A RAND NOTE

AN ANALYTIC METHOD FOR CONSTRUCTING SCENARIOS FROM A SUBJECTIVE JOINT PROBABILITY DISTRIBUTION

Frank Camm, James K. Hammitt

May 1986

N-2442-EPA

Prepared for

The U.S. Environmental Protection Agency

Rand
1700 MAIN STREET
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SANTA MONICA, CA 90406-2138

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PREFACE

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

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

Published papers in the series include the following:

- A. R. Palmer, W. E. Mooz, T. H. Quinn, and K. A. Wolf, *Economic Implications of Regulating Chlorofluorocarbon Emissions from Nonaerosol Applications,* R-2524-EPA, June 1980.
- A. R. Palmer, W. E. Mooz, T. H. Quinn, and K. A. Wolf, *Economic Implications of Regulating Nonaerosol Chlorofluorocarbon Emissions: An Executive Briefing,* R-2575-EPA, July 1980.
- K. A. Wolf, *Regulating Chlorofluorocarbon Emissions: Effects on Chemical Production,* N-1483-EPA, August 1980.
- A. R. Palmer and T. H. Quinn, *Economic Impact Assessment of a Chlorofluorocarbon Production Cap,* N-1656-EPA, February 1981.
- A. R. Palmer and T. H. Quinn, *Allocating Chlorofluorocarbon Permits: Who Gains, Who Loses, and What Is the Cost?* R-2806-EPA, July 1981.
- W. E. Mooz, S. H. Dole, D. L. Jaquette, W. H. Krase, P. F. Morrison, S. L. Salem, R. G. Salter, and K. A. Wolf, *Technical Options for Reducing Chlorofluorocarbon Emissions,* R-2879-EPA, March 1982.
- E. M. Sloss and T. P. Rose, *Possible Health Effects of Increased Exposure to Ultraviolet Radiation,* N-2330-EPA, July 1985.
- T. H. Quinn, K. A. Wolf, W. E. Mooz, J. K. Hammitt, T. W. Chesnutt, and S. Sarma, *Projected Use, Emissions, and Banks of Potential Ozone-Depleting Substances,* N-2282-EPA, January 1986.
- F. Camm, T. H. Quinn, A. Bamezai, J. K. Hammitt, M. Meltzer, W. E. Mooz, and K. A. Wolf, *Social Cost of Technical Control Options to Reduce the Use of Potential Ozone Depleters in the United States: An Update,* N-2440-EPA, May 1986.
- J. K. Hammitt, K. A. Wolf, F. Camm, W. E. Mooz, T. H. Quinn, and A. Bamezai, *Product Uses and Market Trends for Potential Ozone-Depleting Substances: 1985-2000,* R-3386-EPA, May 1986.
- W. E. Mooz, K. A. Wolf, and F. Camm, *Potential Constraints on Cumulative Global Production of Chlorofluorocarbons,* R-3400-EPA, May 1986.

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SUMMARY

Over the last 12 years, photochemical models of the upper atmosphere have suggested that chlorofluorocarbons (CFCs) and several related chemicals may reduce the concentration of stratospheric ozone. Reducing the concentration of stratospheric ozone may increase the quantities of ultraviolet radiation penetrating to the earth's surface, which may harm human health, reduce crop yields, accelerate the degradation of certain materials, and have other important adverse effects. These chemicals, which we call "potential ozone depleters" or PODs, are emitted to the atmosphere primarily through human activities. As a result, changes in government policies could reduce emissions of PODs, thereby reducing their effects on ozone and reducing the potential negative effects mentioned above. This Note is one of a series of publications being produced by The Rand Corporation to support the development of better information on this policy issue.

Many uncertainties are important to the issue of potential ozone depletion and its possible effects. It is not even certain that PODs affect ozone or that changes in ozone concentrations have any of the negative effects mentioned above. The Environmental Protection Agency (EPA) has developed a large model that allows consideration of these uncertainties and their importance in policy decisions. It is developing scenarios to capsulize in simple illustrations important information about the range of outcomes possible with current uncertainty. For example, to represent uncertainty about future global emissions of methane, the EPA uses both a high growth and a low growth scenario. As part of its effort, The Rand Corporation is helping the EPA characterize the uncertainties about market and technological factors that may affect the future global production of seven PODs: CFC-11, -12, -113, carbon tetrachloride, methyl chloroform, and Halons 1201 and 1301. This Note explains how we use information about the uncertainties associated with each of these chemicals *separately* to develop scenarios that illustrate these uncertainties *jointly* in a useful way.

It is important to view the uncertainties associated with these chemicals jointly. For example, suppose we developed high growth scenarios for each chemical separately and then used them to construct a high growth scenario for the seven chemicals together. Unless the production levels of these chemicals always moved together, one would be highly unlikely to observe high growth levels for all of them simultaneously. Historically, they have not moved together. Hence, such an approach would yield a scenario so unlikely as to be irrelevant to policy considerations.

The high growth scenario chosen must be meaningful to policymakers in the sense that it must represent some likely range of events with, from their perspective, a "high" effect. The policymaker's perspective in this problem is focused primarily on ozone depletion (although chemicals discussed here probably also have an effect on climatic change, another concern to EPA). Hence, a "high" growth scenario should include production patterns for those chemicals that, if ozone depletion is a serious problem, are likely to lead to high ozone depletion. Similarly, a low growth scenario should be associated with a low level of potential ozone depletion. Simply put, this Note provides a way to define production scenarios for the seven chemicals examined here that policymakers could reasonably associate with a range of likely levels of potential ozone depletion.

The technique used here starts with subjective probability distributions for each chemical. These are based on detailed Rand analysis, reported elsewhere, of possible production of these chemicals during the period 1985-2040. Uncertainty about the growth rate for each chemical is characterized by the probability distribution of the sum of two normal variates. The first captures uncertainty about general economic growth, and the second captures uncertainty about the growth in intensity of use of each chemical relative to general economic growth.

The technique then uses these growth rates to calculate a rough proxy for the general rate of growth of these PODs. The proxy is defined by a "score function" that weights and sums the growth rates for the seven chemicals. The weights used reflect three important factors that help determine how likely a chemical is to affect ozone

concentration: its annual rate of production, the fraction of its production ultimately emitted into the atmosphere, and its ozone-depleting potential per gram in the atmosphere. That is, the score function simply weights growth rates to reflect their relative potential effects on ozone depletion. Because of the way it is constructed, uncertainty about the value of the score function is also captured by a normal distribution.

We define scenarios in terms of quantiles of the distribution of the score function. For example, a "high" growth scenario is associated with the 75th percentile of the distribution; a "low" growth scenario corresponds to the 25th percentile. Each of these corresponds to a set of events likely to have a "high" or "low" effect relevant to the policymaker. For each scenario, we then pick growth rates for the seven chemicals that, when weighted and summed, yield the value of the score function for that scenario. An infinite variety of individual growth rates is consistent with any value of the score function; this is a generic problem in scenario construction. We use a simple convention to pick growth rates that treats all sources of uncertainty equally.

Table S.1 illustrates the scenarios generated with this technique by showing the production levels for the seven chemicals in selected years under each of three scenarios.

The specific technique developed here allows us to convolute all uncertainties about POD growth rates analytically. To do this, we express all sources of uncertainty as normal distributions and use some simple approximations. The same general approach could be used with a broader range of distributional assumptions and without the approximations used here. It would require a simulation technique like Monte Carlo, which is substantially more costly and usually requires other kinds of approximations. The technique developed here illustrates the application of a general approach and provides a specific method to implement it. Although the general approach would easily allow more complex implementations, it is by no means clear that they would be superior to the technique used here.

The specific technique used here would allow greater subtlety in the specification of the subjective probability distribution that provides its inputs. For example, the scenarios developed here assume

Table S.1

SELECTED PRODUCTION LEVELS FOR SCENARIOS
BASED ON QUANTILES OF THE SCORE FUNCTION

(In thousands of metric tons)

		Scenarios/Quantiles of the Score Function		
Chemical	Year	"Low" 0.25	"Medium" 0.50	"High" 0.75
CFC-11	1985	342	342	342
	2000	498	556	619
	2040	1017	1435	2022
CFC-12	1985	444	444	444
	2000	555	622	696
	2040	1124	1606	2287
Carbon tetrachloride	1985	1029	1029	1029
	2000	1391	1554	1736
	2040	2827	4014	5686
CFC-113	1985	163	163	163
	2000	367	422	485
	2040	700	1091	1695
Methyl chloroform	1985	545	545	545
	2000	752	844	946
	2040	1517	2179	3123
Halon 1301	1985	11	11	11
	2000	17	20	24
	2040	26	44	76
Halon 1211	1985	11	11	11
	2000	17	20	24
	2040	31	53	91

that the intensities of use relative to general economic activity for any two chemicals are unrelated. As better empirical information becomes available on the substitutability of different PODs in consumption or their jointness in production, the technique presented

here could easily accommodate it. The intensities of use for substitutes in consumption would be negatively correlated; those for chemicals produced jointly would be positively correlated. Such relationships can have significant effects on the joint distributions of related chemicals and should ultimately be reflected in this kind of analysis.

The specific technique can also be used to develop scenarios that incorporate a much broader range of factors than those presented here. Scenarios that reflect additional factors may be important because of the correlations among economic variables. For example, if global economic growth is high, both the rate of production for PODs and the activities like agriculture that may potentially be affected by ozone depletion will grow faster. Assuring that "high economic growth" scenarios for PODs are matched with similar scenarios for the effects of ozone depletion on crop yields will yield a larger--and more accurate--measure of the benefit from limiting POD emissions than would be calculated if such scenarios were not matched. Developing scenarios that are conditional on general economic growth would allow such matching. The technique presented here would allow us to develop such conditional scenarios in the future.

Understanding how all of the uncertainties associated with stratospheric ozone depletion relate to one another is a complex task. The EPA is approaching this task by breaking it into manageable pieces, where complex information about uncertainties can be condensed into scenarios that effectively illustrate the breadth of the uncertainty. The technique developed here shows a way to assure that, even though scenarios relevant to different sources of uncertainty are developed separately, they can still be related to the primary issue relevant to policymakers--ozone depletion--and hence to the goals of the analysis as a whole.

ACKNOWLEDGMENTS

John Hoffman and Stephen Seidel organized an informal workshop that gave us an early opportunity to present the general approach used here and get suggestions. Suggestions from Michael Gibbs, Michael Kavanaugh, and Gary Yohe were especially helpful. James Hodges read an earlier draft and provided detailed comments that have significantly improved the Note. Jan Acton helped facilitate its production and review under tight deadlines. Mary Vaiana helped prepare the presentation of material in this Note to the Environmental Protection Agency's March 1986 workshop, "Protecting the Ozone Layer." Participants in that workshop, particularly Toby Page, provided helpful feedback. Alyce Shigg oversaw production of the many drafts underlying this Note and Patricia Bedrosian edited the final draft. We thank them all and retain responsibility for any errors that remain.

CONTENTS

FIGURES

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I. INTRODUCTION

Over the past 12 years photochemical models of the atmosphere have suggested that global human-caused emissions of certain chlorofluorocarbons (CFCs) and related chemicals may reduce the concentration of stratospheric ozone. We refer to these chemicals as potential ozone depleters or PODs. A sufficient reduction in stratospheric ozone could allow substantially greater amounts of ultraviolet radiation to penetrate to the earth's surface, potentially causing a wide variety of detrimental effects. These effects include significant threats to human health, reductions in crop yields, degradation of certain materials, and other important adverse ecological consequences.[1] Scientists studying the possibility of ozone depletion have not reached a consensus on the likelihood that these adverse effects will occur in the foreseeable future. However, because the PODs survive in the atmosphere for many decades after their release, current emissions may affect stratospheric ozone concentrations well into the next century. Consequently, if the probability that the PODs will cause serious adverse effects is sufficiently high, policies that reduce current human emissions of these chemicals may be warranted.

The U.S. Environmental Protection Agency (EPA) has undertaken a major effort to study these potential effects, to characterize systematically the uncertainties about them, and to examine the likely effects of alternative policies to control the emissions of PODs. Ultimately, this effort will help policymakers compare the social costs of controlling POD emissions with the social benefits. The social costs of controls are represented by the benefits that must be forgone if the commercial use of these chemicals is restricted. The social benefits are amelioration of the kinds of adverse effects mentioned above, where possible expressed in monetary terms.

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[1]For details, see National Academy of Sciences (1976, 1979, 1982, 1984) or Ramanthan et al. (1985).

The Rand Corporation is participating in this effort by, among other things, studying the market and technological factors that affect current and future human emissions of PODs. We focus on the seven most important of these: CFC-11, -12, and -113, carbon tetrachloride, methyl chloroform, and Halon 1211 and 1301. Rand has developed information on the likely sources of uncertainty associated with production of these seven PODs (Hammitt et al., 1986; Quinn et al., 1986). Previous Rand reports analyze the production of each chemical independently. Given EPA's approach to convoluting uncertainties, however, it is important to analyze the combined effect of all these chemicals on potential ozone depletion. Thus, we must characterize the joint uncertainty about production of the PODs. This Note explains why that is true and develops a simple methodology for doing so.

Our method focuses on uncertainties about *production* over time.[2] However, it is not production but ultimate emissions of the PODs that are relevant to potential ozone depletion. At present, we calculate the time path of emissions for each chemical production trajectory using deterministic algorithms similar to those used in prior Rand work (Palmer et al., 1980) and by the Chemical Manufacturers Association (CMA). Hence, the method does not capture the effect of any uncertainties about the relationship between production and emission of the chemicals.[3]

Section II provides additional background on EPA's policy analytic approach to potential ozone depletion and Rand's role in that approach. It explains the conceptual basis for integrating Rand's information on uncertainties about future chemical production into EPA's approach. Section III describes the specific analytic method we use to convolute uncertainties about the production of individual PODs to derive the probability distribution for the joint production of these chemicals. Our subjective probability distributions for production of individual

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[2]We treat annual production and use as equivalent, since production inventories over periods of several years are negligible.

[3]The character and importance of these uncertainties is an important topic for future analysis.

chemicals are reported in Sec. IV. These are based on Rand's past work on future production and emissions of PODs. Section V presents production scenarios based on the joint distribution derived from the distributions for each chemical. Conclusions and suggested directions for future work are presented in Sec. VI, and the computer code used to implement our method is documented in the Appendix.

II. BACKGROUND: THE NEED TO COMBINE DISTRIBUTIONS FOR POTENTIAL OZONE DEPLETERS

Many uncertainties impinge on the question of the costs imposed over the next century by continuing emissions of PODs. These range from questions about the future emissions trajectories of PODs and of other gases that influence ozone concentration, to questions about the effect of a specified set of emission paths on actual ozone concentration, to questions about the effects of greater ultraviolet radiation on human health, crop yields, and degradation of materials, and of other consequences of policy interest. Uncertainties about each of these factors contribute to the uncertainty about the magnitude of the potential threat and the effects of alternative global strategies for controlling the emission of PODs. Moreover, the presence of this pervasive uncertainty is an important factor in choosing an appropriate policy, since a more flexible policy may be preferred even to alternatives that would perform better in a more certain environment.

The EPA has designed a strategy for comparing the effects of alternative policies in the face of these many sources of uncertainty. The strategy first reduces the broad range of possible futures to a fairly small set of cases and then examines the effects of alternative policies in each case. The cases are constructed through the following method:

- Isolate the principal factors that contribute to uncertainty.
- For each factor, select a small number of scenarios to represent the range of uncertainty about it.
- Construct cases by taking all possible combinations of the scenarios for the different factors.

The Rand Corporation is analyzing uncertainties about the emissions of seven PODs. To incorporate its work into EPA's framework, Rand must develop scenarios to reflect the nature of uncertainty about future emissions trajectories for these PODs. In this section, we ask what

kinds of scenarios would be appropriate. We begin by noting that an explicit probability distribution for ozone depletion would be preferable to the current use of discrete scenarios if costs allowed. However, because of the extreme complexity of the computer simulation models of the atmospheric chemistry involved, computation costs prevent the use of Monte Carlo analysis to generate a distribution function for ozone depletion. As an alternative, we suggest an analytic method to develop scenarios that approximate the kind of information that would be produced by the preferred focus on a subjective probability distribution for ozone depletion.[1]

WANTED: A SUBJECTIVE PROBABILITY DISTRIBUTION FOR OZONE DEPLETION

The extent of possible ozone depletion lies at the heart of EPA's policy concerns.[2] Essentially, the concern is that certain human activities may lead to ozone depletion, which may in turn affect the quality of human life. Figure 2.1 summarizes, in a very cursory fashion, the EPA's view of the problem and the links that must be understood. To understand it, start at the top of the figure and work down. Market and technological factors and government policies, ranging from the ban on most uses of CFCs as aerosol propellants to workplace safety standards, currently affect POD emissions. The EPA is

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[1]There are two main alternative interpretations of probability--the frequency interpretation and the subjective interpretation. In the frequency interpretation, which is more widely understood, "the probability of event A" is understood to mean the relative frequency of occurrence of event A in some (invariably hypothetical) infinite sequence of repetitions of the mechanism in question. In the subjective interpretation, "the probability of event A" is a representation of one's belief about the likelihood of event A's occurring. That is, the first presumes the existence of a stochastic process that can be observed to get empirical information about the probability of an event, whereas the second is a formal way of presenting a subjective judgment. In this Note, all references to probability use the second interpretation; we provide a formal method for developing the implications of a set of subjective judgments about the state of the world. We thank James Hodges for emphasizing the importance of distinguishing these interpretations to make our intentions and discussion clearer.

[2]The chemicals analyzed here may also affect general climatic change, an issue that also concerns the EPA.

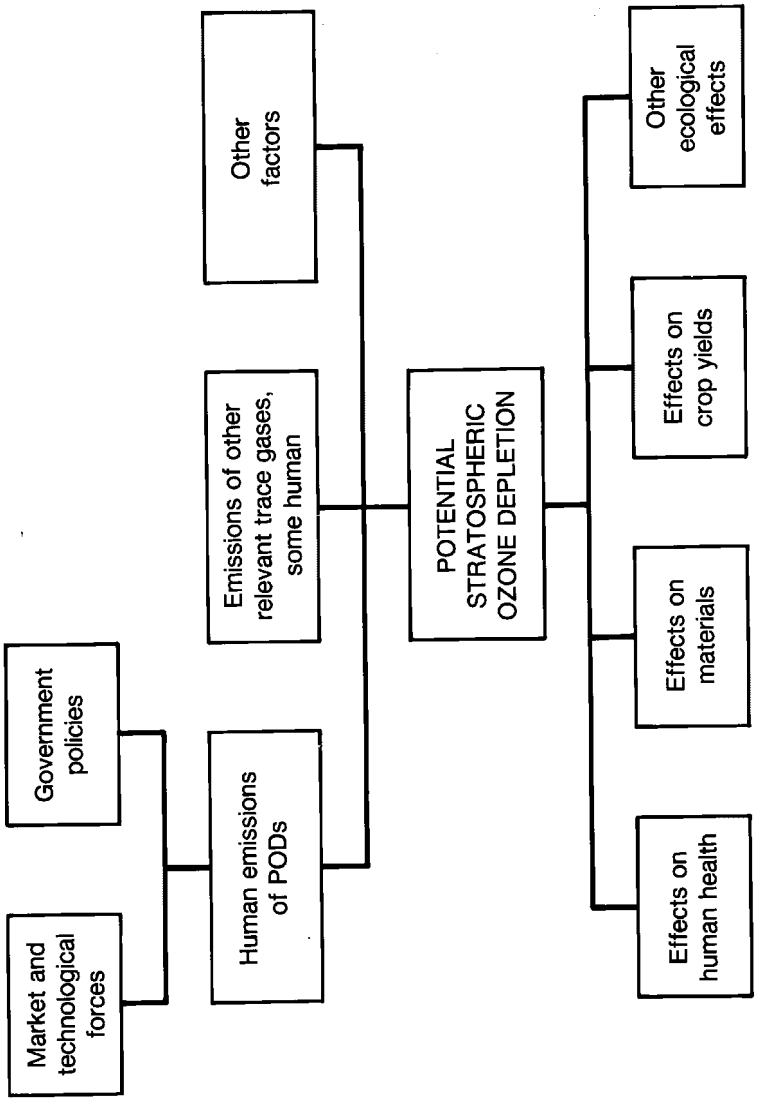

Fig. 2.1.—Schematic view of potential causes and effects of stratospheric ozone depletion

considering new government policies that could also affect emissions. After release to the atmosphere, PODs and other trace gases diffuse and react in a complex fashion that may be influenced by other factors such as global temperatures and the amount of solar radiation. One of the potential results of these complex interactions is a reduction in the concentration of stratospheric ozone. The diffusion and chemical reactions are simulated by computer models that produce time profiles of estimated ozone concentrations at different altitudes and, in some cases, latitudes. These time profiles can in turn be transformed into estimated time profiles of the various effects shown at the bottom of the figure, using a variety of models.

Each box has uncertainties associated with it. As noted above, the EPA plans to account for each of the identified uncertainties by developing scenarios to represent alternative possible outcomes corresponding to each box. For example, it might choose three scenarios to represent market and technological forces, eight to represent two possibilities each for emissions of three "other" gases, four to represent two parameterizations each of two models of the upper atmosphere, and so on. If these numbers of scenarios were used, the analysis would generate 96 alternative possible time profiles for stratospheric ozone. Each of these cases would then be compounded with scenarios that encapsulate information about uncertainties associated with the effects of each time profile, to generate the full number of cases to be analyzed for alternative policies.

So many sources of uncertainty are important that even a simplistic method of allowing each source to be represented by two or three scenarios leads to an unwieldy number of cases to use in policy analysis. However, the structure of the problem lends itself to a simplification that could potentially allow a much less simplistic treatment of uncertainty. Note that all of the information from the top half of the figure funnels through a single time profile--that for the extent of stratospheric ozone depletion--that is the only input required to study the remaining sources of uncertainty.[3] Thus, in theory, it is

[3]This is a slight oversimplification. Certain factors that affect emissions in the top part of the figure may also be important to the

possible to develop a subjective probability distribution for the extent of ozone depletion that summarizes all of the uncertainties in the boxes that feed into the POTENTIAL STRATOSPHERIC OZONE DEPLETION box in Fig. 2.1 that are relevant to the analysis of the effects in the final row of boxes.

A probability distribution for the extent of ozone depletion could be developed by first developing subjective probability distributions for the uncertain quantities in each of the boxes that feed into the POTENTIAL STRATOSPHERIC OZONE DEPLETION box and using Monte Carlo analysis to convolute these distributions. Actually, one would want a set of such ozone-depletion distributions, each conditional on a specified government policy. These distributions would not only summarize the extent of the known information about the factors that may influence depletion but would also allow the assigning of probabilities to particular ozone-depletion scenarios. Thus, one could state that the (subjectively assessed) probability that ozone depletion will fall between two specified levels in a given year is x percent (conditional on the corresponding government policy).

The difficulty with this approach lies in representing the chemical interactions in the atmosphere in a cost-effective way. Current models of the upper atmosphere are too complex and costly to use for more than a limited number of cases.

This difficulty does not eliminate the usefulness of using the concept of a probability distribution for ozone depletion. As we shall see, it can provide a basis for developing emission scenarios used as inputs to the atmospheric models. Ideally, we should be able to interpret cases easily in terms of this subjective probability distribution. For example, a "high" case should be developed from scenarios for market and technological factors, other trace gases, and other factors that together yield a "high" level of ozone depletion, perhaps one consistent with the 75th percentile of the subjective

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size of effects in the bottom half of the figure. For example, the level of general economic activity could affect the size of crops or quantities of materials that might be harmed by ozone depletion. These kinds of dependencies can be integrated by making the distribution for ozone depletion explicitly a function of general economic growth.

probability distribution for ozone depletion under current government policies. Of course, we cannot accurately estimate the subjective probability distribution without actually running the atmospheric models, which we cannot do often enough to generate the distribution. Nonetheless, if we must choose scenarios for the inputs to the atmospheric models, it makes sense to think about how to choose them in light of what they are ultimately meant to do: Provide the kind of information that a subjective probability distribution for ozone depletion would provide if we could develop it directly.

SCENARIOS BASED ON A PROXY FOR STRATOSPHERIC OZONE DEPLETION

The scenarios developed here are intended to approximate those that would be derived from a subjective probability distribution for the extent of ozone depletion, if one were to be developed. We focus on growth rates for each potential ozone depleter so that a single random variable--the growth rate--can describe a time profile for production. We identify the main independent sources of uncertainty for the growth rate of each chemical, designate them as "component" random variates, and parameterize "component" distributions for these variates. The available information on economic and technological factors that affect growth in use of these chemicals is embodied in the distributions for these component variates. If the production growth rates of two chemicals are related, they will both be dependent on at least one common component variate.

To combine the distributions for the individual chemicals, we develop a "score function" that relates production growth rates of the seven PODs to a scalar value that has some policy relevance. Ideally, the score function would be a monotone transformation of some relevant measure of ozone depletion, so that its subjective distribution could easily be related to the distribution of ozone depletion. Because that is not possible, we seek the best proxy that we can implement in a simple way. We derive the subjective probability distribution for this score function by convoluting the distributions for each of the component variates underlying the POD production growth rates.

We then *define* scenarios in terms of quantiles of the score function. For example, an "upper limit" growth scenario might use the 95th percentile of the distribution; a "high" growth scenario might use the 75th percentile. We then seek the quantile of the distributions for the component random variates that, if chosen for all *component* variates simultaneously, would yield the value of the score function for the quantile used to define the scenario. For example, using the 82nd percentile for each component variate might yield values of growth rates that, when placed in the score function, yield its value at the 95th percentile of its distribution.[4] We then use the production growth rates for each chemical that are consistent with these values of the component variates to define the scenario in terms of the chemicals themselves. The resulting set of production paths for the seven chemicals is a scenario that can be used to generate emissions inputs for the atmospheric models. Consider the key steps of this procedure in turn.

Subjective Probability Distributions for Individual Chemicals

Our approach begins as a standard Monte Carlo analysis would. We seek a set of independent probability distributions and then derive a joint probability distribution for the seven chemicals based on these independent distributions. The joint distribution developed in this Note, discussed in more detail in Sec. IV, is based on the assumption that general economic growth is one source of uncertainty that affects the production of all chemicals. Otherwise, uncertainties about the production of these chemicals are unrelated. The approach, however, could easily accommodate information on other interrelationships by adding additional component variables to the analysis.

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[4]Note that the quantiles used for the component variates will differ from the quantile of the score function and will be closer to their respective medians, unless all of the component variates are perfectly correlated.

Score Function

The score function is designed to do two things. First, as a practical matter, it provides a scalar value that summarizes the information in the subjective joint probability distribution for the individual chemicals. This single value provides a simple way to relate scenarios to one another. Second, and equally important, the value is designed to have policy significance. Increased production of any of the PODs will increase the value of the score function and should also be associated with greater ozone depletion. Hence, "high" growth scenarios should be associated with high ozone depletion and "low" growth scenarios with low ozone depletion. This relationship between the score function and the extent of ozone depletion is obviously not perfect. If it were, we would not need the atmospheric models. But it is designed to yield scenarios that can be interpreted roughly in terms of the likely corresponding ozone depletion.[5]

One way to think about the score function is as a simple tool that policymakers can use to rank alternative sets of POD production levels. A simple score function would be the sum of POD production in a given year. However, this function would be inadequate because of the widely different effects that a unit of each POD may have on the ozone concentration. The score function we propose weights the production levels of the chemicals, transforming them to a standard value so that a unit of each is believed to have approximately the same effect on the ozone.

The EPA has proposed a similar approach to ozone depletion in the past.[6] Although our analysis does not use exactly the approach EPA proposed, the use of a score function to order policy thinking about chemicals that policymakers do not consider to be equally dangerous is consistent with that approach.

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[5]Holding other factors, including the emissions of other gases, constant.

[6]See U.S. EPA (1980).

Specifically, of the many different score functions that might be used, we use a simple weighted sum of the production growth rates for individual chemicals. The subjectively chosen weights are intended to reflect the chemicals' relative potential to deplete stratospheric ozone. The ith chemical's weight is defined as

$$w_i \equiv (p_i\ f_i\ e_i)/\Sigma\ (p_i\ f_i\ e_i)$$

where

p_i = the annual global production of the chemical,

f_i = the fraction of production of the ith chemical that is likely to be released to the atmosphere, and

e_i = the estimated effect of an emitted kilogram of the chemical on stratospheric ozone relative to that of CFC-11.

None of these factors can be specified with certainty. We estimate the 1985 production and use levels for each chemical based on the best available data (see Hammitt et al., 1986.) The fraction of production that will ultimately be released is based on detailed study of the applications of each chemical (see Hammitt et al., 1986, and Palmer et al., 1980). The estimated relative ozone-depletion potencies are based on information from atmospheric models (see Quinn et al., 1986). These relative potencies are sensitive to assumptions in the atmospheric models; we use them only to suggest orders of magnitude for the weights.

We construct two sets of weights: one for the period 1985-2000 and another for 2000-2040. The weight for each chemical is proportional to the product of the chemical's annual production at the start of the relevant period and a subjective factor designed to capture the other two terms, f_i and e_i. The factors for CFC-11, -12, and -113 are 1 because, despite their diverse uses, the majority of annual production of each CFC is emitted relatively promptly, and each presents about the same potential threat to ozone per kilogram. For carbon tetrachloride,

the weight is 0.064, the estimated share of production that is emitted (most carbon tetrachloride produced is consumed in the production of CFC-11 and -12). Carbon tetrachloride presents about the same potential threat per kilogram to ozone as the three CFCs. The factor for methyl chloroform is 0.1, since atmospheric models suggest its effect on ozone is an order of magnitude smaller than the three CFCs. Like the CFCs, emissions are typically prompt. Finally, we use a factor of 10 for both Halons. Their effect per kilogram on stratospheric ozone may be an order of magnitude or more greater than that of the CFCs above. We choose a factor at the low end of this scale to reflect the fact that Halons are banked for long periods of time between production and emission, and consequently should not begin to contribute to ozone depletion until much later, and also because a large fraction of the banked Halon 1301 may be recovered and never emitted.

The most important result of using this weighting scheme is that the growth rates of chemicals produced in large volume, or likely to have a larger depletion effect per gram, contribute more to the score function than others. As a result, the score function should serve as a proxy for the potential for ozone depletion.

From Score Function to Component Distributions

Our approach makes ozone depletion the focus of concern, even though it is represented only by a proxy. Any value of the score function could be produced by an infinite variety of production growth rates for individual chemicals. That problem lies at the core of using scenarios; no one seriously expects any one scenario to occur in the sense that all growth rates specified in the scenario persist as expected over the life of the scenario. Scenarios are designed to illustrate the implications of an underlying probability distribution or to represent some general kind of event that the probability distribution suggests has a significant probability of occurring. We need a simple convention to pick the single set of time profiles that make up a scenario.

We seek scenarios that illustrate the different time profiles of ozone depletion that production of the seven PODs might induce. Otherwise, we are indifferent about the specific time profiles chosen

for individual chemicals. It seems reasonable to seek a convention that treats sources of uncertainty equally to avoid any manipulation of the approach aimed at emphasizing one chemical over another. Accordingly, we choose as a convention to use the same quantiles for each of the independent component distributions. Other conventions could be chosen, just as scenarios with similar policy implications can be defined in different ways.

The subjective probability distribution for ozone depletion stands at the heart of EPA policy analysis. If that distribution could be approached directly, that would be the best path to follow. This section presents an alternative approach to take when the best alternative appears too costly. Our approach still focuses on the central point of interest--ozone depletion. It seeks a method to generate scenarios that are likely to capture and illustrate the range of ways in which economic and technological factors relevant to the seven PODs could affect stratospheric ozone depletion.

The approach suggested in this section is conceptual in nature; it could be implemented in many different ways. Section III explains the specific method we have developed to implement this concept.

III. THE DISTRIBUTION OF THE SCORE FUNCTION

To implement our approach, we need explicit subjective probability distributions for production growth rates and for the score function. In this section we develop a formulation that allows us to use a closed analytic solution to convolute the distributions for the individual PODs and to derive the distribution of the score function. The subjective probability distributions for the individual chemicals are described in Sec. IV.

Our method approximates the distribution for the score function that would be developed if all the component variates that describe the growth rates of individual PODs were distributed normally.[1] Normal distributions appear reasonable in all but a few instances, and these can be accommodated without serious difficulty. Our approximation would be exact if the relative production shares of each chemical remained constant over time. These shares change in our analysis but not enough to seriously threaten the integrity of the general results.

The general conceptual approach outlined in Sec. II would allow a more general implementation based on standard Monte Carlo techniques that would require neither an assumption of approximate normality nor the kinds of approximations used here. Whether this approach would justify the additional costs is unclear, since a Monte Carlo analysis requires approximations when continuous distributions are approximated by discrete ones.

The approach presented in this section allows quick, low-cost development of scenarios without sacrificing much accuracy. We discuss in turn the role of linear approximations in aggregating chemical use and the closed analytic solution we use to choose chemical growth rates that are consistent with any scenario chosen using the score function.

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[1]Equivalently, we assume that the future quantities of PODs are distributed approximately log-normally. The correspondence between a normally distributed growth rate and a log-normally distributed future production level is good for modest growth rates. Let $Y_t = Y_0 (1 + r)^t$ where Y_i is production in year i and r is the growth rate. Then $\log Y_t = \log Y_0 + t \log (1 + r) \simeq \log Y_0 + t\, r$ for small r.

AGGREGATING CHEMICAL USE

The growth rate for the production of each chemical is characterized as the sum of the growth rates of general economic activity (GNP) and of the specific intensity of use of each chemical, defined as the level of use relative to the GNP.[2] We focus on the average annual growth rates of GNP and intensity for each chemical. Our subjective probability distributions for the growth rates of these components are normal distributions. Because the score function is a linear combination of the component variables, our uncertainty about its value is also described by a normal distribution. The parameters of the distribution of the score function's value can be expressed as simple functions of the parameters of the distributions of the component variables.

We have subjective distributions for use of the seven PODs before 2000 for different world regions and, for CFC-11 and CFC-12, for product applications. We must aggregate these distributions to derive the distributions for world use of each chemical and similarly aggregate across chemicals to derive the distribution for the score function. We rely on linear approximations in making these aggregations.

First consider the aggregation of growth rates for different uses of a chemical or for total use of a hemical in different world regions. For example, we have developed subjective probability distributions for CFC-12 use in aerosols, foam blowing, refrigeration, air conditioning, and other applications (Hammitt et al., 1986). Let x_i be the amount of CFC-12 used in the ith application. Then the total amount of CFC-12, x, is simply $\Sigma\, x_i$ and the rate of change in x can be related to the rate of change of the $\{x_i\}$ at any instant in time in the following way:

$$(1/x)(dx/dt) = \sum_i [(x_i/x)(1/x_i)(dx_i/dt)] \qquad (3.1)$$

[2]This is an approximation, but one that works well for small growth rates. The exact relationship is $(1 + r_k) = (1 + g)(1 + u_k) = 1 + g + u_k + gu_k$, where r_k is the growth rate for the kth chemical, g is the growth rate for GNP, and u_k is the growth rate for the intensity of use of the kth chemical relative to GNP. For small g and u_k, $gu_k \approx 0$ and $r_k \approx g + u_k$. This standard approximation is often used in economics.

If we define r as the growth rate of CFC-12, r_i as the growth rate of the ith application of CFC-12, and a_i as the share of CFC-12 used in the ith application ($a_i = x_i/\Sigma\, x_i$), Eq. (3.1) can be reexpressed as

$$r = \sum_i (a_i\, r_i) \tag{3.2}$$

Given our small growth rates, $r_i \simeq g + u_i$,[3] where g is the percentage growth rate for GNP and u_i is the growth rate for the intensity of use of the ith application relative to GNP. Hence, Eq. (3.2) can be rewritten as

$$r \simeq g + \sum_i (a_i\, u_i). \tag{3.3}$$

The derivation of Eq. (3.3) incorporates two linear approximations. First, it assumes that the growth rates of two factors affecting a variable can simply be summed to calculate the growth rate of the variable itself. Given the small growth rates we are considering, this is adequate. Second, although Eq. (3.2) is exact at any instant, it is not exact over a discrete period of time unless all u_i are equal and hence all a_i remain constant over the period. Since we use the $\{a_i\}$ corresponding to the beginning of the period, we are essentially using a Laspeyres index to approximate aggregated growth rates; this index is adequate so long as the $\{a_i\}$ do not shift too much over the period of interest.[4]

Similarly, to aggregate use across world regions we use a linear formula to approximate the global growth rate. If r_j is the rate of

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[3] See footnote 2 above.

[4] Alternatives would include using the weights corresponding to the end of the period (a Paasche index) or an intermediate set of weights. As long as the correct weights do not shift much over the period, any of these choices will produce similar results. This is a specific example of the general problem of defining index numbers. For further discussion, see Hirshleifer (1976) or other economics texts.

growth in the jth region and b_j is the share of global use there, the global growth rate

$$r \simeq \sum_j (b_j\ r_j). \tag{3.4}$$

The $\{b_j\}$ are fairly stable as long as uses in different regions do not grow at markedly different rates.

The second place where linear aggregation is important is in the definition of the score function. We *define* the score function as

$$s = \sum_k (w_k\ r_k)$$

$$\simeq g + \sum_k (w_k\ u_k) \tag{3.5}$$

where w_k is the subjective weight for the kth POD, described in Sec. II, and u_k is the growth rate for the intensity of use of the kth POD.

DERIVING SCENARIOS FOR INDIVIDUAL CHEMICALS FROM THE SCORE FUNCTION

If g and u_k in Eq. (3.5) are normally distributed, then s is normally distributed as well. This observation is the key not only to convoluting uncertainties in the components into a distribution for the score function but also to moving in the opposite direction. Once a scenario is defined in terms of a quantile of the distribution for s, we can use the normality of the score function and its components to find the common quantile for the component distributions that is consistent with this scenario.

Start by noting that the mean (m_s) and variance (v_s) of s can be defined in terms of the means (m_k), variances (v_k), and covariances ($v_{\ell k}$) of its components:

$$m_s = m_g + \sum_k (w_k m_k)$$

$$v_s = v_g + \sum_k (w_k^2 v_k) + 2 \sum_{k>\ell} (w_k w_\ell v_{k\ell}) \tag{3.6}$$

The value of the score function at the q_sth quantile of its distribution is

$$s(q_s) = m_s + v_s^{.5} z(q_s) \tag{3.7}$$

where $z(q_s)$ is the value of the z-statistic corresponding to the q_sth quantile of the standard normal distribution. Analogously, the q_cth quantiles of the growth rates of GNP and the intensity of use of the ith chemical can be defined as:

$$g(q_c) = m_g + v_g^{.5} z(q_c)$$

and (3.8)

$$u_i(q_c) = m_i + v_i^{.5} z(q_c).$$

We would like to find the value $z(q_c)$, and thus implicitly the quantile q_c, so that if we fix g and all the u_k at their q_cth quantiles, s will take the value at its q_sth quantile. To do this, for a given value of s, substitute Eq. (3.8) into Eq. (3.5) and Eq. (3.6) into Eq. (3.7) and set Eq. (3.5) equal to Eq. (3.7). Rearranging yields

$$z(q_c) \left[v_g^{.5} + \sum_i (w_i v_i^{.5})\right]$$

$$= z(q_s) \left[v_g + \sum_i (w_i^2 v_i) + 2 \sum_{k>\ell} (w_k w_\ell v_{k\ell})\right]^{.5} \tag{3.9}$$

or

$$z(q_c) = z(q_s) \;/\; \beta \tag{3.10}$$

where

$$\beta = \frac{v_g^{.5} + \Sigma\,(w_i\, v_i^{.5})}{[v_g + \Sigma\,(w_i^2\, v_i) + 2 \underset{k>\ell}{\Sigma}\,(w_k\, w_\ell\, v_{k\ell})]^{.5}} .$$

Equation (3.10) allows one easily to transform quantiles of the distribution of the score function into the corresponding quantiles of the distributions underlying the POD growth rates. Each scenario is based on a value of q_s, which yields $z(q_s)$, which in Eq. (3.10) yields $z(q_c)$.[5] We know that $\beta > 1$ so that the quantiles for the component distributions are closer to their medians than the corresponding quantiles for the distribution of the score function.[6] That is, the quantiles of the component variates that correspond to a specified subjective probability interval for the score function will span an interval associated with a lower level of subjective probability for the component variates. As shown in Table 5.2 below, the quantiles of the component distributions corresponding to the 90 percent subjective probability interval for the score function approximately span a 62 percent subjective probability interval for each component variate.

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[5]Note that we need not determine q_c to calculate the growth rates relevant to any scenario. Once $z(q_c)$ is calculated from Eq. (3.10), it can be substituted into Eq. (3.8) and the appropriate values of the component growth rates can be calculated.

[6]To see this, square the expression that defines β in Eq. (3.10) and subtract the denominator from the numerator. This yields an expression

$$2 \sum_i [w_i v_g^{.5} v_i^{.5}] + 2 \underset{i>j}{\Sigma} [w_i w_j ((v_i v_j)^{.5} - v_{ij})] .$$

The first term must be positive. To sign the second, note that the subjective analog of the Pearson correlation coefficient, $v_{ij}/(v_i v_j)^{.5}$, cannot exceed unity. Hence, the second term is also positive. Therefore the numerator must exceed the denominator and β must exceed one.

Adopting normal distributions for the component growth rates and using linear approximations to convolute uncertainties and thereby construct distributions for aggregations of the component random variates considerably simplifies our analysis. The scenarios generated will reflect the influence of the approximations used. The alternative is to use a simulation technique like Monte Carlo, which itself normally requires that we approximate the underlying distributions. Given the likely sources of error associated with the method presented here, we believe it provides a good, quick, and low-cost method for developing scenarios that reflect the jointness of the underlying subjective probability distribution for production levels of the chemicals of interest to policymakers.

IV. SUBJECTIVE MARGINAL PROBABILITY DISTRIBUTIONS FOR POTENTIAL OZONE DEPLETERS

To construct scenarios from our subjective probability distribution for the production growth rates for the seven chemicals we are studying, we must choose subjectively based parameter values with which to characterize it. This section explains how we choose these parameter values for the period 1985 to 2040.[1] It begins with a brief explanation of the methodology used to develop the distribution based on information reported in other Rand documents. It then summarizes our analysis of the period 1985-2000. Because Hammitt et al. (1986) document our choice of parameter values for this portion of our analysis, we simply outline the approach used and summarize the results. Finally, the section explains how parameters were developed for the period 2000-2040.

METHODOLOGY

The ultimate object of interest in developing the subjective probability distribution is how the production of seven chemicals grows over time. To examine this, we focus on production growth rates. How exactly should we represent correlations among growth rates over time for each chemical? And how exactly should we express relationships among growth rates for different chemicals in any year? Specifying these relationships completely would entail a density of detail not warranted by the extent of our knowledge about the relationships. We seek a simplified specification of the relationships that captures their most important features.

[1]It is obviously difficult to think about events this far in the future. We look ahead this far to accommodate the needs of atmospheric modelers. Because the chemicals we are studying can remain in the atmosphere for decades following their emission, atmospheric models rely on long time series of emissions as inputs. We try to reflect the degree of our uncertainty about the far future in our choice of parameter values.

Relationships Across Time

Because our primary concern is with cumulative POD production, we focus on average annual growth rates over long periods of time. Specifically, to choose normal distributions to represent uncertainty about growth rates, we must choose means and variances for our distributions for the secular growth rate for each chemical and covariances among growth rates for different chemicals in each period. Because of our focus on long-term average rates we need not address year-to-year variations associated with the business cycle or temporary market conditions. It is reasonable to ignore these events because their influence on the variance of the average growth rate falls as the length of the period grows and should be quite modest over the 15-year and longer periods we consider.

We break the total period from 1985 to 2040 into two subperiods and examine the means and covariance structure of secular growth within each. Parameter values for the period 1985-2000 are based on analysis in Hammitt et al. (1986), whose results reflect subjective judgments about the range of reasonable growth rates for chemicals in different applications. These judgments are based on a detailed analysis of market trends and potential changes in markets, technologies, and regulations that could affect the use of these chemicals. Parameter values for the period 2000-2040 are based on concepts developed in Quinn et al. (1986). That document looks at historical trends in the relationship between chemical use and income and uses these to project a range of use levels over the period in question. The analysis is necessarily less detailed than that in Hammitt et al. (1986). We draw on results from Hammitt et al. in the later period to assure that our assumptions in the two periods are mutually consistent.

Although the structure of growth rates within each period may be conceived as a set of means and a covariance matrix for each period, the relationship between the periods is more difficult to represent parametrically. We choose a relationship that carries over the implicit assumption of a positive correlation between yearly growth rates across time within the two periods.[2] To construct a high growth scenario for

[2]Heuristically, we can think of a growth rate as having two

the full period, we use high growth scenarios in each period. Similarly, low growth scenarios use low growth rates in both periods.

Relationships between Chemicals

We treat the average annual growth rate as the sum of two terms: (1) general economic growth and (2) growth of intensity of use relative to GNP, which includes both growth in the product markets where the chemical is used (relative to GNP) and growth in the use of the chemical in the manufacture of the products. We assume that sources of uncertainty in the intensity of use of each chemical are uncorrelated between chemicals, both within and across periods. With a better empirical understanding of the chemicals markets, it should be possible to identify relationships of this kind in the future. For now, however, we assume them away.

The general economic growth component is common to all of the chemicals and consequently creates a positive covariance among the growth rates for all of the chemicals. Before 2000, we divide the world into regions and specify general economic growth and chemical intensity distributions for each; after 2000, we treat the world as a single unit. When dealing with more than one region, we assume that growth rates in different regions are positively correlated with one another. The next subsection discusses this in more detail.

In sum, our method characterizes a wide variety of factors relevant to uncertainty about the future use of these chemicals. It reflects interrelationships across time and across chemicals. A more complicated framework for relating growth rates could potentially capture subtleties not represented here. However, empirical data of the type and quality necessary even to quantify all of the details of this system in a historical period are not currently available. Until better data are available, a more detailed structure is difficult to justify.

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components. The first is a secular component that can be represented by a single random variate for each chemical. The second is an annual component that requires separate random variates for each year. These can be independent of one another over time (though not necessarily across chemicals). The first component embodies the positive correlation we wish to capture in our choice of a method to relate the two periods. The second is an additional source of uncertainty that helps explain why the variance of a mean growth rate can decrease for longer periods.

SUBJECTIVE PROBABILITY DISTRIBUTION FOR THE PRE-2000 PERIOD

The subjective probability distribution for the period before 2000 is taken from Hammitt et al. (1986). That source develops explicit 80 percent subjective probability intervals for the use and production of the seven PODs through the end of the century. It divides world use into use in three major regions, and projects future use of CFC-11 and -12 in each of the major products in which they are used. The mean rates of growth are based on analysis of trends and industry forecasts for each application or chemical. Although the reported mean rates are not constant over the period for some of the uses, we have calculated average annual rates over the period for use here.

We aggregate our distributions for growth rates across applications of a single chemical, and across chemical use in different regions, to obtain our distributions for world GNP and chemical intensity growth using the methods described in Sec. III. When aggregating distributions across regions, we use a positive correlation (a coefficient of 0.75) across regions for both GNP and chemical intensity growth rates. The parameters of the resulting distributions are reported in Table 4.1.

The table displays the parameters of the growth rate distributions in two forms. The columns labeled "Intensity" include the mean and standard deviation of our distributions for the rate of growth of intensity of use of each chemical, relative to general economic growth. The last row of the table shows the mean and standard deviation of our distribution for the general economic growth rate itself in these columns. The columns labeled "Production" report the mean and standard deviation of our distributions for growth rates for production of each chemical, including the effects of both general economic growth and intensity of chemical use. The mean of our distribution for the production growth rate is the sum of the means of our distributions for general economic growth and intensity of use. The standard deviation of the distribution for the production growth rate is the square root of the sum of variances for general economic growth and intensity of use.

Table 4.1

PARAMETERS OF THE SUBJECTIVE JOINT PROBABILITY DISTRIBUTION IN THE PRE-2000 PERIOD

(Use in thousands of metric tons, rates in % per year)

Chemical	1985 Use	Intensity		Production	
		Mean	Standard Deviation	Mean	Standard Deviation[a]
CFC-11	341.5	0.02	0.98	3.30	1.51
CFC-12	443.7	-1.00	1.05	2.28	1.56
Carbon tetrachloride	1029.0	-0.49	1.02	2.79	1.54
CFC-113	163.2	3.27	1.67	6.55	2.03
Methyl chloroform	544.6	-0.32	1.10	2.96	1.59
Halon 1301	10.8	1.08	2.29	4.36	2.56
Halon 1211	10.8	0.96	2.33	4.24	2.60
Gross global product		3.28	1.15		

[a] The covariance among the chemical production growth rates is the variance of gross global product or 1.32.

As shown by Table 4.1, we expect use of CFC-113 and the Halons to grow more rapidly during the remainder of the century than do the other chemicals. This reflects a typical pattern of chemical use, in that relatively recently marketed "specialty" chemicals that are produced in limited quantities grow rapidly as they are adopted in applications to which they are well suited. Older chemicals, that are produced in larger quantities, may not grow as quickly because they have already been adopted in the applications for which they are best suited. The covariance among the production growth rates is equal to the variance of general global economic growth because the intensities are uncorrelated with one another and with general economic growth.[3]

[3]The total growth rate for the ith chemical, r_i, equals $g + u_i$, where g is the general growth rate and u_i is the growth of intensity of use of the ith chemical relative to general economic growth. Hence, $cov(r_i,r_j) = cov(g + u_i, g + u_j) = var(g) + cov(g,u_i) + cov(g,u_j) + cov(u_i,u_j) = var(g)$, since all the covariances in the last step are equal to zero.

SUBJECTIVE PROBABILITY DISTRIBUTION FOR THE POST-2000 PERIOD

The subjective probability distribution for the post-2000 period is derived from information from a number of sources. We chose parameter values that reflect the rate of general economic growth based on data from William Nordhaus and Gary Yohe.[4] We chose parameter values to reflect the rate of growth of chemicals relative to general economic growth based on concepts developed in Quinn et al. (1986) and the parameter values chosen for the pre-2000 period. Information from the pre-2000 period is used to assure internal consistency in the distribution. This subsection first considers how information from these sources was used and then reports the resulting distribution for the post-2000 period.

Development of the Subjective Probability Distribution

During the post-2000 period, it is much more difficult to rely on detailed analyses of individual chemical applications and markets than it is in the pre-2000 period. Our basic level of uncertainty about events in this period makes it difficult to imagine the range of events that might occur. Quinn et al. (1986), for example, present the best available analysis of the kinds of events that might be important to the markets for PODs after the turn of the century. But even this analysis generally shows less variation in growth rates after 2000 than before. In particular, it allows for no variation in the rate of general economic growth. As a result, we build on the basic concepts developed in Quinn et al. (1986), but seek a more realistically broad range of uncertainty for the growth of production during this period.

Consider first the parameter values of the distribution for the global economic growth rate. We develop parameters for this distribution based on distributions Nordhaus and Yohe have developed on the projected rates of population and labor productivity growth. We start with a weighted average of their parameters for these distributions over the periods 2000-2025 and 2025-2050. We posit a

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[4]Personal communication with Gary Yohe, Wesleyan University, Middletown, Connecticut, 8 January 1986.

correlation coefficient of -0.2 between population growth and growth in labor productivity over the period 2000-2040.[5] From these, we calculate parameters for use in our analysis. Since the GNP growth rate is approximately the sum of the population and labor productivity growth rates,[6] our mean GNP growth rate is the sum of the means that Nordhaus and Yohe use for population and labor productivity, and our variance is the sum of the variances that they use for population and labor productivity, less a small quantity to take account of the negative correlation between them.[7]

Now consider parameter values of the distributions for growth rates of intensity of use relative to general economic growth. The most important concept in Quinn et al. (1986) is that the rate of growth in the production of PODs will tend toward the rate of general economic growth over the long run. Quinn et al. use gross national product (GNP) per capita as a measure of general economic income. We believe a more appropriate measure is GNP itself, since this captures growth in the income of individuals and in the population as a whole.[8] Hence, we assume that on average intensity of use will not change over the long run.

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[5]Global labor productivity and population are likely to be inversely correlated over this period because population increases are likely to be in the poorer nations that suffer from shortages of human and physical capital. Using an input-output model of the world economy, Leontief (1979) simulates how variations in population are likely to be inversely correlated with per capita GNP. His results are consistent with the use of a correlation coefficient of -0.2.

[6]See footnote 2 in Sec. III.

[7]The adjustment term is (-0.2)(2)(standard deviation for population growth rate)(standard deviation for growth rate of labor productivity). This term is small enough so that the choice of a correlation coefficient does not change our results much.

[8]It has been suggested that a rate of growth between that of GNP per capita and GNP itself might be most appropriate. That is because, as indicated above, it is likely that population and GNP per capita are negatively correlated. We recognize that by reflecting this negative correlation in our distribution for GNP itself. Once that relationship is accounted for, GNP is a more useful measure of income than GNP per capita.

For most chemicals, that implies a mean of zero for the rate of growth of intensity. The Halons are treated slightly differently. For Halon 1301, we expect recycle and recovery to become important after 2000, creating a source of Halon 1301 that can compete with new production. As a result, even if the annual demand for new Halon 1301 grows at the rate of growth of the GNP, production will grow more slowly. This implies a negative growth rate of intensity of use. For Halon 1201, we expect penetration of the fire extinguishant market to slow beyond 2000, leading to a slightly negative growth rate for intensity of use.

Appropriate variances are harder to choose for these distributions because the range of uncertainty is difficult to conceptualize in markets for individual chemicals this far into the future. We start with the ranges suggested in Quinn et al. (1986). This document develops ranges of growth rates for CFC-11 and -12 and, to a lesser extent, CFC-113. We then compare these ranges with the ranges for these chemicals developed in Quinn et al. and Hammitt et al. (1986) to the pre-2000 period, a period we understand much better.

Our comparison of the range of growth rates in the two periods is based on a second important concept developed in Quinn et al. Uncertainty in either period reflects the joint probabilities of many individual events over time. In a short time period, the number of events relevant to our analysis--changes in regulation, technology, product line, and so on--is small, leading to a possibility that any one of these could lead to very large changes relative to the mean rate of growth. Over a longer period of time, these events tend to have offsetting effects, suggesting that a reasonable range of average annual growth rates in intensity of use should fall over time if the range of events likely in any fixed length of time remains constant. This is simply a reflection of the fact that the variance of a mean of a set of independent, identically distributed random variables falls as the number of variables rises. Because the pre-2000 period is so much shorter than the post-2000 period, we must adjust variances in the two periods before comparing them.

We can use this view of the uncertainties underlying our distributions for intensity growth rates to choose the variance of growth rates in the post-2000 period based on those in the pre-2000 period. To do so, calculate the variance for the pre-2000 period by squaring the chosen standard deviation for each chemical. Multiply this by 15/40 = 0.375 to find the equivalent variance for the longer post-2000 period.[9] Adjust this variance up by a factor to reflect our belief that uncertainty is higher in the post-2000 period. Choosing this factor is inherently arbitrary; after a review of the analysis of likely trends in the post-2000 period in Quinn et al. (1986) and other available sources, we choose a factor of 1.25. Use this new variance as a basis for the standard deviation of the post-2000 distribution for the rate of growth of intensity of use relative to general economic growth. The standard deviations reported in Table 4.2 are based on this calculation.

Parameters of the Joint Distribution

Table 4.2 presents the parameter values of the subjective probability distribution for growth rates in the post-2000 period. Note that the means of our subjective probability distribution for growth rates are generally lower than for the period before 2000, and the standard deviations are also smaller, as discussed above. The means of our subjective probability distribution for the growth rates for all of the PODs except the Halons are equal. Growth rates for the Halons are lower because we expect growth to slow as the likely new applications

[9]The variance of a mean of n independently and identically distributed random variables with variance v is v/n. Hence, the ratio of variances for means based on two groups of these variables with group sizes n_1 and n_2 is n_1/n_2. We are not suggesting that events in individual years are independent of one another. But events in a time period as long as five years probably are more or less independent of events in the next five-year period. The proportionality of the two periods is the same whether we consider events within each period associated with one-year or five-year subperiods. We emphasize here that we are dealing with subjective distributions. We use statistical concepts most commonly associated with a frequency view of statistics to formalize our view of the sources of uncertainty underlying our distributions for the two periods.

Table 4.2

PARAMETERS OF THE SUBJECTIVE JOINT PROBABILITY DISTRIBUTION IN THE POST-2000 PERIOD

(In % per year)

	Intensity		Production	
Chemical	Mean	Standard Deviation	Mean	Standard Deviation[a]
CFC-11	0	0.67	2.4	1.17
CFC-12	0	0.72	2.4	1.20
Carbon tetrachloride	0	0.70	2.4	1.19
CFC-113	0	1.15	2.4	1.50
Methyl chloroform	0	0.75	2.4	1.22
Halon 1301	-0.45	1.57	1.95	1.84
Halon 1211	-0.05	1.60	2.35	1.87
Gross global product	2.4	0.96		

[a] The covariance among the chemical production growth rates is the variance of gross global product or 0.92.

for these chemicals are exhausted. The growth is slowest for Halon 1301 where recovery and reuse of the chemical should significantly affect the need for new production as its likely markets are penetrated. Standard deviations are also similar for all of the PODs but CFC-113 and the Halons. Regulatory uncertainty will remain high for CFC-113. We are significantly less certain in general about the future of the Halons than about the future of the other chemicals.

MARGINAL DISTRIBUTIONS FOR INDIVIDUAL CHEMICAL PRODUCTION

Table 4.3 presents some illustrative quantiles of the marginal distributions for production of individual chemicals in 2000, 2020, and 2040, together with estimated current world use. These results suggest that a wide range of outcomes are possible as we move into the future. To understand the full implications of the subjective probability distribution described here, we must view outcomes for chemicals jointly. The joint results are presented in Sec. V.

Table 4.3

PRODUCTION LEVELS AT SPECIFIED QUANTILES OF THE SUBJECTIVE MARGINAL PROBABILITY DISTRIBUTIONS FOR INDIVIDUAL CHEMICALS

(In thousands of metric tons)

Chemical/ Year	Quantile				
	0.05	0.25	0.50	0.75	0.95
CFC-11					
1985	342	342	342	342	342
2000	386	479	556	644	794
2040	466	907	1435	2263	4326
CFC-12					
1985	444	444	444	444	444
2000	425	532	622	725	901
2040	504	1001	1606	2565	4994
Carbon tetrachloride					
1985	1029	1029	1029	1029	1029
2000	1070	1335	1554	1807	2237
2040	1280	2519	4014	6371	12290
CFC-113					
1985	163	163	163	163	163
2000	262	348	422	512	671
2040	256	605	1091	1956	4476
Methyl chloroform					
1985	545	545	545	545	545
2000	574	721	844	986	1229
2040	672	1349	2179	3506	6893
Halon 1301					
1985	11	11	11	11	11
2000	11	16	20	26	37
2040	7	21	44	92	259
Halon 1211					
1985	11	11	11	11	11
2000	11	16	20	26	37
2040	8	25	53	111	315

V. PRODUCTION SCENARIOS BASED ON QUANTILES OF THE SCORE FUNCTION

Applying the methods described in Sec. III to the subjective probability distribution defined in Sec. IV yields scenarios that we can use to project alternative futures for the seven PODs analyzed here. This section explains how the final calculations are made and presents a set of production scenarios based on our technique.

CHOOSING THE QUANTILES TO USE FOR SCENARIO DEVELOPMENT

A production scenario is based on a particular quantile of the distribution of the score function defined in Sec. III. We use the 5th, 25th, 50th, 75th, and 95th percentiles as a basis for scenarios that represent, respectively, lower limit, low, middle, high, and upper limit cases relevant to policy decisions. Other scenarios could obviously be developed without difficulty using the techniques described here. These five appear to describe the relevant policy space in a way that facilitates analysis.

Viewed in the context of EPA's policy analysis, the middle three scenarios--representing low, middle, and high growth--should be the most useful. The middle case represents a scenario defined such that the effect of these seven PODs on ozone depletion is equally likely to be greater or smaller than the effect corresponding to this scenario. Analogously, the low and high growth scenarios are defined such that the probabilities of greater or lesser effects as a result of these chemicals, conditional on the effect being greater or smaller than the median case, are equal. Thus, these three scenarios encapsulate information on regions of the distribution for ozone depletion that reflect the likely range of outcomes for these seven chemicals. The limiting scenarios at the 5th and 95th percentiles are better used to think about the outer bounds of reasonable results than to convolute with other sources of uncertainty in EPA's planned generation of many cases.

We start the development of scenarios with chemical weights for the score function that reflect relative production levels in 1985. Table 5.1 presents these weights. These weights, together with the values of the standard deviations from Sec. IV and Eq. (3.8) from Sec. III, allow us to calculate the value β with which to transform z-statistics from the distribution for the score function into z-statistics for the component economic-growth and intensity distributions. These identify intensity and general economic growth rates that can be used to calculate a growth rate for each chemical for each scenario during the pre-2000 period. These growth rates, applied to actual production levels in 1985, allow us to calculate the production paths relevant to each chemical for each scenario up to 2000.

The calculations for the post-2000 period are analogous. We use different weights and consequently a different value of β, based on 2000 production levels for the 50th percentile growth scenario. These are also reported in Table 5.1.

Table 5.1

CHEMICAL WEIGHTS

Chemical	1985	2000	Difference
CFC-11	0.265	0.255	-0.010
CFC-12	0.344	0.285	-0.059
Carbon tetrachloride	0.051	0.045	-0.006
CFC-113	0.126	0.193	0.067
Methyl chloroform	0.043	0.038	-0.005
Halon 1301	0.085	0.092	0.007
Halon 1211	0.085	0.092	0.007

NOTE: The concepts underlying these weights are explained in Secs. II and III. They reflect the production level, share of production that is emitted, and potential ozone-depletion risk per gram in the atmosphere of each chemical. Of these factors, we assume that only production levels differ between the periods before and after 2000.

Median growth rates differ enough across chemicals during the pre-2000 period to lead to significant shifts in the chemical weights between 1985 and 2000. This means that our weighting system is only approximate over this period; it effectively represents the use of a Laspeyres index, with its potential problems. Median growth rates after 2000 are equal for all chemicals but the Halons. Although we use a constant set of weights over a significantly longer period of time after 2000, the actual weights do not shift as much over this period as they do from 1985 to 2000.[1]

Applying these weights in Eq. (3.8) yields β values of 1.93 before 2000 and 1.83 afterward. These yield the z-statistics for individual scenarios shown in Table 5.2. The results in this table make it clear how important it is to view chemicals jointly rather than individually. To construct scenarios for the 5th percentile of the score function, we must use z-statistics for component distributions that are consistent with the 18th to 20th percentiles of these distributions. A 25th percentile scenario uses z-statistics consistent with the 36th percentile of the component distributions. Similar adjustments apply for higher percentile scenarios. Viewing these seven chemicals together significantly narrows the range of growth rates represented in the scenarios before and after 2000; the effect is slightly smaller after 2000.

CHEMICAL USE SCENARIOS

Taken together with the parameter values from Sec. IV, the z-statistics in Table 5.2 yield the growth rates in Table 5.3 as the bases for production scenarios. Table 5.4 shows the production levels that result from these growth rates for 1985, 2000, 2020, and 2040. Numbers like these calculated for the intervening years provide the basis for calculating emission scenarios, which in turn can provide inputs to the type of policy analysis EPA is currently pursuing. Moving

[1]The largest difference is about 0.013, for Halon 1301. Weights corresponding to the median growth scenario in 2040 are CFC-11, 0.257; CFC-12, 0.288; carbon tetrachloride, 0.046; CFC-113, 0.196; methyl chloroform, 0.039; Halon 1301, 0.079; and Halon 1211, 0.095.

Table 5.2

Z-STATISTICS AND β VALUES FOR DISTRIBUTIONS OF THE SCORE FUNCTION AND COMPONENTS

Quantile of the Score Function	z-Statistics		
	Score Function	Pre-2000 Components	Post-2000 Components
0.05	-1.645	-.854	-.899
0.25	-0.675	-.351	-.369
0.50	0	0	0
0.75	0.675	.351	.369
0.95	1.645	.854	.899
β value		1.93	1.83

beyond these productions scenarios, however, takes us beyond the scope of this Note.[2]

[2]For information on how to transform production scenarios into emission scenarios, see Palmer et al. (1980).

Table 5.3

GROWTH RATES FOR SCENARIOS BEFORE AND AFTER 2000

(In % per year)

Chemical	Period	Scenarios/Quantiles of the Score Function				
		0.05	0.25	0.50	0.75	0.95
CFC-11	Pre-2000	1.47	2.54	3.29	4.03	5.12
	Post-2000	0.93	1.80	2.40	3.00	3.86
CFC-12	Pre-2000	0.39	1.50	2.27	3.04	4.15
	Post-2000	0.89	1.78	2.40	3.02	3.91
Carbon tetrachloride	Pre-2000	4.15	5.56	6.55	7.54	8.97
	Post-2000	0.51	1.63	2.40	3.18	4.29
CFC-113	Pre-2000	1.03	2.17	2.96	3.74	4.88
	Post-2000	0.86	1.77	2.40	3.03	3.94
Methyl chloroform	Pre-2000	0.93	2.03	2.79	3.55	4.64
	Post-2000	0.91	1.79	2.40	3.01	3.89
Halon 1301	Pre-2000	1.12	2.94	4.07	5.34	7.15
	Post-2000	-0.20	-1.07	2.00	2.92	4.22
Halon 1211	Pre-2000	1.12	2.94	4.07	5.34	7.15
	Post-2000	-0.19	1.51	2.47	3.39	4.72

Table 5.4

SELECTED PRODUCTION LEVELS FOR SCENARIOS
BASED ON QUANTILES OF THE SCORE FUNCTION

(In thousands of metric tons)

Chemical/ Year	Quantile				
	0.05	0.25	0.50	0.75	0.95
CFC-11					
1985	342	342	342	342	342
2000	426	498	556	619	723
2040	617	1017	1435	2022	3295
CFC-12					
1985	444	444	444	444	444
2000	471	555	622	696	817
2040	671	1124	1606	2287	3788
Carbon tetrachloride					
1985	1029	1029	1029	1029	1029
2000	1183	1391	1554	1736	2032
2040	1701	2827	4014	5686	9343
CFC-113					
1985	163	163	163	163	163
2000	300	367	422	485	591
2040	367	700	1091	1695	3174
Methyl chloroform					
1985	545	545	545	545	545
2000	636	752	844	946	1113
2040	897	1517	2179	3123	5217
Halon 1301					
1985	11	11	11	11	11
2000	13	17	20	24	31
2040	12	26	44	76	162
Halon 1211					
1985	11	11	11	11	11
2000	13	17	20	24	31
2040	14	31	53	91	196

VI. CONCLUSIONS

The EPA faces a difficult policy problem. The agency needs to understand the many uncertainties that affect the relationship between decisions to reduce the global use of PODs and the effects that such reduction might have on human health, materials degradation, crop yields, and other activities of interest. We address only a small subset of these uncertainties in this Note. But the relationship of these uncertainties to other parts of this policy problem provides the basic motivation. On the one hand, the problem is so complex that it must be broken into pieces if we hope to produce useful results. On the other, the characterization of uncertainties in any part of this problem is likely to be more useful if it properly reflects the concerns of the problem as a whole. We offer a way to build scenarios relevant to one piece of the problem that relates them back to the problem as a whole.

This Note addresses uncertainties associated with production of seven PODs. Ideally, we would like to develop a subjective probability distribution for these chemicals and convolute the uncertainties reflected in this distribution with other sources of uncertainty relevant to stratospheric ozone depletion. In such an approach, developing a probability distribution for the PODs would be one step in a process to develop a distribution for ozone depletion itself. This cannot be done because the cost of calculating ozone-depletion profiles is too high to allow extensive use of the Monte Carlo methods needed to convolute all of the uncertainties relevant to ozone depletion in a complete and detailed way.

Calculation costs dictate that only a limited number of cases be considered in the atmospheric models used to study ozone depletion. Hence, we must assure that the cases considered embody as much information as possible. That is, whether we examine it in detail or not, a distribution for ozone depletion exists that is consistent with our assumptions about the uncertainties associated with inputs to the atmospheric models and with the models themselves. Since we cannot investigate this distribution of ozone depletion directly and in detail,

the cases we use to examine parts of the distribution should tell us something about where they lie in the distribution and about the probability density of the distribution in their vicinity. Our method provides a way to relate scenarios for the future production of seven PODs to the probability distribution for ozone depletion.

The specific method we use is simple; the concept it is based on could be used to develop more complex methods that might be more satisfactory. It remains for future analysis to determine how much improvement additional complexity would allow. For now, the specific method we offer can be thought of as an illustration of a more general conceptual approach and a practical way to implement that approach until a better method is developed.

Here is a quick overview of the approach. Characterize uncertainty about the growth rates of general economic activity and intensity of use of chemicals relative to it with independent normal probability distributions. Choose values for the means and variances of these distributions. Define a policy-relevant score function as a linear combination of these growth rates. Calculate the mean and variance of its subjective probability distribution. Define scenarios in terms of quantiles of the distribution of the score function. Identify growth rates in the component distributions that are compatible with the value of the score function for the quantile defining each scenario; use a simple convention to do this. Use the growth rates of the component distributions for a scenario to calculate the growth rates for each chemical in that scenario.

The key to this approach is the score function. It provides a policy-relevant scale with which to compare alternative scenarios for seven chemicals along a single dimension. The dimension chosen is one that should be related to the ozone depletion likely to result from the scenarios it is used to describe. The relationship is probably crude, but the scale reflects the kind of simple weighting scheme that EPA policymakers have found useful in the past to specify the relative danger associated with different chemicals and hence the joint danger associated with any set of production levels of these chemicals. More complicated score functions could be considered if we were interested in using a Monte Carlo technique to convolute uncertainties. Ironically,

as the score function comes closer to approximating the actual joint effect of a set of chemicals on ozone depletion, using it to develop scenarios may become less attractive. That is because a direct approach to the subjective probability distribution for ozone depletion becomes more attractive, eliminating the need for developing scenarios.

Restricting our subjective distributions to normal distributions and relying on linear approximations simplifies the analysis considerably and in fact makes a closed analytical solution to the convolution of uncertainties possible. Abandoning normality, or some other parametric distributions, would give us greater freedom to reflect uncertainties as we see them but would require the use of a simulation technique like Monte Carlo to convolute uncertainties. Once this step is taken, we probably no longer need to rely on linear approximations. Simulations themselves, of course, typically require simplifying assumptions and approximations to implement them at a reasonable cost. Whether the approximations associated with normal distributions and linear aggregations here induce more serious errors than the simplifications and approximations required by a technique like Monte Carlo is an empirical question. It deserves closer attention if this approach is to be used often in the future.

Whether an analytical approach like that used here or a Monte Carlo approach is taken, the interrelationships among chemicals deserve more attention. For example, CFC-11 and -12 are produced together. Although the proportions in which they are produced are variable, it would be surprising if cost considerations did not induce a positive correlation in their production rates. Alternatively, CFC-113 and methyl chloroform are substitutes, but both are subject to a similar set of government regulations. Changes in markets and regulations that underlie the scenarios used here could induce either a negative or positive correlation in their growth rates. These considerations and others like them suggest that future efforts to build scenarios for these chemicals should give closer attention to the relationships in intensity of use for different chemicals. Our technique makes that simple to do.

The techniques proposed here can produce a wide variety of scenarios. They are based on simple quantiles of the score function. The low, middle, and high growth scenarios associated with the 25th,

50th, and 75th percentiles of its distribution characterize the relevant policy space and should properly represent a reasonable range of effects of market and technological developments in the larger context of EPA's policy analysis. Developing scenarios for other factors conditional on the rate of general economic growth might also be worth exploring. That is because the level of the effects of ozone depletion on human activities like materials degradation and crop yields is likely to depend on the general rate of economic growth: Higher chemical growth rates will presumably have larger effects on ozone depletion which, in turn, will have more effect on crop yields if high economic growth has created a demand for more crops. Such relationships may prove to be quite important in sorting out the joint effects of different sources of uncertainty. Our technique could accommodate scenarios conditioned on general economic growth by calculating the moments for score functions conditional on economic growth rates; how those growth rates would be chosen remains a problem.

In the end, the approach taken in this Note offers a simple solution to a complex problem. More complex solutions may well justify their additional costs but that is not immediately clear. Additional attention to substantive issues associated with the construction of scenarios for application to the issue of potential ozone depletion is likely to be more productive in the short run.

Appendix

BASIC CODE USED TO IMPLEMENT AGGREGATIONS AND CONVOLUTION

This appendix documents four BASIC programs that we employ to convolute the distributions corresponding to different applications of CFC-11 and CFC-12, and to total use of each chemical. In general, variable names follow a few rules. Those beginning with "mid" indicate mean growth rates; those beginning with "sig" indicate standard deviations. The suffix ".g" refers to GNP, ".int" to intensity of use, and ".com" to total use (combined GNP and intensity effects).

The first program is used to derive the means and standard deviations of the distributions of the intensity growth rates for CFC-11 and CFC-12 from the information presented in Hammitt et al. (1986). That source projects use in each major application for the United States and the other CMA reporting countries separately. It provides a baseline projected use for each application and region together with factors that, when multiplied by the base projected use in 2000, characterize an 80 percent subjective probability interval for use. The program uses the estimated 1985 use, the projected base use in 2000, the factors characterizing the uncertainty range, and the parameters of the subjective distribution for GNP growth to calculate the parameters of the intensity growth rates for each region and application. It also convolutes these distributions to calculate the parameters of the distribution of rate of growth of intensity of total CFC-11 or CFC-12 use by region.

The second program is used to aggregate chemical use across regions. It takes as input the estimated 1985 use, projected baseline 2000 use, and factors characterizing the 80 percent subjective probability interval to calculate the parameters of the intensity growth rates by region, and convolute these to find the parameters of the world intensity growth rate. A similar program that uses the parameters of the intensity growth rate distributions for each region is used to calculate the parameters of the distribution of world intensity growth rates for CFC-11 and -12.

The third program calculates the parameters of the score function distribution. As input, it requires the parameters of the distribution of world GNP growth, world intensity growth for each chemical, and weights that reflect the relative ozone-depletion potency of each chemical. We run this program twice to calculate the parameters corresponding to each period separately.

The last program is used to calculate the production of each chemical corresponding to different quantiles of the score function, and to quantiles of the marginal distributions for individual chemical growth. As input it requires the intensity and GNP growth rates for the pre- and post-2000 periods and the values of β for each period. Variable names ending in ".e" indicate first (early) period values whereas names ending in ".l" indicate values in the later period. These suffixes are sometimes combined with the suffixes mentioned earlier; for example, ".eg" refers to GNP growth in the first period.

A listing of the program code follows:

PROGRAM 1: BASIC CODE TO CALCULATE PARAMETERS OF CFC-11 AND CFC-12 INTENSITY GROWTH RATES, BY REGION AND APPLICATION, 1985-2000

```
100     rem  file cfc.bas to calculate CFC-11 and 12 intensity
110     rem  for US and non-US reporting companies
120     open "incfc" for input as #1
130     input#1,n,mid.g,sig.g
140     for i = 1 to n
150     input#1,b0(i),bn(i),lofact(i),hifact(i)
160     next
170     base = 0
180     for i = 1 to n
190     lorate(i) = (bn(i) * lofact(i) / b0(i))^(1/15)
200     lorate(i) = (lorate(i) - 1) * 100
210     hirate(i) = (bn(i) * hifact(i) / b0(i))^(1/15)
220     hirate(i) = (hirate(i) - 1) * 100
230     mid(i) = (lorate(i) + hirate(i)) / 2 - mid.g
240     sig(i) = (hirate(i) - lorate(i)) / (2 * 1.2816)
241     sig(i) = (sig(i)^2 - sig.g^2)^0.5
250     base = base + b0(i)
260     next
270     mid.int = 0
280     sig.int = 0
290     for i = 1 to n
300     share(i) = b0(i) / base
310     midterm(i) = share(i) * mid(i)
320     sigt(i) = share(i) * sig(i)
```

```
330     sigtsq(i) = sigt(i)^2
340     mid.int = mid.int + midterm(i)
350     sig.int = sig.int + sigtsq(i)
360     next
370     mid.com = mid.int + mid.g
380     sig.com = (sig.int + sig.g^2)^0.5
390     sig.int = sig.int^0.5
400     open "outcfc" for output as #2
410     print "mid.int = ",mid.int
420     print "sig.int = ",sig.int
430     print#2,"mid.int = ",mid.int
440     print#2,"sig.int = ",sig.int
450     print#2,"mid.g = ",mid.g
460     print#2,"sig.g = ",sig.g
470     print#2,"mid.com = ",mid.com
480     print#2,"sig.com = ",sig.com
490     print#2,"  share(i)";"  mid(i)  ";"  sig(i)"
500     for i = 1 to n
510     print#2,using"#####.####";share(i),mid(i),sig(i)
520     next
530     print#2,"b0","bn","lofact","hifact","lorate","hirate"
540     for i = 1 to n
550     print#2,b0(i),bn(i),lofact(i),hifact(i),lorate(i),hirate(i)
560     next
```

PROGRAM 2: BASIC CODE TO CALCULATE PARAMETERS OF WORLD INTENSITY GROWTH RATES FOR OTHER CHEMICALS, 1985-2000

```
100     rem  file chm.bas to calculate world intensity for other chemicals
110     open "inchm" for input as #1
120     input#1,n
130     rho(1) = 1.00
140     rho(2) = 0.75
150     mid.g(1) = 3.0
160     sig.g(1) = 1.17
170     mid.g(2) = 3.5
180     sig.g(2) = 1.17
190     mid.g(3) = 3.0
200     sig.g(3) = 1.56
210     for i = 1 to n
220     input#1,b0(i),bn(i),lofact(i),hifact(i)
230     next
240     base = 0
250     for i = 1 to n
260     lorate(i) = (bn(i) * lofact(i) / b0(i))^(1/15)
270     lorate(i) = ((lorate(i) - 1) * 100) - mid.g(i)
280     hirate(i) = (bn(i) * hifact(i) / b0(i))^(1/15)
290     hirate(i) = ((hirate(i) - 1) * 100) - mid.g(i)
300     mid(i) = (lorate(i) + hirate(i)) / 2
310     sig.c(i) = (hirate(i) - lorate(i)) / (2 * 1.2816)
320     sig(i) = ((sig.c(i)^2) - (sig.g(i)^2))^0.5
330     base = base + b0(i)
340     next
```

```
350     mid.int = 0
360     sig.int = 0
370     for i = 1 to n
380     share(i) = b0(i) / base
390     midterm(i) = share(i) * mid(i)
400     sigt(i) = share(i) * sig(i)
410     sigtsq(i) = sigt(i)^2
420     mid.int = mid.int + midterm(i)
430     sig.int = sig.int + sigtsq(i)
440     next
450     if n = 3 then goto 480
460     crossprd = 2 * sigt(1) * sigt(2)
470     goto 490
480     crossprd = 2 * (sigt(1)*sigt(2) + sigt(1)*sigt(3) + sigt(2)*sigt(3))
490     for i = 1 to 2
500     sig.int(i) = (sig.int + rho(i) * crossprd)^0.5
510     next
520     open "outchm" for output as #2
530     print "mid.int = ",mid.int
540     print "rho,std dev"
550     for i = 1 to 2
560     print rho(i),sig.int(i)
570     next
580     print#2,"mid.int = ",mid.int
590     print#2,"rho,std dev"
600     for i = 1 to 2
610     print#2,rho(i),sig.int(i)
620     next
630     print#2,"mid(i)","sig(i)","share(i)"
640     for i = 1 to n
650     print#2,mid(i),sig(i),share(i)
660     next
670     print#2,"b0","bn","lofact","hifact","lorate","hirate"
680     for i = 1 to n
690     print#2,b0(i),bn(i),lofact(i),hifact(i),lorate(i),hirate(i)
700     next
```

PROGRAM 3: BASIC CODE TO CALCULATE PARAMETERS OF THE DISTRIBUTION OF THE SCORE FUNCTION

```
100     rem  file joint.bas to calculate joint scenarios for all chemicals
110     rem  uses world gnp and world intensity distributions for each chemical
120     open "injoint" for input as #1
130     input#1,n,mid.g,sig.g
140     base = 0
150     for i = 1 to n
160     input#1,wgt(i),b0(i),mid(i),sig(i)
170     share(i) = wgt(i) * b0(i)
180     base = base + share(i)
190     next
200     mid.int = 0
210     sig.int = 0
220     beta = 0
```

```
230     for i = 1 to n
240     share(i) = share(i) / base
250     midterm(i) = share(i) * mid(i)
260     mid.int = mid.int + midterm(i)
270     sigt(i) = share(i) * sig(i)
280     sig.int = sig.int + sigt(i)^2
290     beta = beta + sigt(i)
300     next
310     mid.com = mid.int + mid.g
320     sig.com = (sig.int + sig.g^2)^0.5
330     sig.int = sig.int^0.5
340     beta = (beta + sig.g) / sig.com
350     open "outjoint" for output as #2
360     print "mid.com = ",mid.com
370     print "sig.com = ",sig.com
380     print "mid.int = ",mid.int
390     print "sig.int = ",sig.int
400     print"mid.g= ",mid.g
410     print"sig.g= ",sig.g
420     print "beta = ",beta
430     print#2,"mid.com = ",mid.com
440     print#2,"sig.com = ",sig.com
450     print#2,"mid.int = ",mid.int
460     print#2,"sig.int = ",sig.int
470     print#2,"mid.g = ",mid.g
480     print#2,"sig.g = ",sig.g
490     print#2,"beta = ",beta
500     print#2,"mid(i)","sig(i)","share(i)"
510     for i = 1 to n
520     print#2,mid(i),sig(i),share(i)
530     next
540     print#2,"wgt(i)","b0(i)","midterm(i)","sigt(i)"
550     for i = 1 to n
560     print#2,wgt(i),b0(i),midterm(i),sigt(i)
570     next
```

PROGRAM 4: BASIC CODE TO CALCULATE CHEMICAL PRODUCTION CORRESPONDING TO QUANTILES OF THE SCORE FUNCTION AND TO QUANTILES OF MARGINAL CHEMICAL USE DISTRIBUTIONS

```
100     rem  file scenar.bas to calculate quantiles of joint and individual
110     rem  chemical production distributions over time
120     rem  subscript 1--CFC-11, 2--CFC-12, 3--CT, 4--CFC-113, 5--MC,
130     rem  6--Halon 1301, 7--Halon 1211, 0--Joint weighted production
140     open "inscen" for input as #1
150     dim g(5,11),q(5,7,11),c(5,7,11),year(11)
160     input#1,beta.e,beta.l
170     input#1,mid.eg,sig.eg,mid.lg,sig.lg
180     for i = 0 to 7
190     input#1,b0(i),mid.e(i),sig.e(i),mid.l(i),sig.l(i)
200     next
210     data -1.645,-0.675,0.0,0.675,1.645
220     for j = 1 to 5
```

```
230     read zj(j)
240     zc.e(j) = zj(j) / beta.e
250     zc.l(j) = zj(j) / beta.l
260     rate.eg(j) = mid.eg + zc.e(j) * sig.eg
270     rate.e(j,0) = mid.e(0) + zj(j) * sig.e(0)
280     for t = 0 to 3
290     g(j,t) = (1 + rate.eg(j)/100)^(t * 5)
300     q(j,0,t) = b0(0) * (1 + rate.e(j,0)/100)^(t * 5)
310     next t
320     rate.lg(j) = mid.lg + zc.l(j) * sig.lg
330     rate.l(j,0) = mid.l(0) + zj(j) * sig.l(0)
340     for t = 4 to 11
350     tm3 = t - 3
360     g(j,t) = g(j,3) * (1 + rate.lg(j)/100)^(tm3 * 5)
370     q(j,0,t) = q(j,0,3) * (1 + rate.l(j,0)/100)^(tm3 * 5)
380     next t
390     for i = 1 to 7
400     rate.e(j,i) = mid.e(i) + zc.e(j) * sig.e(i) + rate.eg(j)
410     rc.e(j,i) = mid.e(i) + mid.eg + (zj(j) * (sig.e(i)^2 + sig.eg^2)^0.5)
420     for t = 0 to 3
430     q(j,i,t) = b0(i) * (1 + rate.e(j,i)/100)^(t * 5)
440     c(j,i,t) = b0(i) * (1 + rc.e(j,i)/100)^(t * 5)
450     next t
460     rate.l(j,i) = mid.l(i) + zc.l(j) * sig.l(i) + rate.lg(j)
470     rc.l(j,i) = mid.l(i) + mid.lg + (zj(j) * (sig.l(i)^2 + sig.lg^2)^0.5)
480     for t = 4 to 11
490     tm3 = t - 3
500     q(j,i,t) = q(j,i,3) * (1 + rate.l(j,i)/100)^(tm3 * 5)
510     c(j,i,t) = c(j,i,3) * (1 + rc.l(j,i)/100)^(tm3 * 5)
520     next t
530     next i
540     next j
550     open "outscen" for output as #2
560     print#2,"zj(k)","zc.e(k)","zc.l(k)"
570     for k = 1 to 5
580     print#2,zj(k),zc.e(k),zc.l(k)
590     next k
600     print#2,"  "
610     print#2,"GNP"
620     print#2,"Components of Joint Quantiles"
630     print#2,"year","g(.05)","g(.25)","g(.50)","g(.75)","g(.95)"
640     for t = 0 to 11
650     year(t) = t * 5 + 1985
660     print#2,year(t),g(1,t),g(2,t),g(3,t),g(4,t),g(5,t)
670     next t
680     for i = 0 to 7
690     print#2,"  "
700     if i = 0 then print#2,"Joint weighted chemical production"
810     if i = 1 then print#2,"CFC-11"
820     if i = 2 then print#2,"CFC-12"
830     if i = 3 then print#2,"Carbon tetrachloride"
840     if i = 4 then print#2,"CFC-113"
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850     if i = 5 then print#2,"Methyl chloroform"
860     if i = 6 then print#2,"Halon 1301"
870     if i = 7 then print#2,"Halon 1211"
880     print#2,"Components of Joint Quantiles"
890     print#2," year";"       c(.05)";"      c(.25)";"      c(.50)";
            "      c(.75)";"      c(.95)"
900     for t = 0 to 11
910     print#2,using"#####       ";year(t),q(1,i,t),q(2,i,t),q(3,i,t),
            q(4,i,t),q(5,i,t)
920     next t
930     next i
940     for i = 1 to 7
950     print#2,"  "
960     if i = 1 then print#2,"CFC-11"
970     if i = 2 then print#2,"CFC-12"
980     if i = 3 then print#2,"Carbon tetrachloride"
990     if i = 4 then print#2,"CFC-113"
1000    if i = 5 then print#2,"Methyl chloroform"
1010    if i = 6 then print#2,"Halon 1301"
1020    if i = 7 then print#2,"Halon 1211"
1030    print#2,"Quantiles of Chemical Production"
1040    print#2," year";"       c(.05)";"      c(.25)";"      c(.50)";
            "      c(.75)";"      c(.95)"
1050    for t = 0 to 11
1060    print#2,using"#####       ";year(t),c(1,i,t),c(2,i,t),c(3,i,t),
            c(4,i,t),c(5,i,t)
1070    next t
1080    next i
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