated prices than current estimates sug-
gest. Moreover, it cannot be calculated for cases in which very large
emission reductions may be necessary, since the simulated demand
curves do not allow calculation of the resource costs of eliminating
potential ozone depleter emissions.

These results are by necessity based on an extensive set of detailed
assumptions about potential ozone depleter use. The assumptions are
based on the most detailed information available but the data are
limited, especially for relatively costly emission-reducing measures and for chemical use outside the United States. Further research is needed to reduce the uncertainty about demand for potential ozone depleters at increased prices. But the remarkable stability of the results across alternative assumptions suggests that conclusions about appropriate policy should not be overly sensitive to the specific assumptions chosen.
ACKNOWLEDGMENTS

Many individuals contributed to this report. I thank Jan Acton, Frank Camm, Peter Connell, Daniel Dudek, Michael Gibbs, William Mooz, and Kathleen Wolf for helpful discussions, Anil Bamezai for comments and programming assistance, and Timothy Quinn for initially encouraging me to develop the computer code needed to simulate demand curves. Participants at the United Nations Environment Programme Workshop on the Control of Chlorofluorocarbons (September 1986) and RAND seminars also offered valuable comments. James Dertouzos and David Draper provided thoughtful reviews of earlier drafts, and Patricia Bedrosian skillfully edited the final document. Naturally, none of these people are responsible for any of the report’s shortcomings.
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I. INTRODUCTION

Release of chlorofluorocarbons (CFCs) and several related chemicals to the atmosphere may reduce the concentration of stratospheric ozone and contribute to changes in the earth's climate through the "greenhouse effect." These events could threaten global and human welfare: Depletion of stratospheric ozone would increase the quantity of ultraviolet radiation reaching the earth's surface, potentially increasing human skin cancer incidence, promoting cataracts, suppressing immune responses in humans and other animals, and causing other adverse effects to animals, plants, and valuable materials. The greenhouse effect is expected to cause a general global warming that would affect climate and weather patterns, sea levels, agricultural productivity, and the distribution of plant and animal species.

The exact effects of releasing CFCs and other potential ozone depleters to the atmosphere are uncertain, however. The atmospheric transport and chemical processes leading to stratospheric ozone depletion are not completely understood. Projections of future depletion are based on complex simulation models that have not been reconciled with limited available measurements of the concentration of ozone and other trace gases. Moreover, the effect of any quantity of potential ozone depleters depends on concentrations of other gases that are emitted through poorly understood natural as well as human activities. Further complicating the problem, the effects of potential ozone depleter emissions are expected to be long-lived: These gases are believed to remain in the atmosphere for periods of 50 or 100 years or more.1

Potential ozone depleters are man-made chemicals. They are released to the atmosphere solely as a consequence of their use in a wide range of industrial processes and consumer products. CFC-11 and CFC-12 are probably the most important: They are produced in substantial quantities and are believed to be moderately efficient ozone depleters per unit mass. CFC-11 is used largely as an aerosol

1The projected global warming is likely to be caused as much by carbon dioxide emissions (largely from burning fossil fuels) as by releases of other gases. For more information on the current understanding of ozone depletion, the contribution of potential ozone depleters to global warming, and the likely consequences for the biosphere, see the comprehensive three-volume study issued by the World Meteorological Organization (1985), National Academy of Sciences (1976, 1979, 1982, 1984), National Research Council (1983), Ramanathan et al. (1985), Seidel and Keyes (1983), Titus (1986), and Watson et al. (1986).
propellant (except in the United States and a few other countries, where most such uses were banned in the late 1970s), as a blowing agent for manufacturing rigid insulating and flexible cushioning foams, and as a refrigerant in chillers (large industrial and commercial air-conditioning systems). CFC-12 is also used as an aerosol propellant (outside the United States), as a blowing agent in foam manufacturing, and as a refrigerant in automotive air conditioners, chillers, and home and retail food refrigeration equipment.

Other important potential ozone depleters include the solvents CFC-113 and methyl chloroform, carbon tetrachloride, Halon-1211, and Halon-1301. CFC-113 is used primarily in manufacturing electronic equipment, but it is also used in dry cleaning and other applications. Methyl chloroform is a general-purpose solvent used in a variety of manufacturing processes. It is believed to be a relatively inefficient ozone depleter but is emitted in larger quantities than the other chemicals. Carbon tetrachloride is used largely to produce CFC-11 and CFC-12, although some may be used as a solvent or grain fumigant. Emissions are estimated as only 6 percent of production (Quinn et al., 1986). Halon-1211 and Halon-1301 are fire extinguishing agents used in portable extinguishers and total flooding systems. Although only small quantities are produced, the halons are thought to be the most efficient ozone depleters per unit mass.²

The relationship between commercial use and atmospheric release of the potential ozone depleters varies by application. In some uses, such as aerosol propellants, the chemical is inevitably released to the atmosphere as the product is consumed. In others, such as insulating foam and refrigeration equipment, the chemical is contained in a sealed unit and is released only through unintended leakage or after product disposal. The quantities of potential ozone depleters contained in such products represent a bank that may or may not eventually reach the stratosphere. In any case, the existence of this bank results in a substantial delay between production and release of the chemicals. This delay is approximately 10 to 20 years for most refrigeration equipment and may be 50 or 100 years or more for rigid insulating foams.³

Past emissions of potential ozone depleters are not known to have caused significant depletion, although the recent discovery of low ozone concentrations in the Antarctic springtime (Farman et al., 1985; Stolar-

²See Hammitt et al. (1986) for estimated current production and additional information on the uses of these chemicals.

³Khalil and Rasmussen (1986) report that emissions from rigid foams occur at a rate consistent with a half-life of 100 years or more.
ski et al., 1986) has not been adequately explained.\footnote{No significant trend in globally averaged column ozone has been detected, although statistically significant negative trends have been observed at some altitudes. Interpretation of these results is complicated by changes in solar flux over the solar cycle and increased aerosol content of the atmosphere (which may affect instrument calibration) resulting, in part, from the April 1982 eruption of El Chichon. See World Meteorological Organization (1985), Reinsel et al. (1984), and Tiao et al. (1986).} Whether historical releases, combined with future releases from the existing bank, will cause significant depletion is not known with certainty. Current atmospheric models suggest that continued releases at current rates would not, if positive trends in carbon dioxide and methane concentrations continue (World Meteorological Organization, 1985). However, most observers expect emissions of potential ozone depleters to increase (Camm and Hammitt, 1986; Quinn et al., 1986; World Meteorological Organization, 1985) and the trends for other important gases (notably carbon dioxide, methane, and nitrous oxide), and even their sources, are not well understood. Moreover, because current production decisions may affect emissions and ozone concentrations well into the future, it may be wise to limit releases now rather than to await future scientific developments before deciding whether regulations are necessary. Simply stated, by the time our understanding of these phenomena has developed to a state that allows us to confidently assess the relationship between potential ozone depleting emissions and environmental consequences, it may be too late to avert significant adverse effects. Whether these adverse consequences would be ultimately reversible is not known; in any event, they are likely to persist for a human generation or more.

Because of pervasive uncertainty about the likely extent of future ozone depletion, its relationship to the quantity of potential ozone depleters emitted, its effects in the biosphere, and the appropriate valuation of these consequences, it is not currently possible to choose the level of emission-limiting regulations that will maximize welfare by optimally balancing the costs of environmental damage against those of emission control. Thus, the essential policy question is whether to impose additional regulations to restrict emissions now (the United States and several other countries adopted some regulations in the late 1970s), thereby incurring economic losses that may later prove to have been unnecessary, or to await future scientific developments and thereby risk higher abatement costs and potentially serious adverse environmental change. The question is analogous to that of whether to purchase insurance: By imposing additional regulations now, we incur immediate costs in exchange for reducing the potential future costs of ozone depletion. This report attempts to provide insight into this
question by comparing the expected economic costs of alternative regulatory strategies. Specifically, it characterizes the degree of belief about the severity of the potential problem such that the expected economic cost of awaiting future scientific revelations before deciding at what level to regulate is greater or smaller than the expected cost of imposing interim regulations now. Because the alternative regulatory strategies are constructed to produce equivalent ozone depletion, it is not necessary to estimate the benefits of reducing depletion, so the economic costs may be compared directly. An important limitation of the analysis is that it ignores the possibility that we may not learn whether ozone depletion is likely to produce severe consequences until it is too late to prevent it.

The focus of the report is on the question of whether the world as a whole should impose additional regulations on emissions of potential ozone depleters now or await future developments before deciding. It abstracts from the important issues associated with coordinating action among nations. These issues may be important in determining how to structure regulations and how much ozone depletion to risk. However, the question of whether to adopt additional regulations now must logically be addressed before the question of how to structure such rules.

The following section describes the methodology used to address the timing issue. Section III presents the results of the analysis and Sec. IV discusses the implications and important uncertainties that should be resolved.
II. METHODOLOGY

The ultimate effects of emitting potential ozone depleters to the atmosphere are unknown. Formally, this uncertainty can be characterized by a subjective probability distribution function \( f(e) \) relating global and human welfare to the time path of emissions.\(^1\) The subjective distribution function \( f(e) \) will shift over time as scientific research increases our understanding of the likelihood and extent of ozone depletion, climatic change, and the resulting effects on activities in the biosphere. Increased understanding should reduce the variance of \( f(e) \) as it narrows the range of plausible consequences. The mean of \( f(e) \) may also shift as we learn more about the relationships between emissions and ultimate consequences.

Optimal restrictions on emissions of potential ozone depleters depend on \( f(e) \) and will change over time as \( f(e) \) shifts. In general, one would expect the desirability of limiting emissions now, and the stringency of the appropriate limitation, to be positively correlated with subjective estimates of the likelihood and severity of adverse consequences. In addition, since it will generally be less costly to obtain a fixed reduction in cumulative emissions if the reduction is spread over a longer period, one might expect a strategy of imposing at least some emission restrictions now to always be less costly than risking the possibility of having to impose much harsher restrictions later. As the analysis described below will demonstrate, however, the expected economic cost of imposing emission-limiting regulations now, rather than waiting several years, depends on the relative costs of reducing emissions now and in the future. Depending on the subjective estimate of the likelihood of having to restrict emissions, either strategy—immediate or delayed contingent regulations—may be less costly.\(^2\)

A MODEL OF THE DECISION PROBLEM

This analysis is based on the stylized decision problem shown in Fig. 1. The decision is whether to impose a set of specified emission-limiting regulations now or to await future information. Independent

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\(^1\) \( c \) represents a vector of emissions of each potential ozone depleter over time, and \( f(e) \) may be a vector-valued function describing the likelihood of consequences measured in many dimensions. For expository convenience, consider \( f(e) \) to be scalar valued.

\(^2\) Related research on sequential decisionmaking is reported in Cyert et al. (1978), DeGroot (1970), and Miller and Lad (1984).
of that decision, new information will become available at a fixed future date. At that time, the subjective distribution function for the ultimate consequences of potential ozone depleter emissions will degenerate into a point mass at one of two points, characterized as "good" and "bad" outcomes. In the event of a good outcome we will learn that ozone depletion will not occur, or that its consequences will not be serious, so no emission restrictions are required. If emission regulations have not already been imposed, no restrictions will be required (branch 1 in the decision tree). If restrictions have already been imposed, they can be abolished (branch 3).³ In the event of a bad outcome, we will learn that significant emission limitations are necessary. If regulations have not already been adopted then stringent restrictions will be necessary (branch 2), and if regulations have been adopted some additional regulations may still be required (branch 4).

³More generally, the good outcome could require some limitation on emissions. In this case, mild regulations would be required at branch 1 and existing regulations could be relaxed, but not necessarily terminated, at branch 3.
The levels of emission restrictions incorporated in Fig. 1 are chosen so as to equalize the environmental consequences of the immediate and delayed contingent regulation branches. It is assumed that the new information will arrive early enough to prevent significant adverse effects by imposing sufficiently stringent regulations at that time. (Stratospheric ozone concentrations are not sensitive to variations of a few years in the timing of emissions, because of the potential ozone depleters’ long atmospheric residence times.) Thus the only penalty for awaiting new information before regulating is the lost opportunity to distribute any required emission reductions over a longer period and thereby potentially reduce their cost (this point is discussed further below). Since the environmental consequences do not depend on whether regulations are adopted immediately, the analysis reduces to a comparison of the expected economic costs of the alternatives.

This stylized decision problem abstracts from several important features of the real problem. First, many aspects of the stylized problem are discrete, not continuous as in the real problem. For example, in the stylized problem only two information outcomes are possible: A more realistic subjective distribution for the appropriate level of emission limits would assign positive probability to a continuous range of emission limits. To offset this limitation, the critical probability is calculated for the entire range of possible cumulative-emission limits. Second, new information that substantially reduces uncertainty about the ultimate consequences of emissions arrives in a discrete package at a predetermined date. This simplification should bias the results in favor of delayed contingent regulations, because in the real problem information will arrive in smaller bits at irregular, random intervals, and the uncertainty will never be completely resolved, so we can never avoid the risk of regulating more stringently than necessary. Third, in the stylized problem the date and type of new information are independent of the chosen regulatory strategy (learning is passive). In fact, the rate of scientific progress may depend on the regulations chosen: In the extreme case, if emissions are severely limited we might never learn whether significant ozone depletion would have occurred. The stylized problem does not account for the potentially irreversible effects that regulation may have on demand and on industry, for the administrative and political costs of developing or revising regulations, or for the possibility that advanced notice of impending regulations may reduce the associated transition costs. Finally, the stylized problem abstracts from the issue of choosing the appropriate level of emissions, and consequently environmental and welfare consequences, to accept. In principle, this issue may be solved by comparing the costs of environmental modification with those of emission control, although
the consequences and costs of environmental change cannot credibly be measured at present. There may also be interactions between whether controls have been imposed and the appropriate level of ozone depletion to accept later, but these are not considered. Despite these simplifications, the stylized problem elucidates many of the issues pertinent to the decision.

In the stylized problem, when the decision whether to impose immediate regulations is made, the subjective distribution function \( f(e) \) is Bernoulli. It assigns probability \( p \) to the chance that the new information will reveal that substantial emission reductions are required, and the complementary probability \( (1 - p) \) to the chance that reductions will not be necessary. Conditional on the levels of emission reductions associated with each outcome and with the level of interim regulations proposed, one can solve the stylized decision problem for the "critical probability" \( q \). This value separates the set of possible prior beliefs about the likelihood of good and bad outcomes into two classes: those for which immediate regulations are expected to be less costly than waiting for new information before deciding whether to regulate and those for which they are expected to be more costly. If the subjective probability that new information will reveal that regulations are necessary is higher than this critical probability, immediate regulations will be less costly (in expected value); if the subjective probability is lower, they will be more costly.\(^4\)

The analysis focuses on the critical probability. The results presented in Sec. III describe how it depends on the parameters of the decision problem, including the likely severity of the welfare consequences of emissions (reflected in the degree of emission restrictions that are appropriate) and the date at which significant new information will become available. That section also describes the sensitivity of the critical probability to alternative assumptions about the likely growth in demand for potential ozone depleters, the elasticity of demand for them, the possibility of future innovation that reduces the cost of limiting emissions, and the discount rate used to calculate the present value of future costs.

\(^4\)Evaluating alternative policies by their expected economic costs alone may be inadequate, particularly when the potential outcomes are far apart. There is a presumption that most people are risk averse when facing potentially large losses; that is, they value a risky alternative less than its expected value (Raiffa, 1968). This is one justification for purchasing insurance. Risk aversion would tend to make the immediate regulation branch relatively more favorable, thereby reducing the critical probability.
THE CRITICAL PROBABILITY

Figure 2 illustrates the expected costs of the two main branches of the decision tree, as a function of the probability that emission reductions will be necessary. The values $a$, $b$, and $c$ are the present values of the economic costs of following branches 3, 4, and 2 of the decision tree (Fig. 1), respectively. The expected cost of the delayed contingent regulation strategy is zero if the probability that emission reductions will be necessary is zero and $c$ if the probability is one. Analogously, the immediate regulation strategy has expected cost ranging from $a$, if the probability is zero, to $b$, if it is one. The critical probability ($q$) is the probability that equalizes the expected costs of the two strategies. If the probability that emission reductions will be necessary is less than $q$, the strategy of awaiting new information before deciding whether to regulate imposes lower expected costs; alternatively, if the

![Diagram](image-url)

Fig. 2—The expected costs of alternative regulatory strategies
probability exceeds $q$, immediate regulations impose lower expected costs.

Figure 2 also illustrates the expected cost of choosing the wrong strategy. The expected cost is a linear function of the difference between the probability that emission-limiting regulations will be necessary and the critical probability. It can be calculated as

$$E(L) = | (1 - p) a - p (c - b) | .$$

(1)

The cost of choosing the wrong strategy is $a$, if regulations are adopted now that later prove unnecessary, or $(c-b)$, if we delay and then learn that regulations are needed.

The critical probability solves the formula

$$q = \frac{1}{1 + \frac{c - b}{a}} \quad c - b \geq 0$$

$$q = 1 \quad \text{otherwise.}$$

(2)

It depends on the relative costs of all the branches of the decision tree, discounted to the present. The term $a$ represents the present value of the costs of near-term regulations. If the new information indicates that emission regulations are not necessary the existing regulations will be terminated, so $a$ includes only costs incurred between now and the date of new information. As $a$ ranges from zero to infinity $q$ ranges from zero to one (for $c - b > 0$). Thus, if the present value of near-term costs is small, $q$ will be small, and even if the subjective probability of having to impose future regulations is also small, immediate regulations may be cost-justified. Similarly, if $a$ is large, immediate regulations will not be cost-justified unless the probability of having to impose regulations in the future is high.

The other term in Eq. (2), $(c - b)$, represents the present value of the cost savings resulting from spreading the emission reduction over a longer period, contingent on emission restrictions being necessary. As $(c - b)$ ranges from zero to infinity, $q$ ranges from one to zero. If $(c - b)$ is large, $q$ will be small and immediate regulations may be cost-justified. The term $(c - b)$ is not necessarily positive. Because it measures the difference in the present value of costs, if the discount rate is high relative to the additional cost of imposing sharper emission reductions later instead of modest reductions now, $(c - b)$ may be less than or equal to zero. In that case, there is no possible cost saving to beginning regulations now and immediate regulations cannot be cost-
justified regardless of the subjective probability of having to impose future regulations.\footnote{5}

PARAMETERS OF THE MODEL

To allow comparison of the expected costs of regulating now versus waiting for new information, the emission paths corresponding to the two main branches of the decision tree must impose equivalent risk of environmental damage. In the model, alternative regulatory trajectories are assumed to impose equivalent environmental risk if the cumulative weighted emissions of the seven main potential ozone depleters through the planning horizon are equal.\footnote{6} Clearly, cumulative emissions and ozone concentrations under different regulatory trajectories cannot be equal at all dates; however, variations in the timing of emissions on a scale significantly shorter than that of the long atmospheric residence times of the potential ozone depleters should have little effect on ozone depletion at the horizon and beyond. Differences in ozone concentration before the horizon should also be small (less than 0.1 percent averaged globally) and relatively short-lived (about 10 or 20 years).\footnote{7} The associated differences in health and environmental consequences are assumed to be negligible.

Immediate regulation is characterized as beginning at the start of 1988, and the new information is assumed to arrive in time to allow additional regulations to be implemented at the beginning of 1995. The choice of dates is based on several considerations. Given the current pace of international and U.S. deliberations, the beginning of 1988 appears to be the earliest possible date at which regulations could be implemented.\footnote{8} The choice of 1995 as the date for imposing new

\footnote{5} If \((c - b) < 0\), the contingent regulation line in Fig. 2 lies everywhere below the immediate regulation line. The possibility that \((c - b) < 0\) depends on the discrete nature of the stylized decision problem. If regulations may be adjusted continuously over time, and the cost of emission reductions and its derivative with respect to time are continuous, then \((c - b) \geq 0\).

\footnote{6} The potential ozone depleters are believed to differ in the efficiency with which a unit mass of each contributes to ozone depletion. The weighting factors approximate the relative depletion efficiencies of each potential depleter. (The actual depletion efficiencies can vary with the quantities of each potential depleter and of other trace gases in the atmosphere.) The factors used are the same as those used in Canin and Hammitt (1986): CFC-11, CFC-12, CFC-113, and carbon tetrachloride, 1.0; methyl chloroform, 0.1; and Halon-1211 and Halon-1301, 10.0.

\footnote{7} These estimates are based on preliminary calculations using Connell's (1986) approximation to the Lawrence Livermore National Laboratory one-dimensional atmospheric model.

\footnote{8} Even this date appears optimistic. The U.S. Environmental Protection Agency announced that it will determine whether additional U.S. regulations are warranted by November 1987 (Federal Register, Vol. 51, No. 7, January 10, 1986). International negotiations are proceeding on a parallel schedule.
regulations or terminating existing regulations as appropriate allows eight years from the present for the development of new scientific understanding and the design and implementation of regulations, if necessary. If a decision is made to await further information before deciding whether to regulate, one must be prepared to wait several years to allow significant scientific progress and to reestablish the political and bureaucratic momentum needed to develop international regulations. However, eight years should allow substantial improvement in our understanding of the environmental consequences of potential ozone depleter emissions, especially considering current programs for measuring ozone and other trace-gas concentrations (National Academy of Sciences, 1984; World Meteorological Organization, 1985). The sensitivity of the results to the choice of the date is tested by repeating the calculations using 2000 as the date at which contingent regulations can be implemented.

The horizon is set at 2020 to allow sufficient time for regulations beginning in 1995 to offset unregulated interim emissions growth. Because of the lags between production and emission, and between emission and ultimate effect on ozone concentration, there is substantial delay between changes in production and reversal of any trend in ozone concentration. Thus, if the ozone concentration is falling in 1995, even if production of potential ozone depleters were sharply reduced or even halted, the ozone concentration would likely continue to fall for a few years and would not recover to its 1995 level for perhaps 20 years. The maximum additional depletion over that period should not exceed 1 percent. Sensitivity of the results to the choice of horizon is explored by additional calculations using 2005 and 2010 as the horizon.

Alternative strategies for immediate regulation are compared with the option of awaiting new information and then regulating only if necessary. For each of these alternatives the critical probability is calculated as a function of the total to which cumulative emissions may need to be limited. The strategies differ in the stringency of pre-information regulations compared to the stringency that will be imposed post information if regulations are required then.⁹

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⁹These conclusions are based on projected time paths of ozone concentration in Wuebbles (1983), Stordal and Isaksen (1986), and calculations using Connell's (1986) approximation.

¹⁰For each probability of a bad information outcome, there is an optimal level of pre-information regulations (including the possibility of no regulations). But since the calculations required to determine this optimal level require extensive iteration, critical probabilities are calculated for only a few representative levels of pre-information regulations.
CALCULATION OF RESOURCE COSTS AND CRITICAL PROBABILITIES

Calculation of the critical probability for any proposed immediate regulation and cumulative-emission limit requires calculation of the present value of the resource costs of alternative regulatory trajectories (the values of \( a, b, \) and \( c \) in Figs. 1 and 2). These resource costs are measured as areas under the demand curves for each chemical. The calculations are performed using a computer program that simulates annual demand curves for each application of the potential ozone depleters over the period 1985 through 2020.

The calculations assume that the regulations will consist of surcharges imposed on the use of potential ozone depleters. Using a surcharge, the effective price of the potential ozone depleters can be increased so that consumers will switch to alternative products and manufacturers will substitute other chemicals, more conservative processes, or other technological options that become cost effective. The size of the surcharge can be varied to induce the desired amount of emission reductions. The use of such a surcharge induces manufacturers and consumers to adopt the economically efficient set of emission-reducing measures, thereby minimizing the annual resource costs of emission reductions. To minimize the present value of the cost of limiting cumulative weighted emissions, the surcharges should be proportional to the relative ozone-depletion efficiencies of each chemical and rise over time at the discount rate that firms and consumers use in making investment and consumption decisions.\(^{11}\)

If a surcharge is applied, the resource costs of the regulation can be measured by the area under the demand curve for each chemical between the unregulated price and the price including surcharge.\(^{12}\) Other regulatory programs, such as marketable permits, mandated control technologies, or selective product bans, could also be applied. These alternative programs would generate the same resource costs, unless they fail to induce the most efficient emission-control technologies. In that case, the resource costs would be higher than those calculated.\(^{13}\) Thus, the assumption that regulation will be characterized by a

\(^{11}\) Setting the surcharges proportional to relative ozone-depletion efficiencies is analogous to using Pigouvian taxes and subsidies to equalize the marginal private and social costs of an activity. Similarly, the present value of the costs of limiting cumulative emissions over the planning period is minimized by increasing the surcharges at the discount rate, the optimal solution for pricing exhaustible resources (Fisher, 1981).

\(^{12}\) The resource cost is the reduction in economic surplus resulting from the surcharge: the area bounded by the demand curve, the unregulated price, and the quantity demanded under the surcharge. See Cann et al. (1986) for further discussion.

\(^{13}\) The choice of regulatory strategy can dramatically affect the distribution of consequences among consumers and firms, however. See Palmer and Quinn (1981a, 1981b) for discussion of distributional effects and the relative advantages of various types of regulations.
surcharge is primarily a convenient device to allow calculation of the resource costs.

A total of 28 annual demand curves for specific chemical applications are simulated for the 36 years from 1985 through 2020. These curves measure demand for potential ozone depleter use in 14 applications each in the United States and in the rest of the world. The curves, and their movement over time, are based on earlier RAND work.

The shapes of the demand curves are based on the estimates in Camm et al. (1986) of the chemical prices at which manufacturers would substitute other chemicals or production processes. The curves include the known technological options that are likely to be adopted if the effective price of the potential ozone depleters were to increase by no more than $5 per pound (about a tenfold increase). Camm et al. focus on technological options in the United States and discuss the factors that may limit the applicability of their findings to other countries. However, because no better estimates of the demand curves in other countries are currently available, the simulations assume (with one exception) that firms in other countries would respond in the same manner as U.S. firms.\footnote{There are several differences between the demand curves employed in this simulation and those developed in Camm et al. (1986): (1) The simulation assumes that non-U.S. CFC-11 and CFC-12 use as an aerosol propellant would begin to decline after their prices doubled (to $1.02 and $1.32 per pound), and that use would thereafter decline linearly reaching only 5 percent of initial use if the price rose $5 per pound. (2) Camm et al. do not make any estimate of the reduction in demand for Halon-1211 and Halon-1301 at elevated prices. The simulation assumes that their demand curves have constant elasticity equal to \(-0.32\). The halons currently cost about $2 per pound. Thus a $1 increase would reduce simulated demand by 12 percent; a $5 increase would reduce it 33 percent. (3) Camm et al. did not explicitly report technological options for reducing methyl chloroform emissions, but these are similar to those for CFC-113. The simulation uses a curve for methyl chloroform that is based on that for CFC-113 but adjusted for the difference in the price of the two chemicals. (4) Camm et al. also did not assess demand for the relatively minor uses of carbon tetrachloride other than use as a precursor to CFC-11 and CFC-12. The simulation assumes these other uses would not fall with a price increase of less than $5 per pound. (5) Finally, in some applications Camm et al. report two demand curves, depending on how widely adopted are options they identify as cost effective at current prices. In these cases the simulated demand curves are halfway between the two.}

The simulated demand curves move over time to account for likely growth in demand for chemical use in each application. The likely growth is described in Camm and Hammitt (1986) and Hammitt et al. (1986). These documents develop a set of projected demand scenarios, based on historical trends, analysis of specific product markets, and projected general economic growth. The scenarios are related to a subjective probability density function that describes the likelihood that
future demand will fall in any specified interval. In the standard case, demand is assumed to grow along the median projection.\textsuperscript{15}

The computer programs used to calculate the resource costs, cumulative emissions, and critical probability are given in the appendix. The first program calculates the resource costs and cumulative weighted emissions associated with any regulatory trajectory (defined by the path of the surcharge over time). These results are used by the second program to calculate the critical probability associated with a specified set of proposed immediate regulations and level of acceptable cumulative emissions.

\textsuperscript{15}Hammitt et al. (1986) project demand for each of the major applications of the seven principal potential ozone depleters, by world region, through 2000. Camm and Hammitt (1986) extend the projected aggregate global demand for these chemicals through 2040. To calculate emissions beyond 2000 the current simulations assume that demand for chemical use in all applications of a chemical grows at the same rate, or equivalently, that the distribution of emissions over time resulting from a single year’s use remains constant.
III. RESULTS

The level to which cumulative weighted emissions can be constrained depends on the date at which emission regulations are imposed and the stringency of the regulations. Figure 3 illustrates the effect of these factors. The abscissa indicates the initial base surcharge, ranging between zero and five dollars. In this standard case, demand for potential ozone depleters is assumed to grow at the median rates described in Camm and Hammitt (1986) and the surcharge increases 3 percent per year. The three lines in the figure correspond to regulations beginning in 1988, 1995, and 2000. In the absence of regulations (that is, with a surcharge equal to zero), global cumulative weighted emissions from 1985 through 2020 total about 63.5 million metric tons (63.5 Mt). If regulations were to begin in 1988, limiting emissions to 50 Mt would require an initial worldwide surcharge of about $0.90 per pound, limiting emissions to 40 Mt would require an initial surcharge of about $1.87 per pound, and the minimum attainable level of cumulative emissions, if the initial surcharge were $5 per pound, would be about 32.5 Mt. If regulations were not initiated until 1995 larger surcharges would be necessary to limit emissions to the same levels: A 50 Mt limit would require a surcharge beginning at $1.22 per pound, and a 40 Mt limit would require a surcharge beginning at $2.83 per pound. The smallest attainable cumulative emissions, if regulations did not begin until 1995, would be about 37.2 Mt. If regulations were not imposed until 2000, the range of attainable cumulative emissions is further reduced, and even higher surcharges would be required to hold emissions to any attainable level.

Figure 3 illustrates the apparent inelasticity of the demand for potential ozone depleters: Even with surcharges of several dollars per pound, compared with unregulated prices on the order of 50 cents per pound, simulated cumulative emissions over the next 35 years fall by no more than half. Limiting cumulative emissions to 35.2 Mt, the level

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1The weights used for calculating cumulative weighted emissions, and the surcharges applied to each chemical, are proportional to the approximate estimated relative ozone depletion efficiencies. The surcharge applied to methyl chloroform would be one-tenth the base surcharge listed in the text and the surcharges applied to the halons would be ten times the base surcharge.

2Current average U.S. prices per pound, based on United States International Trade Commission (1984), are: CFC-11, $0.51; CFC-12, $0.67; carbon tetrachloride, $0.16; and methyl chloroform, $0.50. The International Trade Commission does not publish data for CFC-113 or the halons but industry sources suggest the following average prices per pound: CFC-113, $0.88; Halon-1211, $1.95; and Halon-1301, $2.20.
Fig. 3—Cumulative weighted emissions as a function of the initial date and stringency of regulations.
corresponding to continued emissions at 1985 rates (the scenario often assumed for atmospheric-model calculations) would require an initial surcharge of $2.80 per pound if regulations begin in 1988 and would not be possible (under these assumptions) if regulations were delayed until 1995.

In part, the difficulty of reducing emissions reflects the emissions that will occur from the currently existing banks contained in rigid foam and refrigeration equipment. A more important factor, however, is the superior performance of the potential ozone depleters in many applications, requiring large price increases before manufacturers and consumers will substitute alternative chemicals. There is great uncertainty, however, about the technological alternatives that might be adopted if surcharges of several dollars per pound were to be imposed and consequently about the elasticity of the demand curves. Although current estimates (Camm et al., 1986; Mooz et al., 1982; Palmer et al., 1980) suggest that substitution possibilities are limited, a surcharge of several dollars per pound would create strong incentives to develop alternative manufacturing processes and products. Consequently, estimates of the minimum attainable emissions using a surcharge of no more than $5 per pound are particularly uncertain.

The resource costs (lost economic surplus) associated with restrictions that reduce potential ozone depleter emissions are substantial. Figure 4 illustrates the present value (in 1985 using a 3 percent discount rate) of the resource costs associated with a surcharge beginning at the level indicated on the abscissa and increasing at 3 percent per year. Using Figs. 3 and 4, one can estimate the resource cost associated with various cumulative weighted emission levels. For example, limiting cumulative emissions through 2020 to 50 Mt requires a surcharge beginning at $0.90 per pound, if regulations begin in 1988. As shown by Fig. 4, the present value of the associated resource cost is $14.4 billion. If the regulations are not implemented until 1995 the required initial surcharge is $1.22 per pound, which is associated with a resource cost of $15.8 billion in present value. These costs are approximately eight times the estimated value of 1985 world potential ozone depleter production of $1.8 billion.\footnote{This value is calculated using the estimated average U.S. chemical prices noted above.}

Even though a simulated $5 per pound surcharge reduces cumulative emissions through 2020 by about half, it has much less effect on the quantity of potential ozone depleters banked in products. As shown by Fig. 5, the simulated weighted bank in 2020 is about 15 Mt, roughly 25 percent less than would be banked if there were no additional regulations.
Fig. 4—Present value of resource cost as a function of the initial date and stringency of regulations
Fig. 5—Weighted 2020 bank as a function of the initial date and stringency of regulations
THE CRITICAL PROBABILITY

Figure 6 illustrates the critical probability that determines whether the expected cost of regulating immediately is greater or smaller than the expected cost of waiting for new information before regulating. The critical probability varies with the cumulative emissions that can be tolerated and with the proposed level of immediate regulations. For example, assume that the subjective distribution function \( f(e) \) described in Sec. II corresponds to a situation in which the new information to be developed by 1995 may indicate either that cumulative emissions through 2020 must be limited to 55 Mt or that the 63.5 Mt of emissions that would occur without regulations will be acceptable. The proposed immediate regulations consist of a base surcharge of $0.30 per pound, increasing 3 percent per year. If the new information indicates that cumulative emissions must be limited to 55 Mt, the surcharge will be doubled in 1995 (branch 4 in Fig. 1). If the new information indicates that no regulations are required, the surcharge will be dropped (branch 3), and no further costs will be incurred. Alternatively, if the proposed interim regulations are not adopted and the new information indicates that cumulative emissions must be limited to 55 Mt, it would be necessary to impose a surcharge of $0.79 per pound in 1995 that would increase 3 percent annually (branch 2). If the new information indicates that cumulative emissions of 63.5 Mt can be tolerated, no regulations would ever be imposed (branch 1).

The critical probability can be calculated from the present values of the resource costs associated with each of these four possibilities. The values \( a, b, \) and \( c \) are $295 million, $6268 million, and $6785 million. Using Eq. (2) of Sec. II, the critical probability

\[
q = \frac{1}{1 + \frac{6785 - 6268}{295}} = 0.36.
\]

Thus, if the probability is greater than 0.36 that regulations limiting cumulative emissions to 55 Mt will be required, the expected cost of adopting regulations now will be less than the expected cost of awaiting new information and regulating in 1995 only if necessary. If the probability is less than 0.36 that such regulations will be required, the expected costs of waiting will be lower than the expected costs of regulating now.

The critical probability varies with the level of cumulative emissions that can be tolerated but is essentially dichotomous. As shown in Fig. 6, if the level of cumulative emissions that can be tolerated is approximately equal to the unregulated level (63.5 Mt) or higher, immediate
regulations cannot be cost-justified. However, if emission reductions may be necessary (to lower cumulative emissions to 62 Mt or less), the critical probability drops to about 0.35. Over the cumulative-emission range from about 62 to 38 Mt the critical probability is nearly constant. Finally, if the new information might indicate that emissions must be limited to 37 Mt or less, the critical probability cannot be calculated, since it is not possible to limit emissions to this level using the assumed demand curves if regulations are delayed to 1995 (Fig. 3). Thus, Fig. 6 indicates that if the level of acceptable cumulative emissions equals or exceeds the unregulated level, immediate regulations are not appropriate. If some emission reductions may be required (about 25 Mt or less), it is cost-effective to wait for better information only if the probability that such reductions will be necessary is less than about 0.35. If larger reductions may be necessary, the critical probability cannot be calculated using the simulated demand curves.

For reference, the abscissa of Fig. 6 also indicates the projected decrease in globally averaged column ozone in 2020 corresponding to various levels of cumulative emissions. One way of thinking about the results in Fig. 6 is to assume that by 1995 we will learn either that these depletion estimates are correct or that potential ozone depletion is not an important problem (because it will not occur or because the consequences will not be serious). Then whether or not immediate regulations are cost-effective depends on the level of potential depletion we can accept. If depletion of 2.3 percent or more is acceptable, immediate regulations cannot be cost-effective, regardless of the probability that ozone depletion will occur. If depletion of less than 0.2 percent is unacceptable, it is not possible to calculate the critical probability without additional information on the costs of reducing emissions more than allowed by the simulated demand curves. Finally, if the acceptable level of depletion is between 0.2 and 2.3 percent, immediate regulations are cost-effective if the probability that ozone depletion will occur exceeds about 0.35.

The small, erratic variations are due to the varying curvature of the functions relating cumulative emissions to the required surcharge and associated resource costs (illustrated in Figs. 3 and 4) and approximations in simulating the demand curves. The algorithm approximates the demand curves with step functions that have steps at $0.05 intervals.

These estimates are calculated using the Lawrence Livermore National Laboratory one-dimensional atmospheric model with the most recent recommended chemical reaction parameters (DeMore, 1986), assuming continuation of current trends in the growth of carbon dioxide, nitrous oxide, and methane abundances (Connell and Wuebbles, 1986), and potential ozone depleter emissions corresponding to the production growth scenarios developed in Camm and Hammitt (1986). Except for the point at 63.5 Mt, the emission paths corresponding to alternative regulations implicit in the figure differ from those used to calculate the projected ozone concentrations. However, these differences should not affect the projected ozone concentrations substantially.
THE EFFECTS OF ALTERNATIVE PROPOSED CURRENT REGULATIONS

The critical probability depends on the level of interim regulations proposed. In the case illustrated in Fig. 6, the proposed immediate regulations are set so that the surcharge will be doubled in 1995 if the new information indicates that emission limitations are necessary. Figure 7 describes the critical probabilities corresponding to a wider set of immediate regulations. The line labelled "0.50" is the same as the line in Fig. 6. The others describe the critical probabilities corresponding to stronger and weaker interim regulations. The line labelled "1.00" corresponds to immediate regulations that are so stringent that, if regulations are needed, it will not be necessary to increase the surcharge in 1995 (except for the 3 percent increase that occurs every year). These are the regulations that would be least costly if we knew that it was necessary to limit cumulative emissions to some specified level. Each of the other lines corresponds to proposed immediate surcharges that are smaller than the surcharge that will be necessary in 1995, if the new information indicates regulations are needed, by a fixed factor. Specifically, the lines labelled "0.75," "0.50," "0.25," and "0.10" correspond to regulations beginning in 1988 for which the surcharge follows a path from 1988 to 1994 that is smaller than its path from 1995 to 2020 by a factor of 0.75, 0.50, 0.25, and 0.10.6

As shown in Fig. 7, the critical probability first falls then rises as the proposed interim regulations become less stringent. The line corresponding to immediate regulations that impose a surcharge only 75 percent as large as the post-1995 surcharge ("75 percent regulations") is below the 100 percent regulation line, and the 50 percent regulation line is even lower. In contrast, the critical probability for immediate regulations that are only 25 percent as stringent as the post-1995 regulations is almost equal to the critical probability for 50 percent regulations if cumulative emissions may need to be limited to less than 50 Mt. Finally, the critical probability for 10 percent regulations is higher than that for 50 percent regulations and approximates the 75 percent regulation line over the interval from about 52 to 37 Mt.

As discussed above in Sec. II, although one might expect the critical probability to decline with the stringency of the proposed immediate regulations, this is not necessarily the case. Recall from Eq. (2) that the critical probability depends on the ratio of the cost savings from

6For the line labelled "1.00," the surcharge in year $t$ satisfies the formula $s_{1.00}(t) = s^*(1986) \times (1.03)^{t-1986}$. For the other lines, labelled by the factor $f$, the surcharge in year $t$ satisfies the formula $s_f(t) = f \times s^*(1986) \times (1.03)^{t-1986}$ if $t < 1995; s_f(t) = s^*(1986) \times (1.03)^{t-1986}$ otherwise.
Fig. 7—Critical probability as a function of the stringency of proposed immediate regulations: standard case
implementing regulations now \((c - b)\) to the near-term costs \((a)\). These costs are illustrated in Figs. 8 and 9. As the proposed immediate regulations become increasingly mild, both terms become small, and \(q\) may increase or decrease. Figure 7 suggests that the regulations that are most likely to be cost-effective (the critical probability minimizing stringency) consist of a surcharge that is about one-quarter to one-half as large as the surcharge that would be appropriate if we knew that it were necessary to restrict cumulative emissions to a specified limit (100 percent regulations).

**SENSITIVITY OF THE RESULTS TO THE CHOICE OF PARAMETERS**

The following subsections describe the sensitivity of the critical probability to the specific parameters chosen. As will be shown, variations in most of the parameters have little effect on the results, although variations in the assumed demand growth, or dramatic changes in the shape of the demand curves, can substantially affect the critical probability.

The results illustrated in Fig. 6 represent a standard case. The following subsections illustrate the effect of variations in model parameters by comparing results of alternative calculations to those shown in Fig. 6. Note that the figures do not all use the same scale.

**Alternative Planning Horizon**

The calculated critical probability is not sensitive to the choice of 2020 as the horizon through which cumulative emissions and costs are calculated. Figure 10 illustrates the critical probabilities for 50 percent regulations using alternative horizons of 2005 or 2010 as well as 2020 (the standard case). Using any of the three horizons, the critical probability falls sharply to about 0.35 if cumulative emissions must be limited to less than their unregulated level (note that the horizontal scales are shifted so that the unregulated cumulative-emission levels are aligned). The lines corresponding to the alternative horizons do not extend as far to the right, since the maximum absolute cumulative-emission reduction possible before 2005 or 2010 is much less than the maximum possible by 2020.
Alternative Date of New Information

Figure 11 illustrates the effect on the calculated critical probability of delaying the date at which new information on the severity of ozone depletion will be available. As shown, if the new information will become available only in time to allow regulations beginning in 2000, the critical probability is slightly smaller than if the information will be available in time to implement regulations in 1995. That is, whatever level of emission reductions may be required, if immediate regulations are less costly in the standard case, they will also be less costly if the new information will not arrive until later. Moreover, the delay to 2000 limits the range of emission reductions that can be attained, since regulations beginning in 2000 cannot restrict cumulative emissions to less than about 41 Mt. Thus, the longer we must wait to learn whether the potential ozone depletion problem is a serious one, the more likely it is that immediate regulations will be less costly.

Alternative Demand Growth Rates

The standard case assumes that demand for potential ozone depleters grows in accordance with the median scenario developed in Camm and Hammitt (1988). Figure 12 illustrates the effect of alternative demand-growth scenarios on the cumulative emissions that can be attained and the critical probability. In addition to the standard case, the figure illustrates the critical probabilities corresponding to demand growth at the 25th and 75th percentile scenarios developed in that document. These scenarios are intended to span a range of growth such that actual demand growth is as likely to fall within the range as without. The two scenarios consequently represent reasonable high- and low-growth outcomes.

The levels of cumulative emissions that can be achieved are significantly affected by the demand-growth rate. If demand grows at only the 25th percentile rate, cumulative emissions will not exceed 54.5 Mt, even in the absence of regulations (under the standard, 50th percentile, growth scenario, limiting emissions to this level would require an initial surcharge of $0.62 per pound if regulations began in 1988). In contrast, if demand grows at the 75th percentile rate, unregulated cumulative emissions would total almost 73 Mt, and even the maximum $5 per pound surcharge would only limit cumulative emissions to 36.6 Mt.

Changes in the expected rate of demand growth shift the critical probability curve horizontally. Expected high growth limits the domain of cumulative emissions over which awaiting new information is less costly and expands the domain over which immediate regulations are
Fig. 12—Alternative demand growth
less costly. Expected low growth has the opposite effect. However, except for this effect, changes in expected demand growth have little influence on the critical probability. As illustrated by Fig. 12, unless the unregulated cumulative-emission level is acceptable, the critical probability is between about 0.35 and 0.4. Thus, if emissions may need to be limited to about 50 Mt or less, uncertainty about the future rate of demand growth has little effect on the critical probability.

Potential Additional Demand Elasticity

The simulated demand curves are based on analysis of the costs of substitute chemicals, products, and manufacturing processes for various applications. However, the actual response to regulations is highly uncertain, especially for surcharges of several dollars per pound, representing fivefold or greater price increases. Because these prices are so far above current levels, it is extremely difficult to identify the product and process substitutions that might accompany them and to estimate their effects on potential ozone depleter demand.

To assess the sensitivity of the calculated critical probability to the possibility that substantial emission-reducing responses have been overlooked, the simulated demand curves were made uniformly more elastic. Each is multiplied by a constant-elasticity function. The additional elasticity is $-0.53$, which reduces demand, relative to the standard case, by 50 percent at a $1$ surcharge, 64 percent at a $3$ surcharge, and 71 percent at a $5$ surcharge.\footnote{The modified demand function $q(p) = q_0(p) \times (1 + p/p_0)^h$, where $q(p)$ is the quantity demanded at surcharge $p$, $q_0(p)$ is the initial demand function, $p_0$ is the unregulated price of the chemical, and $h$ is the incremental elasticity.}

The effect of this substantially increased elasticity is modest. As shown by Fig. 13, the critical probability is slightly smaller than in the standard case. The additional elasticity also extends the range of simulated emission reductions that can be achieved by regulations beginning in 1988 to a total cumulative emission of about 15 Mt.

Potential Technological Innovation

Technological innovation may reduce the future costs of limiting potential ozone depleter emissions. Such innovation could include the development of substitute chemicals or alternative products or manufacturing processes that release smaller quantities of these chemicals. Although these alternatives may not reduce the demand for

\footnote{These calculations assume an unregulated chemical price of $0.60$ per pound, which is approximately the price of CFC-11 and CFC-12.}
potential ozone depleters at unregulated prices, they could become cost effective at the higher prices associated with regulations. Alternatively, regulations on chemical substitutes for potential ozone depleters could increase the costs of emission reductions. Such regulations would have a similar effect on the critical probability, but in the opposite direction.

Technological innovation can be simulated by making the demand curves progressively more elastic over time. In the standard case the demand curves expand geometrically over time: The demand at a given surcharge is the same fraction of unregulated demand in every year. With innovation, the development of alternative emission-reducing technologies would further reduce the demand for potential ozone depleters at elevated prices. The specific scenario considered entails significant reductions in the future cost of emission reductions. Under this scenario, innovation affects all chemicals and applications identically. For every five-year period except the first (1985–1990), the demand curves for each application are multiplied by a constant-elasticity function. The elasticity of this function increases in each five-year period, to $-0.6$ by the final period (2016–2020). The effect of this procedure is to make the demand curves in each succeeding five-year interval progressively more elastic. Compared with the standard case, the final-period demand curve is substantially more elastic: At a surcharge of $1 per pound the demand is only 56 percent as large, at $3 per pound, 34 percent, and at $5 per pound, only 26 percent of demand in the standard case.

The effect of the simulated increase in elasticity over time is similar to the effect of lower demand growth illustrated in Fig. 12. As shown in Fig. 14, expected innovation shifts the critical probability curve to the right. For mild cumulative-emission limits (about 60 Mt) the critical probability rises to 1.0, so immediate regulations cannot be cost-justified. Innovation also increases the emission reductions that can be achieved, thereby increasing the domain on which the critical probability can be calculated down to about 25 Mt. Over the range of intermediate emission limits, the simulated innovation has little effect. Technological innovation also reduces the cumulative emissions that can be achieved, to about 20 Mt in this case (if regulations begin in 1988).

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9Potential substitutes that are under regulatory scrutiny in the United States include the solvents perchloroethylene, trichloroethylene, and methylene chloride, which can substitute for CFC-113 and methyl chloroform in some applications. Methylene chloride can also be used in place of CFC-11 in manufacturing some flexible foams.

10The incremental elasticities in the other periods are: 1991–1995, $-0.1$; 1996–2000, $-0.2$; 2001–2005, $-0.3$; 2006–2010, $-0.4$; and 2011–2015, $-0.5$.

11These calculations assume an unregulated chemical price of $0.60 per pound, as for the additional-elasticity case.
Fig. 14—Technological innovation

Cumulative emissions (in Mt)

Probability

Technological innovation

Standard
Potential Substitute Chemicals

A dramatic result of technological innovation would be the development of chemicals that substitute for potential ozone depleters in a wide range of applications. Several chemicals that might substitute for the primary potential ozone depleters have been synthesized, but commercially feasible production processes have not been developed. For example, it is believed that CFC-134a could substitute for CFC-12 in nearly all refrigeration applications, and CFC-123 or CFC-141b could potentially replace CFC-11 in rigid-foam applications (Mooz et al., 1982).

Figure 15 illustrates the effect that the development of general chemical substitutes ("backstop" chemicals) could have on the critical probability. Specifically, it assumes that substitutes for all seven potential ozone depleters are available at weighted surcharges of $2 or $5 per pound ($20 or $50 per pound for Halon-1211 and Halon-1301, $0.20 or $0.50 per pound for methyl chloroform). The simulated demand for all seven potential ozone depleters falls to zero when the backstops become cost-effective. As shown, the possible development of substitute chemicals has a significant effect on the critical probability and extends the range of achievable cumulative-emission reductions. The existence of backstop chemicals increases the critical probability over a range of moderate emission reductions, the location of which depends on the price at which the substitutes become available. For more stringent emission reductions, the critical probability is slightly smaller than in the standard case. If only modest cumulative-emission reductions may be necessary (to about 55 Mt), the existence of general chemical substitutes would make the delayed contingent regulation strategy more attractive. For larger reductions it has little effect.

Linear Demand Curves

The simulated demand curves in the standard case produce a relationship between the surcharge and cumulative-emission reductions with nearly constant elasticity (about equal to −0.3). As a result, the elasticity of the resource costs $a, b$, and $c$ with respect to the cumulative-emission limit are nearly the same, and the critical probability is not sensitive to the exact emission limit. However, as noted above, it is difficult to estimate the shape of the demand curves at chemical prices far above current prices. Large surcharges would provide a strong incentive to develop substitute chemicals, manufacturing processes, and products. Thus, even if backstop chemicals are not
available, the demand curves could become more elastic at higher prices.

A simple alternative to the standard simulated demand curves is to assume that the demand curves for all seven potential ozone depleters are linear, and that a $5 per pound surcharge reduces demand by half, about the same as in the standard case. Compared with the standard demand curves, the linear functions have approximately the same arc elasticity over the zero- to five-dollar surcharge range but are less elastic at low surcharges and more elastic at high surcharges. As shown by Fig. 16, the critical probability calculated from the linear demand curves is qualitatively different than in the standard case: It declines monotonically as greater emission reductions may be necessary. At the smallest achievable cumulative emissions, it is about equal to the standard-case critical probability, but for less stringent reductions it is substantially larger. Thus, if the demand curves exhibit substantially greater elasticity at elevated prices, the critical probability may be higher than in the standard case (favoring delayed regulations) and may depend on the level of emission reductions potentially required.

Alternative Discount Rates

The choice of an appropriate discount rate to use in public decision-making is a confusing and contentious issue.\(^{12}\) The 3 percent rate used in the standard case is supported by the argument that the discount rate should approximate the long-term general economic or productivity growth rate. Unfortunately, unlike many other parameters considered, the choice of discount rate used to calculate the present value of future resource costs\(^{13}\) can have a dramatic effect on the critical probability, as illustrated by Fig. 17. The standard case uses a real discount rate of 3 percent. (All prices in the simulation are real.) The critical probability calculated without discounting (that is, using a 0 percent rate) is uniformly lower than in the standard case. Similarly, the critical probabilities calculated using higher rates (6 and 10 percent) are uniformly higher. Using a real discount rate of between 0 and 6 percent, the critical probability is relatively constant over the relevant domain, between about 0.3 and 0.45. Using a 10 percent rate, whether it is cost-effective to impose regulations now depends on the extent of emission reductions that may be necessary. Except for stringent emission limits (45 Mt or less), the critical probability is much higher than for lower discount rates.

\(^{12}\)See Lind et al. (1982) for an overview.

\(^{13}\)The surcharges rise over time at the same discount rate as is used to measure the present value of resource costs. Thus the surcharges always minimize the present value of the resource cost of meeting any cumulative-emission limit.
The discount rate has such a large effect because it directly affects both terms in the formula for the critical probability (Eq. (2) in Sec. II). A large discount rate reduces the present value of future costs, and consequently their difference \((c - b)\), relative to near-term costs \(a\). Consequently, it increases the critical probability. Similarly, a low discount rate increases the present value of future costs and the difference \((c - b)\) and thus decreases the critical probability. Intuitively, if one is less concerned about future costs (uses a high discount rate) it is unlikely to be cost-effective to incur costs now to potentially reduce future costs.
IV. CONCLUSIONS

The results of the calculations reported here are striking. They suggest that whether immediate regulations to reduce the risk of stratospheric ozone depletion and global warming are justified by an expected-resource-cost analysis depends almost entirely on the degree to which emissions may need to be restricted, and on the discount rate used to compare costs incurred at different times. The results are insensitive to substantial variations in most of the other parameters.

The model allows calculation of a "critical probability" that characterizes the conditions under which the insurance benefits of immediate regulations exceed their cost. If the probability that emission reductions will be required is greater than the critical probability, the strategy of adopting regulations immediately will impose lower expected resource costs; if the probability is lower, waiting for improved understanding of the likelihood and consequences of ozone depletion will be cost-effective. This report does not address how to estimate the probability that emission reductions will be needed. Such estimates should consider the best available scientific evidence on the likely extent of future ozone depletion and its consequences.

Over a wide range of assumptions, the critical probability is a nearly dichotomous function of the extent of emission reductions that may be necessary. If the cumulative emissions that will occur in the absence of additional regulations will not produce undesirable environmental changes, immediate regulations cannot be cost-effective. If emission reductions may be necessary, the critical probability falls between about 0.3 and 0.5 over the domain of cumulative-emission limits for which it can be calculated.

The assumptions about demand for potential ozone depleters do not allow calculation of the resource costs of eliminating emissions. The demand curves only include responses that would occur at price increases of less than $5 per pound (a nearly tenfold increase in the current prices of CFC-11 and CFC-12). Under the standard-case assumptions, price increases of no more than $5 per pound reduce cumulative weighted emissions through the 2020 planning horizon by half, to about the level that results from continued emissions at current rates. Development of substitute chemicals or other products or processes that reduce the cost of limiting emissions extends the range of emission reductions for which the critical probability can be calculated.
The calculated critical probability is not sensitive to reasonable variations in most of the parameters. Advancing the planning horizon (the date from which cumulative emissions under the delayed regulation strategy equal those achieved by immediate regulations) from 2020 to 2005 has almost no effect on the critical probability. Delaying the date by which regulations based on new information can become effective from 1995 to 2000 only slightly decreases the critical probability, making immediate regulations more likely to be favored; advancing the date of new information would make immediate regulations less attractive. Changes in assumed growth of demand for these chemicals affect the critical probability, in that immediate regulations cannot be cost-effective if unregulated emissions will not exceed the acceptable level, but otherwise have no effect. Substantially increasing the demand curves' elasticity, in all periods (to reflect additional consumer response or other emission-reducing measures) or progressively (to reflect technological innovation), has almost no effect on the critical probability, and assuming the existence of general substitutes for all seven potential ozone depleters at price increases of $2 to $5 per pound only shifts the critical probability by 0.1 or 0.2 and only for certain cumulative emission limits. In contrast, assuming that the demand curves exhibit markedly increasing elasticity at higher prices (as do linear demand curves) fundamentally changes the critical probability. Instead of remaining constant over the domain of emission reductions for which it can be calculated, it falls almost monotonically with increasing emission reductions. Finally, the choice of discount rate used to compare current and future costs can affect the critical probability. Discount rates between 0 and 6 percent have relatively little effect (shifting the critical probability by about 0.1 or less), but a high rate such as 10 percent has an effect similar to assuming linear demand functions: It substantially increases the critical probability for relatively moderate cumulative-emission reductions (less than about 15 Mt) and makes the critical probability sensitive to the choice of cumulative-emission limit.

If immediate regulations are cost-effective, the choice of appropriate stringency remains. The optimal stringency depends on the probability that restrictions will be necessary. For a specified potential emission limit, the level of immediate reductions that is most likely to be cost-effective is modest, corresponding to surcharges perhaps one-quarter to one-half as large as the surcharge that would be appropriate if one knew that emission reductions would be required (Fig. 7). Thus, if it might be necessary to reduce projected cumulative emissions through 2020 by 20 percent (to about 50 Mt), a reasonable set of immediate regulations would be equivalent to a surcharge beginning at about $0.25 to $0.50 per pound. If more stringent reductions may be necessary, to 40 Mt, a reasonable surcharge would begin at $0.50 to $1.00 per pound.
The current analysis is limited in several important aspects. Perhaps most important is that it starts with the assumption that the level to which cumulative emissions may have to be limited is known. In reality, the choice of an appropriate emission level depends on the relative costs of the environmental damages resulting from emissions and the costs of reducing emissions. It may also depend on how the costs and benefits of regulations are distributed between and within nations. However, it is not possible, at present, to reliably calculate the costs of environmental changes resulting from potential ozone depleter emissions. First, the quantitative relationship between emissions and ozone change depends on complex physical and photochemical atmospheric processes that are not completely understood, on natural and anthropogenic emissions of other gases, and on other factors.\(^1\) Second, the relationships between stratospheric ozone concentrations and effects on humans, plants, animals, and materials are not well understood, and important effects may not yet be identified. Quantitative descriptions necessary to estimate incremental costs are rare, and behavioral adaptations are not considered.\(^2\) Finally, assigning monetary values to effects on human health and on the global ecosystem is notoriously difficult.\(^3\) Fortunately, given the difficulty in choosing an appropriate level of cumulative emissions, the critical probability is not sensitive to the exact level under most of the assumptions considered. Neither is it sensitive to the exact level of regulations proposed: Wide variations in the proposed initial surcharge yield similar critical probabilities (Fig. 7).

The analysis assumes that all uncertainty about the acceptable level of cumulative emissions will be resolved within a few years. In fact, uncertainty will endure. This simplification enhances the attractiveness of delaying regulations in the model and thus increases the calculated critical probability. In the real world, unlike the model, even if we delay the decision of whether to regulate, the risk of making the wrong choice remains.

The analysis is also limited by the available data on the shape of demand curves, especially outside the United States. In large measure, the simulated demands outside the United States mimic those within. Improved information on the alternatives to potential ozone depleters that would become cost-effective at higher prices is also needed, since

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\(^1\) See World Meteorological Organization (1985) for a summary of current understanding.


\(^3\) See Cummings et al. (1986), Freeman (1979), Jones-Lee (1982), and Smith (1981) for current methodologies.
variations in the demand curves reflecting backstop chemicals or increasing elasticity at higher prices can affect the critical probability.

The analysis has not addressed other important issues associated with the decision of whether to adopt additional emission-limiting regulations in the near future. These include possible effects on industry of imposing emission-limiting regulations that cannot be reversed if regulations are removed and potential reductions in the transition cost of regulations if they are preceded by substantial advance notice. Both effects would tend to make immediate regulation less attractive. In contrast, if a strategy of waiting for improved information before deciding whether to regulate is adopted, it may be wise to invest more in research and monitoring to hasten development of that information. Since at least some of the anticipated consequences of reduced ozone concentrations, such as human skin cancer, cataracts, and materials damage, may take many years to manifest, additional research to speed recognition of adverse effects, if they occur, can be valuable. If the additional costs of this research were added to the expected costs of the await-better-information strategy, it would reduce the critical probability and make the immediate-regulation strategy more favorable.

Potential ozone depletion and climatic change are global issues: their effects, if realized, will be felt worldwide. This report explicitly avoids the important issues associated with the coordination of action among nations. It focuses instead on the logically prior question of whether, from a global perspective, immediate regulations may be appropriate. The results suggest that whether immediate regulations are cost-justified depends primarily on the quantity of future emissions that is acceptable and the likelihood that regulations to limit emissions to that level will be necessary.
Appendix

FORTRAN CODE

The following programs are used to simulate demand curves, calculate the cumulative weighted emissions and resource costs associated with a specified surcharge path, and calculate the critical probability. The parameters are read from input data sets that are not printed here.

PROGRAM 1: FORTRAN CODE TO SIMULATE DEMAND CURVES AND CALCULATE CUMULATIVE WEIGHTED EMISSIONS AND RESOURCE COSTS

```
c program v.for
  c calculates demands from inprod
  c calculates quantities given surcharge trajectory
  c calculates associated costs and emissions
  c input data sets: inparams, inprod, history
  c output data sets: outcosts (for use by p.for), outemit
  c q(t,p,x) = quantity of chemical used:
  c t = year (enter as 1985-2020, converted to 0-35)
  c p = price increment (0 to pmax), price = p + p0
  c x = product, region and chemical
  c price grid by princ intervals, number of points = pmax
    common q(0:35,0:100,0:28),w(0:28),pstar(0:35)
    common qstar(0:35,0:28),ipstar(0:35,0:28),crescost(0:35)
    common initreg(1:606),surcharg(1:606),rate(1:606)
    common alpha(1:606),maxt,maxx,princ,discnt, cumemit
  c read in parameters
    open (unit=1,file='inparams')
    read (1,211) maxt, maxx
    read (1,200) maxp, princ
    read (1,200) njobs, discnt
    do 110 k = 1,njobs
      110 read (1,240) initreg(k),surcharg(k),rate(k),alpha(k)
      close (unit=1)
      do 100 j = 0,maxt
        do 100 k = 0,maxp
          do 100 ix = 0,maxx
            q(j,k,ix) = 0.0
            100 continue
    c call cnstrc to cnstrc original product curves
      open (unit=1,file='inprod')
      do 120 i=1,maxx
        call cnstrc
```
continue
close(unit=1)
c call findq to find quantities demanded at regulated prices
c call intcst to calculate costs of restrictions on demand
c call emit to calculate corresponding emissions
open (unit=1, file='outcosts')
open (unit=2, file='outemit')
write (1,291)
write (1,292)
do 600 k = 1, njobs
call findq(k)
call intcst(k)
call emit(k)
c write results to 'outcosts' for use by p.for
write (1,290) initreg(k), surchrg(k), rate(k), alpha(k),
& cumemit, crescost(10), crescost(maxt)
600 continue
close(unit=1)
close (unit=2)
200 format (i8,f8.2)
211 format (2i8)
240 format (i8,3f8.2)
290 format (i8,3f8.2,3f12.2)
291 format(48x,'crescost',4x,'crescost')
292 format (1x,'initreg',1x,'surchrg',4x,'rate',3x,'alpha',
& 5x,'cumemit',8x,'1995',8x,'2020')
end
subroutine cnstrc
c cnstrc demand curves
common q(0:35,0:100,0:28), w(0:28), pstar(0:35)
common qstar(0:35,0:28), ipstar(0:35,0:28), crescost(0:35)
common initreg(1:606), surchrg(1:606), rate(1:606)
common alpha(1:606), maxt, maxp, maxx, princ, discnt, cumemit
real p(10), r(10), g(2), rinnov(7)
integer ip(0:10), iy(2), iyr(7)
c input data contained in infile, output not written
c input product, world region, chemical, base price
read (1,200) ix, price0
c input base use in 1985
read (1,220) w(ix), q(0,0,ix)
c (pi, ri) pairs input
c pi = critical price
c ri = reduction in chemical use as percentage of base use
read (1,215) n
do 300 j = 1, r
read (1,220) p(j), r(j)
300 ip(j) = int(p(j)/princ + princ/2.)
ip(0) = 0
c technical responses ('splines'-interchangeable with 'steps')
do 325 j = 1, n
ipj = ip(j)
ipjml = ip(j-1)
q(0,ipj,ix) = q(0,ipjml,ix)
&
   - r(j)/100 * q(0,0,ix)
delp = 1. * (ipj - ipjml)
delq = 1. * (q(0,ipjml,ix) - q(0,ipj,ix))
do 320  k = ipjml,ipj
    dk = 1. * (k - ipjml)/delp
    q(0,k,ix) = q(0,ipjml,ix) - dk * delq
320  continue

continue
ipn = ip(n)
do 327  k = ipn,maxp
    q(0,k,ix) = q(0,ipn,ix)
327  continue

* consumer response
read (1,210) elast
if (elast .lt. 0.000001) then
    do 330  k = 0,maxp
        price = princ * k
        q(0,k,ix) = q(0,k,ix) *
        (price/price0 + 1.)**elast
    else if (elast .gt. 0.000001) then
        write (*,282)
        format(1x,'elast must be < 0.0')
    stop
end if

* growth over time
* input ng annual percentage growth rates g(i)
* through year iy(i)
read (1,215) ng
do 340  i = 1,ng
    read (1,230) g(i),iy(i)
340  iy(i) = iy(i) - 1985

do 365  j = 1,maxt
    jm1 = j - 1
    do 350  i = 1,ng
        if (j .le. iy(i)) goto 410
350  continue
write (*,280)
280  format (1x,'no growth rate; stopped cnstrc.350')
stop
410  do 360  k = 0,maxp
    q(j,k,ix) = q(jm1,k,ix) * (g(i)/100. + 1.)
360  continue

* increasing elasticity with technical innovation
read (1,215) ni
if (ni .gt. 0.000001) then
    do 370  i = 1,ni
        read (1,230) rinnov(i), iyr(i)
370  iyr(i) = iyr(i) - 1985
    do 500  j = 1,maxt

do 380 i = 1,ni
if (j .le. iyr(i)) goto 420
continue
write (*,281)
format (1x,'no innov rate; stopped cnstrc.380')
stop
do 390 k = 0,maxp
price = princ * k
q(j,k,ix) = q(j,k,ix) *
(price/price0 + 1.)**rinnov(i)
continue
write (*,250)
write (*,200) ix,q(0,0,ix)
format (18,f8.2)
format (f8.2)
format (i8)
format (2f8.2)
format (f8.2,18)
format (6x,'ix q(0,0,x)'
return
subroutine findq(jj)
c find qstar(t) corresponding to pstar(t)
common q(0.35,0.1,0.28),w(0.28),pstar(0.35)
common qstar(0.35,0.28),ipstar(0.35,0.28),crescost(0.35)
common initreg(1:606),surcharg(1:606),rate(1:606)
common alpha(1:606),maxt,maxp,maxx,princ,discnt,cumemit
real wtdprod(0:35)
do 300 j = 0,maxt
jyear = j + 1985
wtdprod(j) = 0.
if (jyear .ge. initreg(jj)) then
k = jyear - initreg(jj)
pstar(j) = surcharg(jj)**(1. + rate(jj)/100.)**k
else
pstar(j) = 0.
endif
if ((initreg(jj) .eq. 1988) .and.
& (jyear .lt. 1995))
& pstar(j) = pstar(j) * alpha(jj)
do 300 jx = 1,maxx
ipstar(j,jx) = int(w(jx)*pstar(j)/princ + .5)
ipstrj = ipstar(j,jx)
if (ipstrj .le. maxp) then
qstar(j,jx) = q(j,ipstrj,jx)
else
qstar(j,jx) = q(j,maxp,jx)
endif
wtdprod(j) = wtdprod(j) + qstar(j,jx) * w(jx)
300 continue
write (*,201)
write (*,210) initreg(jj),surcharg(jj),rate(jj)
cumprod = 0.
do 310 j = 0,maxt
   jyear = j + 1985
   cumprod = cumprod + wtdprod(j)
write (*,202)
write (*,220) cumprod
310 format (1x,'initreg surchrg rate')
201 format (1x,'cumulative wtd production through 2020 =')
210 format(i8,2f8.2)
220 format(f12.2)
return
end

subroutine intcost(jj)
c integrate resource and transfer costs by year and total
common q(0:35,0:100,0:28),w(0:28),pstar(0:35)
common qstar(0:35,0:28),ipstar(0:35,0:28),crescost(0:35)
common initreg(1:606),surcharg(1:606),rate(1:606)
common alpha(1:606),maxt,maxp,maxx,princ,discnt,cumemit
real tcost(0:35,0:28),trans(0:35,0:28)
real rescost(0:35,0:28),atcost(0:35),atrans(0:35)
real arecost(0:35),ctcost(0:35),ctrans(0:35)
c costs are present values in 1985 million dollars
300 do 800 j=0,maxt
   atcost(j)=0
   atrans(j)=0
   arecost(j)=0
   ctcost(j)=0
   ctrans(j)=0
800 crescost(j)=0
dsctrt = 1./(1. + discnt/100.)
do 305 j = 0,maxt
   jyear = j + 1985
do 305 jx = 1,maxx
   ipstrj = ipstar(j,jx)
   ipstrjml = ipstrj - 1
   if (ipstrj .le. maxp) then
tcost(j,jx) = 0.5 * (q(j,0,jx)+q(j,ipstrj,jx))
else
tcost(j,jx) = 0.5 * (q(j,0,jx)+q(j,maxp,jx))
dendif
300 do 300 k = 1,ipstrjml
   if (k .le. maxp) then
tcost(j,jx) = tcost(j,jx) + q(j,k,jx)
else
tcost(j,jx) = tcost(j,jx) + q(j,maxp,jx)
dendif
300 continue
   if (ipstrj .lt. 1) tcost(j,jx) = 0.
\begin{verbatim}
tcost(j,jx) = tcost(j,jx) * princ * 2.2046
trans(j,jx) = qstar(j,jx) * ipstar(j,jx) * princ * 2.2046

rescost(j,jx) = tcost(j,jx) - trans(j,jx)
atcost(j) = atcost(j) + tcost(j,jx)
ats(j) = atrans(j) + trans(j,jx)
arcost(j) = arescost(j) + rescost(j,jx)

continue
  do 310 j=1,maxt
    jml = j - 1
    ctcost(j) = ctcost(jml) + atcost(j) * (dstmt**2)  
    ctrans(j) = ctrans(jml) + atrans(j) * (dstmt**2)  
    crescost(j) = crescost(jml) + arescost(j) * (dstmt**2)
  continue
write (*,204)
write (*,210) ctcost(maxt),ctrans(maxt),crescost(maxt)
format(6X,'ctcost ctrans crescost')
return
end

subroutine emit(jj)
c  calculate emissions
  c  emissions through 2075, but production = zero after 2020
  common q(0:35,0:100,0:28),w(0:28),pstar(0:35)
  common qstar(0:35,0:28),ipstar(0:35,0:28),crescost(0:35)
  common initreg(1:606),surchar(1:606),rate(1:606)
  common alpha(1:606),maxt,maxp,maxx,princ,discnt,cumemit
  real wrdemit(0:35),nhr11(0:115),cfc11(0:115),em11(0:100)
  real bank11(0:100),pem11(0:100),nhr12(0:115),hr12(0:115)
  real cfc12(0:115),em12(0:100),bank12(0:100),pem12(0:100)
  real ctet(0:100),cfc13(0:100),mchl1r(0:100)
  real emth1l(0:100),emth1rr(0:100),useh1l(0:100)
  real useh1r(0:100),bankh1(0:100),inchgr(0:115)
  real bankhrl(0:100),inchgr(0:115)
  open (unit=3,file='history')
c  reading historical prdn data for cfc-11
  do 110 i=0,5
    read (3,610) nhr11(i)
    do 120 i=0,18
      read (3,610) cfc11(i)
      do 130 i=0,35
        ip6 = i + 6
        ip19 = i + 19
        nhr11(ip6) = qstar(i,4) + qstar(i,18)
        cfc11(ip19) = qstar(i,3) + qstar(i,17)
      130     pem11(i) = qstar(i,1) + qstar(i,2) + qstar(i,5) +
                   qstar(i,15) + qstar(i,16) + qstar(i,19)
      140     bank11(0) = 0
      do 150 i=1,6
        bank11(i) = bank11(0) + nhr11(i)*(i/7)
      150     do 140 i=0,19
\end{verbatim}
bank11(0) = bank11(0) + cfc11(i)*exp(-.00693*(20-i))

c reading historical prdn data for cfc-12
   do 160 i = 0, 5
160    read (3,610) nh12(i)
do 170 i = 0, 15
170    read (3,610) hr12(i)
do 180 i = 0, 35
    ip1 = i + 1
    ip6 = i + 6
    ip16 = i + 16
    nh12(ip6) = qstar(i,8) + qstar(i,22)
    hr12(ip16) = qstar(i,7) + qstar(i,21)
    pm12(i) = qstar(i,9) + qstar(i,23)
180    cfc12(ip1) = qstar(i,5) + qstar(i,20)
cfc12(0) = 37.61
    bank12(0) = 0
do 190 i = 1, 6
190    bank12(0) = bank12(0) + nh12(i)*i(i)/7
do 200 i = 1, 16
200    bank12(0) = bank12(0) + hr12(i)*i(i)/17.
    bank12(0) = bank12(0) + cfc12(i)*.5
c reading base and historical data for other chemicals
do 210 i = 0, 12
   read (3,610) inchg(i)
210    inchgr(i) = inchg(i)
do 220 i = 0, 35
    ctet(i) = qstar(i,12) + qstar(i,26)
    cfc113(i) = qstar(i,10) + qstar(i,24)
    mchlor(i) = qstar(i,11) + qstar(i,25)
    usehl(i) = qstar(i,13) + qstar(i,27)
220    usehr(i) = qstar(i,14) + qstar(i,28)
close (unit=3)
c calculation of cfc-11 & 12 emissions begins
   do 390 i = 0, 90
    em11(i) = 0
   do 310 j = 0, ip19
    ip19mj = i + 19 - j
    ip20mj = i + 20 - j
    im10mj = i - 10 - j
    im11mj = i - 11 - j
    if ((ip19mj) .ge. 30) then
       em11(i) = em11(i) + cfc11(j)*(-exp(-.02773*(im10mj))
       & +exp(-.02773*(im11mj)))*.812
    else
       em11(i) = em11(i) + cfc11(j)*(-exp(-.00693*(ip20mj))
       & +exp(-.00693*(ip19mj)))
    endif
310   continue
390   continue
continue
ip6 = i + 6
do 320 j=i,ip6
eml1(i)= eml1(i) + nhr11(j) * (1./7.)
continue
calculation of halon emissions
em11(i)=em11(i) + cfc11(ip19) * 0.1 + pem11(i)
im1 = i - 1
if (i .ne. 0) bank11(i) = bank11(im1) - em11(i) + pem11(i)+nhr11(ip6)+cfc11(ip19)
em12(i)=0
ip1 = i + 1
calculation of halon emissions
em21(i)=em21(i) + (cfc12(i)+cfc12(ip1))*.5 + pem21(i)
do 330 j=i,ip6
em21(i) = em21(i) + nhr12(j) * (1./7.)
continue
calculation of halon emissions
ip6 = i + 16
do 340 j=i,ip6
if (i .ne. 0) bank12(i) = bank12(ip1) - em21(i) + pem21(i)+nhr12(ip6) + cfc12(ip1) + pem21(i)
continue
calculation of halon emissions
em13(i)=useh1(ip1) = .021*bankh1(i)
& - .467*exp(1.789*i/100))/1.2185
& inch(g(ip13)=useh1r(ip1) = .021*bankh1r(i)
& - .467*exp(1.789*i/100))/1.2185
if (i .gt. 34) inchg(ip13)=0
if (i .gt. 34) inchg(ip13)=0
bankh1(ip1)= bankh1(i) + inchg(ip13)
bankh1r(ip1)= bankh1r(i) + inchg(ip13)
if (i .gt. 25) bankh1(ip1)=bankh1(ip1) - inchg(ip26)
if (i .gt. 25) bankh1r(ip1)=bankh1r(ip1) - inchg(ip26)
if (i .gt. 34) useh1(ip1)=1.1975*inchg(ip13)
& + .021*bankh1(ip1)+.467*exp(1.789*i/100)
if (i .gt. 34) useh1r(ip1)=1.1975*inchg(ip13)
& + .021*bankh1r(ip1)+.467*exp(1.789*i/100)
em13(ip1)= useh1(ip1) - inchg(ip13) - .001*bankh1(ip1)
em13r(ip1)= useh1r(ip1) - inchg(ip13)
& - .001*bankh1r(ip1)
if (i .ge. 26) then
endif
400 continue
c calculation of solvent emissions
do 420 i=0,90
clet(i) = 1.2 * clet(i)
cfc13(i) = .845 * cfc13(i)
cmchlor(i) = .87 * cmchlor(i)
c calculation of cumulative weighted emissions
cumemit = 0.
do 440 j=0,maext
wtdemit(j) = em11(j) + em12(j) + cfc13(j) + clet(j) +
& 0.1 * cmchlor(j) + 10. * (emth1(j) + emthlr(j))
cumemit = cumemit + wtdemit(j)
c write output

c Note: remove comments to write emission outputs
write (*,603)
write (*,620) cumemit
write (2,601)
c write (2,630) initreg(jj),surchrg(jj),rate(jj)
c write (2,602)
c do 500 i=0,90,5
c iyear = i + 1985
c write (2,640) iyear,em11(i),em12(i),clet(i),cmchlor(i),
c & cfc13(i),emthlr(i),emth1(i)
c 500 continue
601 format (lx,'initreg',lx,'surchrg',4x,'rate')
602 format (4x,'year',3x,'cfc11',3x,'cfc12',4x,'clet',2x,
& 'cmchlor',2x,'cfc13',lx,'hal1301',lx,'hal1211')
603 format (lx,'cumulative wtd emissions through 2020 =')
610 format (f8.2)
620 format (f12.0)
630 format (i8,2f8.2)
640 format (i8,7f8.1)
return
end

PROGRAM 2: FORTRAN CODE TO CALCULATE CRITICAL PROBABILITY

c program q.for

c calculates critical probabilities for alternative costs
c of waiting to regulate
 real price(6,101),rate(6,101),cumemit(6,101)
 real crescost(6,101,2),limemit(60),prob(60,6)
 real beta(60,6),aprice(60,6),acumemit(60,6)
 real arescost(60,6,2),alpha(6,101)
 integer initreg(6,101),ischg(60,6)
c input data sets: incosts, incases
 open (unit=1,file='incosts')
c number of years in which regulation may begin (6)
number of prices at which surcharge may begin (101)
initreg = initial year of regulation
price = initial surcharge
cumemit = cumulative weighted emissions through 2020
crescost = cumulative resource cost to 1995, 2000 or 2020

read (1,200) nyers,nprices
  nym1 = nyers - 1
do 100 j=1,nyers
  do 100 jx=1,nprices
100  read (1,290) initreg(j,jx),price(j,jx),rate(j,jx),
    & alpha(j,jx),cumemit(j,jx),crescost(j,jx,1),
    & crescost(j,jx,2)
  open (unit=2,file='incases')
  read (2,200) ncases
do 110 i=1,ncases
110  read (2,210) limemit(i)
close (unit=1)
close (unit=2)
find initial surcharge to limit cumulative emissions
to limemit
  do 310 i=1,ncases
    do 310 j=1,nyers
      do 300 jx=nprices,1,-1
        if (cumemit(j,jx) .le. limemit(i))
          ischg(i,j) = jx
          icj = ischg(i,j)
          icjm1 = icj - 1
          beta(i,j) = (limemit(i) - cumemit(j,icjm1)) / 
          & (cumemit(j,icj) - cumemit(j,icjm1))
          aprize(i,j) = beta(i,j) * price(j,icj) + 
          & (1 - beta(i,j)) * price(j,icjm1)
        acumemit(i,j) = beta(i,j) * cumemit(j,icj) + 
          & (1 - beta(i,j)) * cumemit(j,icjm1)
        do 310 k=1,2
          arescost(i,j,k) = beta(i,j) * crescost(j,icj,k) 
          & + (1 - beta(i,j)) * crescost(j,icjm1,k)
310  continue
calculate critical probability
  do 400 i=1,ncases
    do 400 j=1,nyers
      prob(i,j) = arescost(i,j,1) / (arescost(i,j,1) 
      & + arescost(i,nyers,2) - arescost(i,j,2))
400  continue
write output
  open (unit=3,file='outprob')
  write (3,201)
do 500 j=1,nyers
do 500 i=1,ncases
write (3,220) initreg(j,1),rate(j,1),alpha(j,1),
  & limemit(i),aprice(i,j),arescost(i,j,2),
  & aprice(i,nyers),arescost(i,nyers,2),prob(i,j)
continue
close (unit=3)

format (2i8)
 format (f8.2)
 format (i8,2f8.2,f8.0,2(f8.2,f8.0),f8.2)
 format (i8,3f8.2,3f12.2)
 format (lx,'initreg rate alpha limenit',lx,
 & 'srcg98 rcost88 srcg95 rcost95 prob')
end
REFERENCES


Connell, Peter S., and Donald J. Wuebbles, *Ozone Perturbations in the LLNL One-Dimensional Model—Calculated Effects of Projected Trends in CFCs, CH₄, CO₂, N₂O, and Halons over 90 Years*, Lawrence Livermore National Laboratory, UCRL-95548, 1986.


