SOCIAL COST OF TECHNICAL CONTROL OPTIONS TO REDUCE EMISSIONS OF POTENTIAL OZONE DEPLETERS IN THE UNITED STATES: AN UPDATE

F. Camm, T. H. Quinn, A. Bamezai, J. K. Hammitt, M. Meltzer, W. E. Mooz, K. A. Wolf

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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:
This Note was produced under Cooperative Agreement No. CR811991-02-0 with the U.S. Environmental Protection Agency.
SUMMARY

Photochemical models of the stratosphere suggest that chlorofluorocarbons and certain related chemicals may deplete stratospheric ozone. We call these chemicals "potential ozone depleters" or PODs. Depletion of stratospheric ozone may impair human health, speed the degradation of certain man-made materials, reduce crop yields, and have a broad range of negative ecological effects. Human emissions of PODs may speed the depletion of stratospheric ozone and hence may contribute to negative effects associated with depletion. Human emissions of PODs can be reduced, however, only by reducing the use of these chemicals and forgoing the benefits that they provide.

Policymakers in the United States and elsewhere must determine whether the potential threat from human emissions of PODs into the atmosphere is large enough to warrant the costs of reducing their use. This Note provides information relevant to that decision by quantifying the social costs and effects of exercising specific technical options to reduce the use of PODs in the United States. It updates earlier Rand work on this issue by updating the prices and cost of capital relevant to these options and by incorporating new information from industry on the cost and effectiveness of technical options.

We rely on market prices to determine the social value of products made with PODs and the social costs of the inputs used with PODs in production processes or used to produce PODs themselves. This is a common approach in social cost-benefit analysis and works so long as externalities are not important in the markets we examine. Where externalities are present, we identify them, but do not attempt to monetize them. Relying on market prices allows us to value the POD at the price at which private firms would voluntarily switch production processes or consumers would switch products. This amount, less the cost of producing the POD, represents the social loss of regulations that might induce these decisions to reduce dependence on PODs.
As earlier Rand work did, we emphasize technical options that would be voluntarily adopted at "low to moderate" POD prices. This focuses the analysis on options that impose low to moderate social costs, presumably the options that the United States should exercise first in any attempt to reduce the use of these substances. Specifically, we consider only those options that might voluntarily be adopted at POD prices below $5.00 a pound. This price is five to 15 times the levels of 1984 prices for the chemicals examined.

A fairly small number of options account for most of the reductions we examine. Recovery and recycling of PODs in the manufacturing processes in which they are used as inputs reduces requirements for these chemicals and reduces their emissions into the atmosphere. Manufacturers typically weigh the costs of new investment and operating costs against the savings that recovery and recycle of PODs allows. Use of equipment and methods designed to reduce emissions directly involves a similar tradeoff. Substitution of alternative materials for the PODs requires a comparison of their costs and their effects on the productivity of a manufacturing process. This last option may involve social costs that our methodology does not capture because it often involves substitution away from PODs to chemicals that may be dangerous for other reasons. Among the alternatives to PODs are pentane, methylene chloride, and other chlorinated solvents that pose fire and health hazards and disposal problems that may not be reflected in their market prices. This is the only place where externalities affect our analysis.

The technical options that our quantitative analysis suggests that firms would adopt voluntarily at POD prices below $5.00 a pound would have the following effects:

- Cut the use of CFC-11 in slabstock foam manufacturing by about 37 to 63 percent at prices below about $2.00 a pound, a fourfold increase in price;
- Phase out the use of CFC-12 in the manufacture of thermoformed polystyrene sheet at prices below $1.00 a pound, a 50 percent increase in price;
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- Cut the use of CFC-12 in retail food refrigeration by about half at prices below about $1.20 a pound, an 80 percent increase in price;
- Reduce some use of CFC-12 in other refrigeration and air conditioning applications at prices below $3.65 a pound, about a 450 percent increase in price; and
- Cut the use of CFC-113 in cleaning and drying applications by over 90 percent at prices below $5.00 a pound, about a 460 percent increase in price.

We also believe, on the basis of less quantitative analysis, that the use of CFC-11 in molded foam manufacturing could be phased out, that currently exempt uses of CFC-11 and -12 in aerosol applications could be cut in half, that use of CFC-12 in sterilants could be cut in half, that better servicing practices could reduce the emissions of CFC-11 and -12 during servicing of certain refrigeration and air conditioning equipment, and that use of CFC-12 in liquid food freezing could be phased out.

Taken together, these suggest that technical options with low to moderate social costs would be more effective at reducing the use of CFC-113 than the use of CFC-11 and CFC-12. That is true because few good substitutes exist for CFC-11 and -12 in the majority of their applications. As a result, the social cost of reducing the use of these chemicals will be quite high in most applications. The technical options considered in this Note allow a total reduction of about 6 to 16 percent in the use of CFC-11, 6 to 35 percent in CFC-12, and 75 to 80 percent in CFC-113 in the United States.
ACKNOWLEDGMENTS

John Hoffman and Stephen Seidel helped us frame the analysis in this Note. Jan Acton helped facilitate its production and review under tight deadlines. David Rubenson helped collect industry data on refrigeration applications. Hugh Farber and Leland Johnson provided detailed comments on an earlier draft. The Alliance for Responsible CFC Policy and W. J. Rhodes also provided helpful comments. Mary Vaiana helped prepare the presentation of this Note to the Environmental Protection Agency's March 1986 workshop, "Protecting the Ozone Layer." Participants in that workshop provided helpful feedback. Alyce Shigg oversaw production of the many drafts underlying this Note and Patricia Bedrosian edited the final draft. More generally, much of the detail provided here is based on interviews with many knowledgeable industry officials who were generous with their time. We thank them all and retain responsibility for any errors that remain.
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I. INTRODUCTION

Over the last 12 years, photochemical models of the atmosphere have suggested that global human emissions of certain chlorofluorocarbons (CFCs) and related chemicals may deplete stratospheric ozone. We will refer to these chemicals as potential ozone depleters or PODs. We focus our attention here on CFC-11, -12, and -113, but we also consider technical options relevant to methyl chloroform and Halon 1301.

A sufficient reduction in stratospheric ozone could have a wide variety of detrimental effects, including significant threats to human health.\textsuperscript{1} However, scientists have not reached a consensus that these effects do in fact occur or even that they are likely in the future. Nonetheless, if the effects do occur, they could be serious enough to warrant countermeasures that would reduce human emissions of these PODs in the absence of any scientific consensus. It would be easier to justify such countermeasures politically if they did not impose too serious a social cost. In fact, a number of governments have already taken limited steps to reduce current emissions of certain CFCs on precisely these grounds.\textsuperscript{2} This Note updates earlier Rand Corporation estimates of the costs of undertaking a variety of additional control measures in the United States.\textsuperscript{3}

A cost is imposed when a control measure forces an individual or company to change its behavior. That cost may result when a product

\textsuperscript{1}For details, see National Academy of Sciences (1976, 1979, 1982, 1984) or Ramanathan et al. (1985).

\textsuperscript{2} Bans on the use of CFCs in most aerosol products are now in effect in Canada, Norway, Sweden, and the United States. The European Economic Community agreed that, by the end of 1981, CFC aerosol use would be reduced by 30 percent relative to 1976 levels. Australia has reduced CFC aerosol use through voluntary agreements with industry. West Germany and the Netherlands have labeling programs in effect to encourage the use of alternative propellants. Japanese industry has reportedly agreed not to expand the use of CFCs as aerosol propellants.

\textsuperscript{3} See especially Palmer et al. (1980), Palmer and Quinn (1981), and Mooz et al. (1982).
previously produced with PODs must be produced in a different way. Because the alternative was not used before, it presumably will cost more; this difference in production cost is what interests us. Of course, if a product costs more to produce without PODs, its price will rise, encouraging the consumers of that product to seek less expensive alternatives. If consumers can find alternatives, they limit the cost imposed by a control measure. The mitigating effect of product substitution also interests us. Substitution away from PODs in production or consumption may increase the use of substances like methylene chloride or pentane that are themselves dangerous or potentially dangerous. Because new users may not properly recognize the full extent of their dangers, the private cost to companies or individuals of using these substances may underestimate their total cost to society. We identify why our cost estimates might fall short of the full costs relevant to society but we do not attempt the difficult and controversial task of quantifying the extent of the shortfall.

The Rand Corporation's previous work focused on identifying control options with "small to moderate" social costs in the United States. These are presumably the first options that should be employed if U.S. policymakers decide to reduce the emissions of PODs. This update has a similar focus. Where possible, we use engineering cost data to estimate the effects of control measures on production costs. We could not obtain such information for some options that appear to impose only modest costs; we identify these options and recommend future work to identify their costs more clearly.

The estimates offered here improve on Rand's previous estimates by reflecting recent changes in economics and technology. The Rand Corporation's earlier estimates of costs date variously from 1976, 1980, and 1982. At the very least, nominal and real prices of equipment, labor, energy, and, of course, individual chemicals have changed since those estimates were made. Recent and prospective changes in the tax

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4An economist would say that their use imposes an "externality" because it imposes a cost on people who are not a party to the decision to use them. The monetized value of this externality captures the additional cost not examined here.

5Bureau of Labor Statistics data suggest that equipment costs in the chemical industry rose 80 percent from 1976 to 1984 and 31 percent from 1980 to 1984. Labor costs in the chemical industry rose 88 percent
law and in real interest rates have changed the cost of capital to companies that must make new investments to reduce their use of PODs. Some options considered in earlier work have been adopted and foreclose the possibility of further reductions. And additional discussions with industry have refined Rand's understanding of the remaining available options and the costs associated with them. This update incorporates new information on prices, cost of capital, and industry options.

Section II provides background on a variety of issues relevant to the specification and estimation of the social costs of control options. Sections III through VII briefly review the control options for flexible foam, rigid foam, solvents, refrigeration and air conditioning, and other applications that appear to have low to moderate costs in the United States. They update Rand's information on their costs and effectiveness in reducing emissions from PODs. Section VIII summarizes our results on the extent of reductions and their costs for the United States and suggests directions for future work.

Appendix A briefly reviews some methodological issues that arise when results like those developed here are used to compare specific policy alternatives. It emphasizes the specific character of the results reported here and the need for additional work before these kinds of results are used to compare different kinds of policies. Appendix B reviews briefly the methodology and assumptions used to develop results for foam manufacturing and solvent use. Appendix C briefly reviews issues relevant to the use of these U.S. data to infer the costs and effects of applying similar control options in other parts of the world.


The real pretax cost of capital normally used in industry in 1984 was about 15 percent, 25 percent lower than the level assumed in Palmer et al. (1980).
II. BACKGROUND AND METHODS

We use the economic tools of social cost-benefit analysis to measure the minimum social cost of reducing the production and use of specific PODs. In particular, we rely on the close relationship between demand and supply schedules for PODs and the net social costs of eliminating activities associated with those schedules. We assume that activities relevant to any particular chemical are eliminated in ascending order of their social cost to assure that the use of this chemical cannot be reduced in any lower cost way.\(^1\) This section briefly reviews our approach to social cost-benefit analysis and explains how we use demand and supply schedules to implement that approach. It then examines how we quantify points on the demand curve for each chemical.

SOCIAL COST AND DEMAND FOR PODS

Benefit-cost analysis in market economies normally uses market prices to measure the social costs of inputs and the social value of outputs. Prices indicate how much someone would have been willing to pay for the inputs in another use. They also reflect consumers' willingness to pay for the outputs. Because benefit-cost analysis is ultimately based on individuals' willingness to pay for goods given the current distribution of income, free market prices normally provide the proper information for such analysis. And we will lean heavily on market prices wherever possible.\(^2\) The most important circumstance that

\(^1\)This is a restrictive assumption. The types of environmental policies most often observed in the United States and elsewhere do not pursue such priorities. Hence, our analysis offers a lower bound on the social cost likely to be associated with any actual government policy. Future Rand analysis will examine alternative ways to reduce the use and emissions of PODs and compare their social costs. The estimates here can best be thought of as benchmarks for more complex policies. For a further discussion of this and related issues, see Appendix A.

\(^2\)This paragraph is obviously a broad statement about complex issues. The most direct and useful defense of this approach is Harberger (1971). This reference also discusses important caveats in using the approach.
might raise doubts about this approach is one in which an input or output affects people who either are unaware that they are being affected or who--for whatever reason--can do nothing about the effects. We believe that this is most likely to present a problem if a restriction on the use of PODs encourages consumers or producers to increase their demand for certain other chemicals whose true effects are not fully known to the workers who work with them or to the consumers who use products made from them. For example, methylene chloride causes cancer in animals and may be a human carcinogen. If restrictions on the use of CFC-11 encourage greater use of methylene chloride, that use may impose a greater cost on workers using it than they realize and hence may lead them to underprice their labor services in working with methylene chloride. That is, if workers underprice their services, the true social cost of using methylene chloride in production is higher than the cost we would measure using market prices. Asking how much higher opens a controversy that cannot be resolved here. We avoid this by relying on market prices and simply noting where reasons may exist to expect divergences between these prices and the true social values relevant to our analysis.

A decision to rely on market prices for cost information simplifies our problem in an important way. Because the measures of cost that we use are the same as the measures individuals use in making decisions, it allows us to infer social costs from people's behavior. In particular, it allows us to use the fact that the demand schedule for a particular POD reflects the willingness to pay for that substance. Similarly, supply schedules reflect willingness to pay to use the substance--or the resources used to produce it--in alternative uses. When production and use of a POD is restricted, the amount that users would have been willing to pay for the restricted quantity is a measure of how much this restriction hurts them. Users of the POD in other applications or of the resources used to produce it would be willing to pay some amount to obtain the restriction to increase the supplies available for their own use; this is a measure of how much they would benefit from a restriction. The net social effect--neglecting of course the value of effects on stratospheric ozone--is the difference between these two quantities. And this difference can be expressed in terms of areas
under the segments of the demand and supply schedules affected by the particular restriction in question.

To see this, consider the relationship between willingness to pay and areas under demand curves. The total demand for a POD is really an aggregation of individual demands for its use in particular applications. For example, the demand for CFC-11 is an aggregation of demands for specific uses in foam blowing, aerosols, and so on. Further, the demand for foam blowing is really an aggregation of demands for foam blowing in different plants with different production technologies and products. For each specific demand, there is a price of CFC-11 at which that demand stops. At a high enough price, foam blowers switch to alternative blowing agents or final consumers respond to the high product prices forced by the higher CFC-11 price and spend their money on other products. The price at which use ends is the maximum price that foam blowers and final consumers are willing to pay for the POD in a particular use.

This "willingness to pay" varies according to each use. Imagine a rectangle associated with each specific use, with the "switch price" on the vertical dimension and the level of demand in the use on the horizontal dimension. The area of this rectangle is what POD users and final consumers would be willing to pay to avoid losing this use of a POD. And the sum of many analogous areas is the total willingness to pay to avoid losing all the relevant uses of the POD.

In the end, a demand schedule can be thought of in terms of a collection of these rectangles. (See Fig. 2.1.). Place the tallest rectangle to the left and add progressively shorter rectangles; the aggregate demand schedule for a POD (or any other substance) is simply the upper boundary of this collection of rectangles. As a result, we can measure the willingness to pay to avoid a restriction on using a POD by looking at the area under the sections of that demand schedule that cannot be satisfied when use is restricted.

By similar reasoning, it can be shown that the area under a supply schedule measures the willingness to pay for the POD or its inputs in other uses. For simplicity, we will always assume here that the supply schedule for PODs is flat so that the segments of the supply schedule relevant to a restriction are not an issue. This simple assumption
Fig. 2.1 -- Demand and willingness to pay

allows us to measure the social costs of a restriction as the areas between the segments of the demand schedule affected and the supply schedule. For example, if a restriction eliminated the use of a POD associated with segments A and B of the demand schedule in Fig. 2.2, areas AA and BB would measure the social cost of this restriction. Because we assume here that restrictions are imposed in a least cost manner, our measures of social cost will always involve triangular areas bounded by the demand and supply curve and the restriction with the highest incremental social cost.
Fig. 2.2 -- Net social cost of a restriction on POD use

**IMPLICATIONS FOR MEASURING A DEMAND SCHEDULE**

Normally, economists develop empirical demand schedules by using historical data and econometric techniques to estimate them. But the available data are not good enough to use formal econometric methods to estimate reliable demand schedules, even at the aggregate level and for the major PODs--CFC-11 and -12. Even if they were, relevant prices have not varied enough recently to measure a demand schedule over the range of prices that concerns us. Hence, we adopt an alternative approach.
than the switch price for the large rectangle. Actual willingness to pay to avoid an imposed reduction in POD use are lower for these consumers. The switch prices reflect a trade-off and the vertical height of the rectangle-the switch price assumed in consumer choice within this rectangle when the control option in question is each rectangle representing the reduction in POD use for a particular consumer. Notice that each rectangle equals 1/5 PS.2.2.4 In fact, a composite of many to higher prices. Perhaps the easiest way to think about this is to in the second step, we recognize that in each rectangle the high unless we look at the second step.

But these measures of willingness to pay and social cost could be too retaining area under the supply curve yields a measure of social cost. A first, option b next, and so on. Adding up the areas of these rectangles provides a measure of willingness to pay; subtracting the form lowest to highest cost per pound, these rectangles look like those and horizontal (size of reduction) components of each rectangle. Ranks are: 

To evaluate cost data and market data to estimate the vertical (cost) 

First, we should consider specific control measures that might be 

These steps are potentially important to estimating the costs of these 

One way of their contribution to regulatory support is that in more in terms of their contribution to reducing existing demand than in regulations. That is, we estimate reductions like those discussed above on demand from the existing level of demand without
Fig. 2.3 -- Engineering measure of the social cost of reducing POD use.

pay to avoid the restriction is measured by the ordered rectangles in Fig. 2.4(a). If we had stopped with the first step, we would have overestimated the relevant willingness to pay by the shaded areas.

Of course, there is no particular reason to rank the consumer-related rectangles of Step 2 only within the larger rectangles. A complete ranking yields the arrangement in Fig. 2.4(b). The difference between panels (a) and (b) reflects the fact that to minimize the social cost of achieving a given reduction in POD use, it may be appropriate to
Fig. 2.4 -- How consumer response affects the cost of reducing POP use
eliminate consumption by some groups affected by option B, the second best option, before eliminating all consumption relevant to the "best" option, option A. That is, simply using mandatory controls to implement one option after another misses cost savings that could be achieved if consumers with lower switch prices could be identified and dealt with before moving on to consumers with higher switch prices.

A third step would recognize that our information about control options and consumer response is likely to be incomplete. That is, there may be a control option, like option C in Fig. 2.3, that escapes current notice because its effect on demand is so small or because it fills a niche that takes time to discover and exploit. Concentrating only on the "significant" options we now know about ensures that we overestimate the ultimate willingness to pay to avoid a cut in POD use.

In the end, the ranking shown in Fig. 2.4(b) is just a demand schedule, with quantity reductions instead of total quantity on the abscissa. It allows us to walk up the demand schedule from the point of current consumption instead of walking down it from the point of zero consumption; these alternatives differ only in perspective. In effect, the rectangles in Fig. 2.4(b) tell us the true character of the rectangles that a demand schedule bounds.

In the sections that follow, we focus on the first step. Among the reduction options we have been able to identify, it appears that the second step--reflecting the response of final consumers to higher prices--is likely to make a difference for only one POD use--the use of CFC-12 in extruded polystyrene sheet. And the difference is likely to be small and to affect only a portion of the demand schedule for CFC-12. The third step is obviously more difficult to quantify. It is likely to become more important as time passes, allowing time for innovation of new options. It is also more likely to be important in the evaluation of price-oriented policies than in that of mandatory controls.\(^3\) The analysis that follows takes no account of this third step. As a result, we can expect the minimum social cost of reducing the use and emissions of the PODs considered here to fall below our estimates as time passes.

\(^3\)For a discussion of this issue, see Appendix A.
PRICES AT WHICH USERS VOLUNTARILY EXPLOIT TECHNICAL OPTIONS

Our analysis focuses on the amount of PODs associated with specific production processes and the prices of PODs at which users voluntarily change production processes. These prices are the switch prices referred to above.¹

The amount of a POD that a producer must use to produce any particular quantity of a product is not fixed. This is true even if the final product must contain a certain amount of the POD. Certain amounts of a POD are lost in the manufacturing process, through emission during manufacture, through the disposal of contaminated waste not embodied in the final product, or through the disposal of scrap product whose quality is too low to be sold. Through greater care or additional investment, these kinds of losses can be reduced. But greater care and investment are costly. Users of PODs must weigh the cost of reducing their use of PODs against the cost of acquiring PODs. We compare the costs of alternative ways of using PODs in manufacturing and services and determine the prices at which it pays users to switch from one method to another.

We typically start by looking at operations in a plant of some particular size. We then assume that the level of production in the plant is fixed; demand for final product is insensitive to changes in production method.² We then compare the full annualized costs of achieving the assumed production level using different production methods. That is, where new investment is required to implement a particular method, we calculate the return to capital required each year to cover the cost of the investment and include that as the cost of investment. Operating and fixed annual charges are dealt with directly.

¹The approach draws heavily on earlier Rand analysis reported in Palmer et al. (1980), Palmer and Quinn (1981), and Mooz et al. (1982). This subsection briefly summarizes discussions offered in much greater depth in these earlier documents. Appendix B provides additional detail.
²We review the possibility that a change in process could change costs, product prices, and hence demand; this is important in only one case.
The price of the POD used in production is the only cost of direct interest to us. With some reasonable simplifying assumptions, we can express the annualized cost of any production method as a simple linear function of that price. That is, $C_i = a_i + b_i P$, where $C_i$ is the annualized cost for the $i$th production method, $P$ is the per unit cost of the POD in question, and $a_i$ and $b_i$ are constants. At any price, $P$, the user obviously picks the production method with the lowest $C_i$. As the price rises, a user moves progressively toward methods with higher ratios of $a_i$ to $b_i$. We capture the price at which a user switches from one method ($i$) to another ($j$) by calculating the price, $P^*(i,j)$, at which the costs for the two methods are equal:

$$P^*(i,j) = \frac{(a_i - a_j)}{(b_j - b_i)}$$

If no other method (say, $k$) is less costly than these at this price, this switch price is relevant to us and important to the construction of demand schedules as discussed above.\(^6\)

As price rises, we can expect—and in fact observe—a series of prices at which the use of a POD within an industry falls. This is true even if the industry has only one alternative to current practice. Many switch prices may be relevant within the industry because switching often occurs at different kinds of plants at different prices. Differences in scale or product mix can lead to different costs and hence different $a_i$ and $b_i$ for the production methods used in different plants. The reduction in POD use in this case simply represents changing practice in one part of the industry in question.\(^7\) Of course, any particular plant may move through several forms of conservative

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\(^6\)If another method was less costly, then this switch point would be irrelevant because the methods relevant to the switch are dominated by another method at this price. We seek only the lowest cost alternatives and POD prices at which their costs are equal.

\(^7\)We might reasonably expect changes in the price of a POD to affect the competitiveness of different kinds of plants. Plants that can most easily adjust to rising POD prices should presumably be able to compete more effectively against other plants in the same industry. We make no attempt to take account of shifts in market share that might result from this kind of cost competition. That makes our analysis conservative.
practice as the POD price rises. Where this is possible, it simply expands the number of prices at which POD use falls.

In a few cases, our analysis suggests that certain practices not in universal use today should already be in use; they have costs that appear to be lower than the costs of current practice. In some of these cases, representatives from private industry have concurred with this analysis, but would like to see others move first to control the risks associated with innovation. In these cases, we generally cannot determine exactly how much of the industry has moved toward what appears to be a cost effective innovation. Hence we bracket the correct share that has innovated by using alternative base cases. In one, all cost effective innovations have been made; in the other, none have.

SUMMARY

We use standard methods of social cost-benefit analysis to examine the net social cost of reducing the use of PODs in specific ways. Our analysis focuses on identifying the least cost way to do this for each chemical and measuring the cost of the corresponding reductions. Because we rely on market prices to define values relevant to cost-benefit analysis, our analysis is consistent with a behavioral view of these markets; that is, our analysis yields demand schedules that show what actions users of PODs would take if the prices of these PODs were to rise. Future work will examine the costs associated with alternative methods for reducing the use and emissions of PODs.
III. FLEXIBLE FOAM

CFC-11 is used as an auxiliary blowing agent in flexible urethane foam for the manufacture of molded foam and slabstock products. Two technical options exist for reducing CFC emissions from these processes: substituting auxiliary blowing agents, and recovering and recycling the emitted CFC. This section reviews these options briefly and presents quantitative data on their effects on CFC-11 use and the prices of CFC-11 at which manufacturers would adopt them voluntarily.

ALTERNATIVE BLOWING AGENTS

Methylene chloride can be substituted for CFC-11 as a blowing agent for many slabstock foams. The materials costs of methylene chloride formulations are currently lower than those of CFCs for many grades of slabstocks. Quality control of soft foams blown with methylene chloride is more difficult, however, sometimes leading to higher scrap rates. This is especially the case in smaller manufacturing plants that often do not have the technical expertise for using the chemical efficiently. In addition, methylene chloride is presently under regulatory scrutiny and its use might be restricted in the future.

From a technical standpoint, it would be difficult to achieve complete replacement of CFC by methylene chloride unless consumers were willing to accept lower quality foam. Reasons for this range from the unavailability of methylene-chloride-based formulations for some specialty foams to the inability of some foamers to handle the technical problems of blowing agent conversion. Industry observers indicate that perhaps 75 percent of flexible foam blowing could be achieved with methylene chloride.

Until recently, industry sources suggested that substitution among blowing agents was more difficult in molded foams. The quality of foam blown with alternative agents tended to be poor and perhaps unacceptable. New information suggests that substitutes are available that can be implemented without much cost penalty. The specific nature of these substitutes remains confidential. We do not attempt to
quantify the opportunities for substitution here beyond assuming that the use of CFC-11 would be eliminated in molded foam blowing if the price of CFC-11 rose to the top of the range we consider, $5.00 a pound; we cannot say at what price the switch would actually occur.

RECOVERY AND RECYCLE

Flexible foams emit essentially all of their auxiliary blowing agents before leaving the manufacturing plant. Collecting and reusing these emissions would prevent them from being vented into the atmosphere. Flexible slabstock lines appear particularly suited for such collection, since the foam is manufactured in a long tunnel equipped with ventilation fans that collect exhaust gases and discharge them outside of the plant. Measurements by DuPont indicate that in a well designed, modern slabstock plant, CFC collection efficiencies using these ventilation systems may already be between 33 percent and 53 percent.¹

Once collected, CFC may be recovered by carbon adsorption. In this process, CFC-laden air is passed over and adsorbed by beds of carbon. The remaining air is exhausted, and CFC is desorbed from the carbon using steam. This technology is presently successfully and economically practiced in a number of nonfoam industries.

QUANTITATIVE ANALYSIS OF TECHNICAL CONTROL OPTIONS

Our quantitative analysis of options to reduce the use of CFC-11 in flexible slabstock foam focuses on three different sized plants, which would consume respectively 150,000, 225,000, and 1,200,000 pounds of CFC-11 annually if only CFC-11 were employed as an auxiliary blowing agent. To reflect information from industry sources, however, we assume that each of these plants presently uses 50 percent methylene chloride. Each plant has the option of increasing its use of methylene chloride to 75 percent and/or installing recovery and recycling equipment for CFC-11 and methylene chloride. Despite differences in the sizes of the plants, industry sources indicate that this equipment is equally costly for all plants, giving large plants a significant advantage in adopting this

¹See Palmer et al. (1980), p. 52.
option. We reflect that here. Wherever it is used, this equipment recovers half of the blowing agent emitted. Flexible slabstock foam accounts for about 14 percent of the U.S. market for CFC-11.²

Table 3.1 displays the basic results of our analysis. Each row presents information on a particular action to reduce the use of CFC-11. The first column shows the price at which users would take actions voluntarily; this is of course also their willingness to pay for the CFC-11 eliminated by each action. The second column shows the size of plant taking the action. The third indicates what the action is; a plant either "converts" to methylene chloride or "recovers" and recycles CFC-11. The fourth column indicates the share of the slabstock market affected by the action. The fifth shows the reduction in CFC-11 within each sector achieved by the action. The last column, calculated as the product of the numbers in the fourth and fifth, presents the percentage reduction in the total slabstock market. Multiplying the numbers in the final column by 0.14 would yield the effects of these actions on total U.S. use of CFC-11.

Table 3.1
TECHNICAL OPTIONS TO REDUCE THE USE OF CFC-11 IN THE MANUFACTURE OF FLEXIBLE SLABSTOCK FOAM

<table>
<thead>
<tr>
<th>Price ($/lb)</th>
<th>Plant Size</th>
<th>Action Taken[a]</th>
<th>% of Slabstock Market</th>
<th>% Reduction in Plant Use</th>
<th>Total % Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.30</td>
<td>Large</td>
<td>Convert</td>
<td>53</td>
<td>50</td>
<td>26.5</td>
</tr>
<tr>
<td>0.68</td>
<td>Medium</td>
<td>Convert</td>
<td>28</td>
<td>50</td>
<td>14.0</td>
</tr>
<tr>
<td>1.41</td>
<td>Large</td>
<td>Recover</td>
<td>53</td>
<td>25</td>
<td>13.3</td>
</tr>
<tr>
<td>2.05</td>
<td>Small</td>
<td>Convert</td>
<td>19</td>
<td>50</td>
<td>9.5</td>
</tr>
</tbody>
</table>

[a] See text.

²Our analysis draws heavily on methods and data from Palmer et al. (1980), pp. 53-58 and 267-270. For a summary of our assumptions, see this source and Appendix B.
Note first that the current price of CFC-11 is $0.51 per pound, suggesting that large plants should already be converting to higher use of methylene chloride. In fact, we observe this in many large plants. We do not know exactly what share has converted today; we can resolve this by considering two alternative base cases, one without any conversion and another with total conversion among large plants. We take this approach in Sec. VIII.

At somewhat higher prices, medium and then small plants voluntarily convert. Large plants also begin to recover and recycle their blowing agents. Other plants require much higher prices to do this voluntarily because the economies of scale in recovery are substantial.

In the end, all plants consider increasing their use of methylene chloride before recovering blowing agents. Only large plants use recovery in significant numbers at low prices. Within the price range considered, conversion and recovery allow a reduction in the U.S. slabstock foam industry's use of CFC-11 by about 37 to 63 percent and a reduction of total U.S. use of CFC-11 of about 5 to 9 percent.
IV. RIGID FOAM

CFC-12 is used in rigid foam products, like polystyrene (PS) sheet and board and polyolefins, which are used extensively for packaging or temporary containment of foods and other items.¹ Three options are available to reduce the use of CFC-12 in these applications: alternative blowing agents, CFC recovery and recycle during manufacture, and product substitution. This section reviews these options briefly and then presents quantitative estimates of the cost and effectiveness of the first two options. Empirical information is less complete for the last option.

ALTERNATIVE BLOWING AGENTS

Extruded PS sheet is the primary candidate for using a substitute blowing agent. Pentane is currently being employed in a number of situations, and available evidence suggests that it could serve as a blowing agent in virtually all thermoformed sheet products. Thermoformed sheet products accounted for 81 percent of total PS sheet output in 1977, and 74 percent of CFC use in PS sheet production (Palmer et al., 1980, p. 97).

Use of pentane has some drawbacks. First, conversion to pentane would require investment in new equipment. Second, pentane blowing agents can pose a serious fire hazard to production workers, especially if the polystyrene resin is ignited. Third, pentane has in recent years been the subject of several local regulatory actions, as a result of suspicions that as a low-boiling gasoline fraction, it contributes to the formation of photochemical smog.

In spite of these drawbacks, industry observers and the analysis below suggest that the option of substituting pentane for CFC-12 in the production of extruded PS sheet offers a good possibility of bringing about a large reduction in CFC use. Economically competitive facilities

¹CFC-11 is the most common PBD used to blow rigid foam. We do not have information on any low-cost methods to reduce CFC-11 in this application.
for manufacturing and marketing pentane-blown PS sheet already exist for virtually all applications in which PS sheet is now used.

RECOVERY AND RECYCLE DURING MANUFACTURE

Largely in response to potential regulations on pentane use, recovery of manufacturing emissions is being investigated at this time by producers of both pentane and CFC-blown PS sheet. Recovery techniques are already used in the manufacture of extruded polypropylene foam. This process employs carbon adsorption technology, achieves an overall recovery efficiency of 80 percent, and is economical at current CFC prices (DuPont, 1978). Although recovery from extruded PS sheet is economically less attractive, the large quantities of CFC-12 available for collection in a single plant and the probable absence of chemical contaminants in the air stream suggest that recovery is possible as a voluntary industry response to regulatory stimulus, and might be an enforceable control candidate.

PRODUCT SUBSTITUTES

Product substitutes such as wood fiber products exist for foam packaging and container applications, and are economically competitive in a limited group of those applications. In uses such as egg cartons and food service packages and trays, for instance, foam and wood fiber products sometimes compete side by side in the same supermarket.

QUANTITATIVE ANALYSIS OF TECHNICAL CONTROL OPTIONS

Like the flexible urethane foams, the price responsiveness of CFC use in thermoformed extruded PS sheet depends on the costs of alternative blowing agents and CFC recovery, and varies with plant size. Unlike flexible foams, however, consumer response can be expected to be substantial here. That is because packaging materials using wood fiber compete closely with similar products made from PS sheet.

Our analysis distinguishes among small, medium, and large plants, consuming 350,000, 500,000, and 750,000 pounds of CFC-12 per year, respectively. Extruded PS sheet accounts for about 4.7 percent of total use of CFC-12 in the United States. For more information on the cost assumptions underlying our analysis, see Appendix B.
1985 dollars, at which these plants should voluntarily reduce their use of CFC-12. The format for this table is the same as that in Table 3.1.

Two patterns are immediately apparent. First, larger plants always act to reduce their use of CFC-12 at lower prices than smaller plants. Second, it appears that any size plant would prefer to convert to pentane than to recover and recycle CFC-12. This second point suggests that recovery and recycle will occur only if conversion to pentane is not possible; recovery and recycle options are shown below the dotted line to emphasize their conditional nature. Concern over pentane's contribution to smog, noted above, could make conversion difficult. The reduction numbers shown here for recovery and recycling assume that, for whatever reason, no conversion occurs. These reduction numbers do not reflect substitution toward wood-fiber-based packaging materials if the price of CFC-12 rises. Such substitution could be substantial. Although good empirical data on the elasticity of demand for CFC-based

<table>
<thead>
<tr>
<th>Price ($/lb)</th>
<th>Plant Size</th>
<th>Action</th>
<th>% of Market</th>
<th>% Reduction in Plant Use</th>
<th>Total % Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.62</td>
<td>Large</td>
<td>Convert</td>
<td>25</td>
<td>100</td>
<td>25.0</td>
</tr>
<tr>
<td>0.79</td>
<td>Medium</td>
<td>Convert</td>
<td>50</td>
<td>100</td>
<td>50.0</td>
</tr>
<tr>
<td>0.99</td>
<td>Small</td>
<td>Convert</td>
<td>25</td>
<td>100</td>
<td>25.0</td>
</tr>
<tr>
<td>0.80</td>
<td>Large</td>
<td>Recycle</td>
<td>25</td>
<td>50</td>
<td>12.5</td>
</tr>
<tr>
<td>1.20</td>
<td>Medium</td>
<td>Recycle</td>
<td>50</td>
<td>50</td>
<td>25.0</td>
</tr>
<tr>
<td>1.70</td>
<td>Small</td>
<td>Recycle</td>
<td>25</td>
<td>50</td>
<td>12.5</td>
</tr>
</tbody>
</table>

[a] See the text for an explanation of the options shown below the dotted line.
packaging material do not exist, most industry observers agree that wood fiber and plastic are close enough substitutes to make this elasticity very high. The actual value of this elasticity is not relevant to policy unless foamers cannot convert to pentane, because conversion is cost-effective at such a low price that foamers stop using CFC-12 quickly, leaving little opportunity for consumer response to affect its use.

The current price of CFC-12 is $0.67 per pound, suggesting that large plants should already have converted to pentane. In fact, as noted above, pentane is a competitive substitute for CFC-12. We do not know exactly what share of the market currently uses pentane; we can resolve this by considering two alternative base cases, one without any conversion and another with total conversion among large plants. This is how we treat the reduction options shown here in Sec. VIII.

Technical control options, then, can easily eliminate the use of CFC-12 in the manufacture of thermoformed PS sheet. But this is a small use of CFC-12. Even total elimination of this market would cut the use of CFC-12 in the United States by only 4 to 5 percent.
V. SOLVENTS

In the United States, CFC-113 and methyl chloroform are used primarily as solvents. About 85 percent of CFC-113 production is used to clean and dry electronic, metal, and plastic parts. About 70 percent of methyl chloroform is used to degrease and clean metal and electronic parts. We focus here on technical control options that could reduce the use of these PODs in cleaning and drying applications; they fall into three categories: vapor recovery, recovery from waste, and product substitution. We have quantified the social cost and effectiveness of these options for reducing the use of CFC-113 and the discussion below focuses on this chemical. We have not examined methyl chloroform in as great detail, but believe that similar measures could be applied to this POD with similar effectiveness and somewhat higher social costs.¹

VAPOR RECOVERY

Vapor recovery can be effected by means of improved equipment designs or carbon adsorption techniques.

Improved Equipment Design

Improved equipment designs include increasing the freeboard height of the equipment (the height of the equipment wall above the solvent surface), using refrigerated condensing coils, adding a freeboard chiller, and reducing the throughput speed of items being cleaned to allow more time for the solvent to drain back into the equipment.

¹Carbon tetrachloride may be an important solvent in the developing world but plays no such role in the United States. In the near future, almost all U. S. carbon tetrachloride production will be used to produce CFC-11 and -12. As a result, we do not discuss it here. However, technical control options like those discussed here may be relevant to some uses of carbon tetrachloride outside the United States.
Carbon Adsorption Techniques

Carbon adsorption techniques employ specially prepared carbon beds over which solvent-laden air is passed. The solvent adsorbs onto the carbon, after which it is desorbed, usually with steam, and recycled. If mixtures of solvents are used rather than pure CFC-113, the soluble components of the mixture will at least partially be retained in the water in the steam desorption step. In this case, the original proportions of the solvent mixture must be reconstituted before it can be reused and the water phase presents disposal problems of its own with associated costs.

RECOVERY FROM WASTE

Purification of CFC-113 from the waste liquids that are removed from vapor degreasers or cold cleaning units is accomplished through one or both of the following methods: in-house distillation techniques, and external-to-the-plant reclamation services.

In-House Distillation

Distillation units boil off, condense, and collect purified solvent from the waste liquids that have been removed from a piece of equipment, leaving behind contaminants such as oil, grease, and bits of solid material and flux from the cleaned components. If nonazeotrope mixtures of two or more solvents are used, each component of the mixture will boil off at a different temperature, necessitating the additional step of reconstitution of the original proportions of the mixture.

One in-house distillation unit is able simultaneously to supply purified, reclaimed solvent to several vapor degreasing machines. Because of this, in-house distillation is most attractive for users with multiple degreasers.

External Reclamation

About 20 percent of cleaning and drying solvent losses\(^2\) end up as

\(^2\)Cleaning and drying applications represent about 84 percent of CFC-113 total use.
wastes that could be sent to external reclamation services. Not all of this waste would be reclaimed, since some is too contaminated to warrant reclamation and some cannot be extracted from the waste even with good distillation. Moreover, some waste from small users accumulates slowly, making outside reclamation uneconomical because of the costs of collection and transportation. Finally, because reclamation is largely an option only in cleaning and drying applications, even if as much as 90 percent of the waste could be returned to use, total CFC-113 emissions could be reduced by no more than 15 percent.

PRODUCT SUBSTITUTES

The most commonly mentioned substitutes for CFC-113 are methyl chloroform (which is itself a potential ozone depleter), methylene chloride, trichloroethylene, perchloroethylene, and in some cases, deionized water. Except for water, however, none of these substitutes is as gentle a solvent as CFC-113. They may affect some plastics or some of the delicate materials in electronics components and are not suitable for certain specialty dry cleaning operations, such as the cleaning of leather. In addition, none of the substitutes except water has as high a threshold limit value as CFC-113, and thus more care would have to be taken with the substitute solvents to see that their levels in the workplace remain within Occupational Safety and Health Administration health standards.3

A ban on land disposal of chlorinated solvents was mandated in the 1984 amendments to the Resource Conservation and Recovery Act. These amendments, which will go into effect in November 1986, might induce some solvent consumers to adopt alternatives, rather than pay for more expensive disposal options such as incineration. Incineration of CFC-113 is likely to be more costly than incineration of the other chlorinated solvents. CFC-113 contains fluorine, which industry sources indicate deteriorates some of the refractory materials lining incinerators. This might constitute an additional incentive for substitution of other solvents for CFC-113.

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3In general, the higher the threshold limit value, the less hazardous the substance.
QUANTITATIVE ANALYSIS OF TECHNICAL CONTROL OPTIONS

Our quantitative analysis of technical options to reduce the use--
and hence emissions--of solvents starts by recognizing that CFC-113 is
not embodied in the final products that create the demand for CFC-113.
To reduce the use of this chemical, we must reduce the CFC-113 vapor and
waste losses that occur during the cleaning or drying process. We
identify six market segments in which these losses can be reduced, based
on three sizes of units and on whether the CFC-113 is used in pure form
or mixed with other chemicals. Hence, our analysis focuses on 12 places
where actions might be taken to reduce losses. Table 5.1 indicates
their relative importance in the U.S. market for CFC-113. The table
indicates that losses are most important in small units and that vapor
losses are more important than waste losses. This is true in part
because the owners of larger units have already taken actions to reduce
losses and waste losses are easier to reduce than losses from vapor.

Table 5.1

WHERE LOSSES CURRENTLY OCCUR IN THE U.S. MARKET FOR CFC-113

(Percent of total loss)

<table>
<thead>
<tr>
<th>Type of Loss</th>
<th>Small (15 Gallon) Unit</th>
<th>Medium (60 Gallon) Unit</th>
<th>Large (375 Gallon) Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapor losses with pure CFC-113</td>
<td>16.0</td>
<td>11.7</td>
<td>9.6</td>
</tr>
<tr>
<td>Waste losses with pure CFC-113</td>
<td>8.0</td>
<td>3.3</td>
<td>1.4</td>
</tr>
<tr>
<td>Vapor losses with combined solvent</td>
<td>16.0</td>
<td>11.7</td>
<td>9.6</td>
</tr>
<tr>
<td>Waste losses with combined solvent</td>
<td>8.0</td>
<td>3.3</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Within the appropriate sectors, our analysis considers the opportunities for reducing losses by using more conservative equipment, recovering and recycling vapor losses, distilling waste CFC-113 in-house, reclaiming waste CFC-113 externally, or substituting toward alternative solvents. We model the first three options by comparing the costs of providing a given level of solvent services in each sector under different arrangements. We assume that users increase their use of external reclamation and switch more toward other solvents as the price of CFC-113 rises. Table 5.2 summarizes the results of this analysis. Because it is a complicated table, we review its structure briefly before considering the implications of the numbers reported in it.

The first column lists prices of CFC-113 at which changes occur. The second column indicates where the changes occur. The third shows the action taken at each price. "Recover" refers to recovery and recycle of vapor losses, "conserve" to a purchase of more conservative equipment, "new solvent" to a decision of some fraction of CFC-113 users to replace CFC-113 with another solvent, "reclaim" to external purification, and "distill" to the use of in-house distillation equipment to recover waste. The fourth column shows the share of the total market for CFC-113 affected by these changes. The last column reports the total incremental percentage effect of each change on the demand for CFC-113 in drying and cleaning. The fifth column shows the

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*For more detail on the analysis of technical options for reducing the use of CFC-113, see Appendix B.

*Table 5.2 summarizes results for the "High Quantitative" case in Sec. VIII, which assumes that none of the options that are cost-effective at the current price of $0.89 per pound have been exploited. A similar table underlies the "Low Quantitative" case, but is not shown here.

*In each case, with one exception, the action refers to a decision to add a measure to those already undertaken at lower prices. The one exception occurs in medium size units using pure solvent. Here, the user will adopt more conservative equipment only in a price range from $0.89 to $1.16. The user adopts recovery and recycle only for prices between $1.16 and $4.46. For prices above $4.46, the user adopts both more conservative equipment and recovery and recycle technology.
Table 5.2  
TECHNICAL OPTIONS TO REDUCE THE USE OF CFC-113 IN CLEANING AND DRYING APPLICATIONS

<table>
<thead>
<tr>
<th>Price ($/lb)</th>
<th>Unit Type</th>
<th>Action Taken</th>
<th>% of Market</th>
<th>% Reduction from Action</th>
<th>Total % Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.89</td>
<td>Large pure</td>
<td>Recover</td>
<td>9.6</td>
<td>80</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>Medium pure</td>
<td>Conserve</td>
<td>11.7</td>
<td>51</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Medium comb.</td>
<td>Conserve</td>
<td>11.7</td>
<td>51</td>
<td>6.0</td>
</tr>
<tr>
<td>1.00</td>
<td>All waste</td>
<td>New solvent</td>
<td>100.0</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reclaim</td>
<td>25.4</td>
<td>2.0</td>
<td>.5</td>
</tr>
<tr>
<td>1.13</td>
<td>Small pure</td>
<td>Recover</td>
<td>16.0</td>
<td>80</td>
<td>12.8</td>
</tr>
<tr>
<td>1.16</td>
<td>Medium pure</td>
<td>Recover</td>
<td>11.7</td>
<td>28</td>
<td>3.3</td>
</tr>
<tr>
<td>1.27</td>
<td>Large combin.</td>
<td>Recover</td>
<td>9.6</td>
<td>80</td>
<td>7.7</td>
</tr>
<tr>
<td>2.00</td>
<td>All waste</td>
<td>New solvent</td>
<td>100.0</td>
<td>25</td>
<td>24.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reclaim</td>
<td>25.4</td>
<td>19</td>
<td>4.8</td>
</tr>
<tr>
<td>2.11</td>
<td>Medium combin.</td>
<td>Distill</td>
<td>3.3</td>
<td>32</td>
<td>1.0</td>
</tr>
<tr>
<td>2.56</td>
<td>Small combin.</td>
<td>Conserve</td>
<td>16.0</td>
<td>23</td>
<td>3.6</td>
</tr>
<tr>
<td>3.00</td>
<td>All waste</td>
<td>New solvent</td>
<td>100.0</td>
<td>6.7</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reclaim</td>
<td>25.4</td>
<td>4.7</td>
<td>1.2</td>
</tr>
<tr>
<td>3.46</td>
<td>Small combin.</td>
<td>Distill</td>
<td>8.0</td>
<td>18</td>
<td>1.4</td>
</tr>
<tr>
<td>4.00</td>
<td>All waste</td>
<td>New solvent</td>
<td>100.0</td>
<td>2.9</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reclaim</td>
<td>25.4</td>
<td>1.2</td>
<td>0.3</td>
</tr>
<tr>
<td>4.46</td>
<td>Medium pure</td>
<td>Conserve and recover</td>
<td>11.7</td>
<td>3</td>
<td>0.3</td>
</tr>
<tr>
<td>5.00</td>
<td>All waste</td>
<td>New solvent</td>
<td>100.0</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reclaim</td>
<td>25.4</td>
<td>.8</td>
<td>0.2</td>
</tr>
</tbody>
</table>

NOTE: For an explanation of the terms used in the table, see the text.
implied percentage effect on the relevant sector. Each row identifies a specific action. Because the effects of switching to other solvents and reclaiming externally rise as price rises, their incremental effects over certain price ranges are aggregated and reported at specific prices. For example, switching and reclamation reported at $4.00 includes all of the effects of these actions over the range from $3.00 to $4.00. In each case, switching accounts for two-thirds of this aggregation for waste losses and reclamation for the remaining third; only switching affects vapor losses. As in earlier tables, we stop arbitrarily at $5.00.

Notice first that large reductions occur at lower prices and that incremental reductions get very small as price rises. That is because the level of the demand of CFC-113 falls as price rises, making it difficult for actions that occur at higher prices to have much effect relative to the current size of the market. At $5.00, the market has fallen to 6 percent of the baseline, suggesting that actions induced at prices higher than this have little policy relevance.

Notice next that in-house distillation is induced in only two market segments. That is because our analysis indicates that in-house distillation is so cost-effective that users in all other segments would adopt in-house distillation at prices well below the current price of $0.89 a pound. In fact, in-house distillation is widely practiced in industry, so this is not surprising. Nonetheless, it might be argued that some opportunities for in-house distillation have not been exploited in the segments excluded here, suggesting that we understated the opportunities for reduction. Including these opportunities, however, would not change the aggregate results significantly. It would suggest that distillation in these segments could cut total use about 10 percent. But CFC-113 saved through distillation would no longer be "available" to be saved through switching and external reclamation;
reductions in the effectiveness of these options would offset the
effects of distillation, leaving the total effect on CFC-113 use only
marginally larger. Whether we include or exclude these highly cost-
effective reduction opportunities, then, makes little difference.

Options associated with vapor losses have much larger effects than
those associated with waste losses. In the price range shown, recovery
and recycling with carbon adsorption reduces use over 30 percent and use
of more conservative equipment over 15 percent. All effects on waste
losses, on the other hand, sum to about 10 percent. That is true in
part because vapor losses currently account for most losses and because,
in this analysis, most segments have already exploited the effective
strategy of adopting in-house distillation. We use a rather arbitrary
assumption to calculate the effects of external reclamation, but
alternative assumptions within a reasonable range would not change the
qualitative results reported here.8

Decisions to switch to an alternative solvent shrink demand by
about 30 percent over the price range shown, accounting for a
substantial share of the reductions here. Our assumption about how
users respond to rising prices could significantly affect this result
and hence the aggregate results shown.9 Hence better information on the
empirical adequacy of that assumption would be desirable; it is not
available at this time.

In the end, the most important implication of Table 5.2 is that
almost all use of CFC-113 can be eliminated in drying and cleaning
applications at an incremental social cost of little more than $4.00 per
pound ($5.00 - $0.89). Although that cost is high relative to the
current price of CFC-113, it is much lower than the cost one might

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8We assume that reclamation shrinks waste losses by 0.5 percent of
actual losses for every 1 percent rise in the price of CFC-113 above
$0.89. Because reclamation accounts for only about a 7 percent
reduction, changing the elasticity from 0.5 to some other number would
not affect the aggregate results much.

9We assume that, above a certain "switching price," users will
reduce their use of CFC-113 by 1 percent of the actual use for every 1
percent rise in its price. The switching prices, $1.05 for small units,
$0.97 for medium units, and $1.21 for large units, reflect the increase
in price above current prices required to recover the incremental
investment needed to make a change in solvent feasible.
associate with implementing other CFC control options, for example, in refrigeration applications. Much of the reduction, however, comes from switching to alternative solvents. Using price incentives to induce this would be more effective than using mandatory controls because of the detailed analysis required to determine where switches can occur, and to what alternative, without significantly degrading the cleaning and drying function. Again, cleaning and drying accounts for about 85 percent of the total U.S. use of CFC-113, suggesting that the options shown here could significantly reduce total use of this chemical. Other options are available to reduce CFC-113 use in other applications but, because of the small size of these individual applications, they are not discussed here.

Although we have not studied it in detail, we believe similar techniques could be used to reduce U.S. use of methyl chloroform in solvent cleaning operations. Options associated with external reclamation and switching to alternative solvents could occur at costs similar to those presented here;¹⁸ the costs of other options, including in-house distillation and carbon adsorption, would be higher than those shown here. Like the use of CFC-113, then, the use of methyl chloroform in drying and cleaning could be effectively eliminated in this country at a reasonable incremental social cost. This includes about 70 percent of the U.S. market for methyl chloroform. Options not discussed here could be used to reduce the use of methyl chloroform in certain other individual applications.

¹⁸CFC-113 and methyl chloroform are potential substitutes for one another in some applications. We do not address such interactions here.
VI. REFRIGERATION AND AIR CONDITIONING

Refrigeration and air conditioning applications employ CFC-11 and CFC-12, as well as other chemicals. CFC-11 is used in commercial and industrial air conditioning systems (chillers), and CFC-12 is employed in mobile air conditioning units, chillers, retail food refrigeration systems, and home refrigerators and freezers.

Many options have been identified for reducing CFC emissions from refrigeration and air conditioning applications. Those for which we have sufficient information to formulate price-reduction pairs are: substitution of chemicals used to locate system leaks at manufacturing and installation and used as refrigerants; and recovery at disposal.

After discussing these options, we turn to other potentially important options for which our information is not so complete.

OPTIONS DOCUMENTED WITH QUANTITATIVE ANALYSIS
Chemical Substitution: Test Gases for Locating System Leaks

Manufacturers and installers of chillers and retail food refrigeration units can substitute the refrigerant gas CFC-22 for CFC-12 in leak testing applications. CFC-22 is a POD, but its potential effect per gram on stratospheric ozone is so much smaller than that of CFC-12 that substitution would be worthwhile. Halide "sniffers," which are used widely throughout the industry, could effectively detect leaks of the halogen. Substituting CFC-22 (or another gas) can be inconvenient for an installer, however, who charges the refrigeration unit on site (as is done with retail food refrigerators). The convenience to the service person of carrying one or more cylinders containing only one refrigerant, using that both to test and to charge the system, and avoiding one additional evacuation of the test gas is influential in the service person's choice of test gas. The possibility of contaminating the CFC-12 with the CFC-22 test gas is also a drawback. The two CFCs form an azeotrope that is difficult to separate.
Chemical Substitution: Refrigerant Replacement of CFC-12 with CFC-502

CFC-502 is an azeotrope composed of CFC-22 and CFC-115. It is considered to pose a far smaller potential threat to the stratospheric ozone layer than CFC-12. Low temperature retail food applications today almost exclusively employ CFC-502. Its use in medium temperature units has been increasing in recent years, possibly because of the convenience of using one refrigerant for both applications. Furthermore, CFC-502 requires a smaller, less costly compressor. The disadvantage of CFC-502 is that it is almost three and a half times more expensive than CFC-12. If the price of CFC-12 were to rise enough, there would be a strong incentive to use CFC-502 in all new medium temperature freezer applications.

Recovery at Disposal

Recovery is already practiced to some extent in chiller and retail food applications. The design of most home refrigerators and freezers does not allow recovery and the small amount of CFC-12 that could be recovered from them is unlikely to warrant redesign. The major unexploited opportunity to recover CFC-12 at disposal is in mobile air conditioning units. Motor vehicle salvage yards recover a wide variety of materials, and they might also collect used CFC if there were a large enough market for it.

OTHER OPTIONS TO REDUCE POD EMISSIONS

For some potentially important technical control options, our information is more qualitative than for the options discussed above. These options are ranked in the order of their estimated potential impact on POD use.

Chemical Substitution Using New Gases under Development

FC-134a is a fluorocarbon that contains no chlorine, and thus poses no known threat to the stratospheric ozone layer. The chemical can be substituted for CFC-12 in existing refrigeration and air conditioning equipment with little or no redesign, although it does require that a different oil be used with it. Refrigeration and air conditioning
applications in 1984 accounted for 37 percent to 74 percent of total U.S. CFC-12 use.\textsuperscript{1} To date, however, no commercial manufacturing process for FC-134a is known to be available. Until such a process is developed, it does not offer a viable option for reducing the use of CFC-12.

Reduction of Emissions during Servicing

Servicing emissions could be reduced if refrigeration and air conditioning units were pumped down before servicing, and the recovered refrigerant decontaminated if necessary and reused. About 16 percent of the total CFC-12 used in the United States in 1984 was lost because of venting during servicing of mobile air conditioners. CFC-11 and CFC-12 losses in 1984 during servicing of chillers amounted to 1.3 percent and 0.6 percent of the total U.S. use of those chemicals during that year. Losses from retail food refrigerators during servicing amounted to 0.8 to 8.7 percent of U.S. CFC-12 use during 1984.\textsuperscript{2}

Equipment Replacement

Reciprocating and screw compressor chillers using the refrigerant CFC-22 have the potential to compete with centrifugal chillers in the 200, 300, and possibly 400 ton range. By replacing centrifugal machines in these ranges, CFC-11 and CFC-12 use in all centrifugal machines could be reduced by about 25 percent, which in 1984 would have corresponded to about a 1 percent reduction in combined U.S. CFC-11 and CFC-12 use.

\textsuperscript{1}In work elsewhere, Rand identifies 37 percent of CFC-12 as being used in these applications in the United States. The applications of another 42 percent of CFC-12 use cannot be identified. The available data suggest that as much as 88 percent of this unexplained portion may be used for refrigeration and air conditioning. For details, see Hammit et al. (1986).

\textsuperscript{2}As indicated in the footnote above, how much CFC-12 is used for refrigeration applications is uncertain. Retail food refrigerators account for 3 to 33 percent of all U.S. CFC-12 use.
QUANTITATIVE ANALYSIS OF TECHNICAL CONTROL OPTIONS

Our analysis of control options relevant to air conditioning and refrigeration is simpler than the analyses underlying other results reported here. For two options, we compare the prices of CFC-22 and -502 with that of CFC-12; when relative prices have changed sufficiently, users switch from CFC-12 to the relevant alternative. For the third, we use a simple cash flow analysis to determine at what price it would pay the owner of a typical salvage yard to invest in recovery equipment. We draw heavily on the methods and data reported in Palmer et al. (1980, pp. 141, 158, 185-189) to make these calculations; for methodological details, see that reference.

Table 6.1 summarizes the results of this analysis. Its format is similar to that used above. Because we do not look at individual market segments within each application, the fourth column shows the share of each application in total U.S. use of CFC-12. The final column shows the effect on total U.S. CFC-12 use. A brief explanation of the result in each row follows.

Table 6.1

TECHNICAL OPTIONS TO REDUCE THE USE OF CFC-12 IN AIR CONDITIONING AND REFRIGERATION APPLICATIONS

<table>
<thead>
<tr>
<th>Price ($/lb)</th>
<th>Application</th>
<th>Action Taken</th>
<th>% Share of Use[a]</th>
<th>% Reduction in Application</th>
<th>Total % Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>Retail food</td>
<td>Use CFC-502</td>
<td>3-33</td>
<td>48.0</td>
<td>1.4-15.6</td>
</tr>
<tr>
<td>1.17</td>
<td>Retail food</td>
<td>Use CFC-22</td>
<td>3-33</td>
<td>5.0</td>
<td>0.15-1.6</td>
</tr>
<tr>
<td></td>
<td>Cent. chiller</td>
<td>Use CFC-22</td>
<td></td>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td>3.64</td>
<td>Mobile air cond.</td>
<td>Recover</td>
<td>32.6</td>
<td>2.5</td>
<td>0.82</td>
</tr>
</tbody>
</table>

NOTE: See the text for an explanation of the abbreviated expressions used in the table.

[a] This range results from uncertainty about how CFC-12 is used in the United States. For details, see Hammitt et al. (1986).
Chemical Substitution of CFC-12 with CFC-502

The first row shows that a CFC-12 price increase to $1.00 per pound, which reduces the price differential between CFC-12 and CFC-502 by 20 percent, would lead to all new medium temperature retail store refrigeration systems being charged with CFC-502. Because of the convenience of using a single refrigerant for leak testing as well as charging, implementation of the above option would probably eliminate some or all use of CFC-12 during installation of retail systems. A conservative estimate is that half of all CFC-12 leak testing would be replaced by the use of CFC-502. Although switching to CFC-502 as the charge installed in new medium temperature retail food units has a large effect on this application of CFC-12, this application may account for only a small share of total CFC-12 use. Rand has identified only 3 percent of CFC-12 as being used in retail food refrigeration. Evidence suggests, however, that that estimate could be ten times higher, in which case this substitution would have a substantial effect.

Chemical Substitution of Test Gases

CFC-22 can be substituted for CFC-12 on a pound-for-pound basis for leak testing at manufacture in centrifugal chillers and for leak testing at manufacture and installation in retail refrigeration units. Because CFC-22 currently costs $1.17 per pound in real terms, the switch to CFC-22 as the test gas would occur if the CFC-12 price rose $0.50 above its current bulk price of $0.67. The first row at a price of $1.17 shows the remaining half of leak testing in retail food refrigeration units switching from CFC-12 to CFC-22. The second row shows a similar shift in centrifugal chillers. In both cases, the effect on the particular application of CFC-12 is small and the shares of these applications in total U.S. use of CFC-12 are also small.

Recovery at Disposal

The last row indicates that motor vehicle salvage yard operators would find it cost-effective to recover CFC-12 from mobile air conditioning units at a CFC-12 price of about $3.64 per pound. Despite the importance of mobile air conditioning to total CFC-12 use, however, this option has a small aggregate effect.
In sum, few options are available to reduce the use of CFC-12 in air conditioning and refrigeration at a reasonable social cost. That is true either because the applications where options exist account for a small share of total use of CFC-12 or because the options that are available have only small effects where they are applied. It is worth noting that a large portion of current CFC-12 cannot easily be associated with any particular use.\(^3\) But even if all of the unexplained portion of CFC-12 use in the United States were in fact associated with air conditioning or refrigeration applications, this would not change the basic qualitative conclusion that flows from this table. Only if a new chemical, like FC-134a, can replace CFC-12 in a wide variety of these applications can we expect to see a significant reduction in its use here at reasonable social costs.

\(^3\)For a discussion of this point, see Hammitt et al. (1986).
VII. MISCELLANEOUS APPLICATIONS

Potential ozone depleters are used in a number of smaller applications in addition to the major categories discussed above. Technical options available in some of these smaller applications are probably effective enough to induce significant reductions in the total use of CFC-11 and -12 and Halon 1301. This section addresses these options. We have not quantified the effectiveness of using these options to reduce the use of PODs nor have we estimated their social costs; these are subjects for future research. But these options could be as cost-effective as the options considered above.

We consider options that can affect the use of CFC-11 and 12 in exempt aerosol uses, liquid food freezing, sterilants, and Halon 1301 in fire extinguishing systems.

EXEMPT AEROSOL PROPELLANT USES

Most uses of CFC-11 and -12 as aerosol propellants were banned in the United States in 1978. In 1985, about 9500 metric tons (mt) of CFC-11 and CFC-12, or 3.9 percent of their total use in the United States, were used in exempt applications, including certain insecticides, military uses, and some medicinal uses. Generally, these exceptions were granted because the alternative propellants that were available at the time the ban was promulgated were unsatisfactory.

Since that time, propellant technology has advanced considerably. Although this in itself has not caused a substantial move away from exempt applications of CFC-11 and CFC-12, some substitution has occurred and more could be expected if the prices of CFC-11 and -12 rose or the definitions of exempt uses were tightened. Two technological changes are particularly important.
Dimethyl Ether/CFC-22 Blends

One recent technological advance has been the introduction of dimethyl ether/CFC-22 blends under the DuPont trade name of Dymel®.\(^1\) This blend is a nonflammable alternative to CFC-11 and -12 that can be used where fire hazards have precluded substituting hydrocarbon propellants for CFCs. For example, naval shipyards often have local rules prohibiting flammable propellants. Since the uses are qualified as military uses, the shipyards can (and do) demand that CFC propellants be used. Carbon dioxide is a nonflammable alternative, but it has had other disadvantages that users have been unwilling to accept. Dimethyl ether/CFC-22 provides a better nonflammable alternative, and at least one shipyard has accepted this type of propellant.

Because Dymel® is more expensive than CFC-11 and CFC-12 in most applications, most manufacturers have not switched. But higher prices for CFC-11 and -12 could promote substitution toward Dymel® in certain exempt uses. The current price for a CFC-11/12 blend is about $0.60 a pound, whereas an equivalent amount of Dymel® currently costs about $0.90. Hence, a 50 percent increase in CFC prices would make the two options far more competitive. For lack of good data on the specific uses of CFC-11 and -12 as aerosol propellants, we cannot estimate how many of these exempt uses Dymel® might be able to displace. A rough guess might be about half.

Improved Technologies for Carbon Dioxide

The technology for using carbon dioxide as an aerosol propellant has also advanced considerably. The original objections to carbon dioxide centered on poor atomization, varying pressure over the life of the can, changing spray delivery rates as the can was used, and the occasional inability to expel the entire contents of the can, as a result of loss of pressure. New mechanical break-up valves have solved many of the atomization problems, and advances in formulation and filling technology have reduced the other problems. As a result, carbon

\(^1\) Dymel® trademark covers a variety of dimethyl ether/CFC blends. Of these, a blend with CFC-22 is nonflammable. Blends with CFC-142b or CFC-152a are flammable.
dioxide now appears to be a cost-effective alternative for many aerosol applications in which it was unacceptable five years ago. Many manufacturers may not have investigated these new options because they are not yet aware of the improvements that have been made in carbon dioxide propellant technology. We do not know how important these applications are to exempt uses of CFC-11 and -12 and hence cannot estimate how much CFC could be displaced by the use of carbon dioxide in these applications.

LIQUID FOOD FREEZING

In 1985, about 3000 mt, or 1.9 percent of CFC-12 total production, were used and emitted in liquid food freezing (LFF) applications. One promising option for reducing CFC-12 emissions from LFF is substitution of alternative freezing methods. Industry sources suggest that one such method, the air blast system, is making strong inroads into the LFF market today. Many current LFF users will eventually replace LFF capacity with air blast systems except in certain seafood and fruit applications (Mooz et al., 1982). This trend is borne out by industry sources who suggest that even at present CFC-12 prices, there is apparently some movement away from LFF systems. If the price of CFC-12 were to rise slightly, we would expect a more rapid shift away from LFF.

STERILANTS

In 1985, about 8000 mt, or 5.0 percent of total CFC-12 production, were used in a mixture with ethylene oxide for sterilizing applications in hospitals and institutional settings. One option that could reduce CFC-12 use and emissions is recovery and recycle of the sterilant in industrial sterilization operations, which account for about half the present use. In our earlier work, two systems with recovery efficiencies ranging between 70 and 100 percent were in various stages of commercialization (Mooz et al., 1982). At that time, the economics appeared attractive, especially for large institutional users. Assuming that industrial facilities fully adopt these systems and maintain a recovery efficiency of 85 percent, the savings in 1985 CFC-12 purchases could amount to 3400 mt or about 2.1 percent of total CFC-12 production.
HALON 1301

Halon 1301 total flooding systems have been used on a large scale for only about a decade. Emissions from such systems are small at present but may become significant because of recent and continuing high growth. Current U.S. use amounts to about 5400 mt.

One option that could reduce future emissions is substitution of alternative extinguishant systems; candidates include water, foam, and carbon dioxide. Although each of these is less costly, the Halon system offers the advantage of leaving no residue on expensive electronic equipment in case of a fire.

A second option is recovery at disposal. Industry sources claim that the high cost of Halon 1301—several dollars a pound—ensures that it is already recovered at disposal or remodel. One installer, however, indicates that systems under about 60 pounds are commonly vented. There is little experience with disposal of such systems and future research will investigate such practices further.
VIII. CONCLUSIONS AND DIRECTIONS FOR FUTURE WORK

The results developed above on the costs and effects of specific technical options provide the building blocks for policy analysis that examines alternative ways to reduce the emissions of potential ozone depleters. We plan to use these results to examine policy alternatives in the future. This section summarizes our results and suggests directions for detailed future analysis. It uses the results developed above to compare the relative price responsiveness of CFC-11, -12, and -113. It summarizes the total effects on the use of these chemicals if all of the options reviewed here were successfully implemented. And it compares the results developed here with those developed in Palmer et al. (1980). This comparison confirms the need for an update just five years after Palmer et al. was published, suggesting that we should be cautious about applying the results presented here or those in Palmer et al. to forecasts in the future.

Palmer et al. (1980) developed demand schedules for CFC-11, -12, and -113 by looking at a set of technical control options similar to those considered quantitatively in this analysis.\(^1\) It developed schedules for 1980 and 1990. The analysis performed here looks at the costs and likely effects of these options again, using 1985 as a reference year. But our analysis deals with these options in somewhat different ways and considers others where the quantitative data are not so complete. These differences in approach, coupled with our access to more up-to-date information, explain the differences between the results in Palmer et al. and those developed in this update.

There are three significant differences between the analysis performed here and that in Palmer et al. First, the analysis here identifies control options that appear to be cost-effective at current

\(^1\)The demand schedules for Palmer et al. are summarized in a table on p. 265 in that document. The schedules shown here for Palmer et al. are based on the data in that table and the price levels assumed in the analysis: $0.34 per pound for CFC-11, $0.41 per pound for CFC-12, and $0.62 and $0.40 per pound for CFC-113 in 1980 and 1990, respectively.
prices. Discussions with industry confirm that portions of the industry have adopted a number of these options. But we do not know how much potential remains for these options; hence, we develop a range of results to bracket the potential that still exists. This issue does not appear in Palmer et al.

Second, although the results in Palmer et al. reflect the fact that the uses of significant portions of total CFC-11 and -12 production have not been satisfactorily explained, that report does not attempt to suggest where those uses might be. We consider alternative ways in which the unexplained portion of the production of these chemicals might be used and their implications for the effects of control options.

Finally, Palmer et al. focused solely on control options for which quantitative data were available on effects and costs. This makes the estimates of effects in Palmer et al. conservative. We consider other options and use some simple rules to suggest what their effects might be.

The net result of these changes is that the results reported here provide a wider range of outcomes than those reported in Palmer et al. Although Palmer et al. can marshal more empirical data to support the specific results reported, our ranges are more likely to include the actual effects of the control options that we believe are available to reduce the use of CFC-11, -12, and -113. Consider the results for each chemical in turn.

Figure 8.1 presents demand schedules for CFC-11. The vertical axis shows percentage increases in price; the horizontal axis shows percentage reductions in use associated with these price increases. Hence, the schedules are "inverted" demand schedules of the type discussed in Sec. II. The figure shows five schedules. Those shown as solid lines are based on material in this Note; the dotted schedules are based on results from Palmer et al.

The three schedules based on the analysis in this Note reflect different assumptions about what options are available to reduce the use of CFC-11. The most conservative schedule is the "Low Quantitative" schedule. It includes only the effects relevant to the one use for which we have quantitative information—flexible slabstock foam blowing—and assumes that all options that appear cost-effective at current
prices have already been exploited. The "High Quantitative" schedule also focuses on slabstock foam blowing, but assumes that no large plants have moved to the 75 percent use of methylene chloride suggested by the first option in Table 3.1. Hence, this option is still available to reduce the use of CFC-11. The "Total" schedule adds options relevant to molded foam, exempt aerosol uses, and uses in chillers. We do not know the exact prices at which users would adopt these options; we adopt the simple rule of allocating a quarter of the total potential reduction
from using these options to each price increment from 100 to 200 percent, 200 to 300 percent, and so on. In sum, options relevant to slabstock foam blowing offer reduction opportunities that fall somewhere between the Low and High Quantitative schedules. The Total schedule indicates the largest reduction we expect to be possible at each price level. Hence, the actual demand schedule should fall somewhere between the Low Quantitative and Total schedules shown here.

The two schedules based on the results of Palmer et al., "Palmer 1980" and "Palmer 1990," reflect demand schedules for 1980 and 1990. Presumably the schedule for 1985, which would be most appropriate for comparison with our results, falls somewhere between these schedules. The Palmer schedules include options relevant to slabstock and molded foam. These schedules indicate that much higher savings are possible here than our results indicate. That is true for two reasons. First, foam blowers have increased their use of methylene chloride since the Palmer et al. analysis was completed, thereby reducing the opportunities available to reduce CFC-11 use in the future. Second, partly as a result, flexible foam blowing does not constitute as large a share of the use of CFC-11 today as expected in Palmer et al. Flexible foam blowing currently accounts for about 17 percent of CFC-11 use. Hence, the Palmer et al. schedules should not include reductions in the use of CFC-11 that exceed this level. Limiting the flexible foam market to 17 percent of CFC-11 use would bring the Palmer et al. schedules more in line with our Total schedule, which includes molded foam.

Our schedules show a significant range of possible outcomes. But all of them point to extremely inelastic demand. Arc elasticities based on a 500 percent price increase range from 0.01 to 0.03.

Figure 8.2 shows a set of schedules for CFC-12 similar to those shown for CFC-11 in Fig. 8.1. The solid schedules reflect results developed here; the dotted schedules reflect results from Palmer et al.

The three solid schedules bear labels similar to those for CFC-11, but they differ in important ways. The Low Quantitative schedule once again focuses on quantitative options, this time the extruded polystyrene sheet foam blowing, mobile air conditioning, chillers, and retail food refrigeration options shown in Table 6.1. It assumes that large foam blowing plants have all exploited the option of converting to pentane, thereby eliminating the first option shown in Table 4.1.
Fig. 8.2 -- Demand schedules for U.S. use of CFC-12

The High Quantitative schedule assumes that this option has not yet been exploited. It also examines the possibility that most of the unexplained use of CFC-12 production in the United States is associated with retail food refrigeration. If this is correct,\(^2\) the effect of converting retail food refrigeration units to CFC-502 is ten times larger than our quantitative analysis based on known uses of CFC-12

\(^2\)For a discussion of this issue, see Appendix A of Hammitt et al. (1986).
would indicate. The High Quantitative schedule also incorporates this possibility.

The Total schedule adds reductions for which we have not collected quantitative information. These include reductions associated with exempt aerosol propellant uses, liquid food freezing, sterilants, chillers, and the servicing of refrigeration applications. As in Table 8.1, a quarter of the total reduction available from these options is attributed to each range of price increase: 100 to 200, 200 to 300, and so on. Hence, the Total schedule once again represents an upper limit on the size of reductions we would expect in CFC-12 uses if its price rose.

The "Palmer 1980" and "Palmer 1990" schedules once again reflect demand schedules from Palmer et al. for 1980 and 1990; for practical purposes, they reflect the same schedule. These schedules reflect the same options included in the Low Qualitative schedule. These schedules closely resemble the Low Qualitative schedule over much of its price range. Because they all reflect the same options and do not consider the unexplained portion of CFC-12 production, this resemblance is not surprising. Two factors account for differences between them.

First, the Palmer et al. schedules assume that extruded polystyrene sheet foam blowing accounts for about 9 percent of CFC-12 use when in fact it currently accounts for only 4.7 percent of CFC-12 use. This allows Palmer et al. to attribute about twice the percentage savings in CFC-12 to options that reduce its use in foam blowing that we estimate. Because foam blowing has not grown as fast as Palmer et al. expected relative to other uses of CFC-12, our assumption is currently more appropriate.

Second, our analysis assumes that the savings that will occur in foam blowing occur at much lower prices than those shown in Palmer et al. In this Note, savings associated with conversion to pentane all occur at price increases of less than 50 percent, giving the Low Quantitative schedule quick reductions at low price rises relative to the Palmer schedules. The Palmer schedules show conversion occurring at price increases of 300 to 350 percent. Changes in the relative prices of pentane, CFC-12, and other inputs since Palmer et al. was written account for this change.
Where Palmer et al. concluded that few opportunities existed to reduce the use of CFC-12, then, our analysis suggests that significant opportunities may exist. Unfortunately, our information on those opportunities is not particularly good. We do not know the actual size of the market for retail food refrigerators that account for so much of the opportunity shown here. And we do not know the prices at which users of CFC-12 would voluntarily adopt the options included in the Total schedule. These issues obviously deserve more careful attention. No matter which of the three solid schedules one accepts, however, the elasticity of demand for CFC-12 is low. Arc elasticities of the schedules shown, based on a price increase of 500 percent, range from 0.01 to 0.07.

Figure 8.3 presents demand schedules for CFC-113. The solid "Low" and "High" schedules are similar to those shown in earlier figures. To derive the Low schedule, we assume that all options cost-effective at current prices are fully exploited. To develop the High schedule, we assume that the distillation and conservation options that become cost effective at prices below $0.89 a pound in Table 5.2 are still available for exploitation. The actual schedule lies between these. The two schedules diverge significantly for small price increases but tend to converge for larger price increases. That is because options that become cost effective at higher prices have larger effects if more CFC-113 is left for them to reduce.

The dotted "Palmer 1980" and "Palmer 1990" schedules reflect demand schedules for 1980 and 1990 in Palmer et al. The 1985 schedule relevant for comparison to our results presumably lies between these and hence cannot differ much from them. Almost all of the difference between the Palmer et al. schedules and our own can be explained by our decision to include recovery and recycle of vapor losses with carbon adsorption as an option. It accounts for 27 to 34 percent of total saving of CFC-113, only slightly less than the gap between our schedules and the Palmer et al. schedules.

Our results appear to be more or less consistent with those reported earlier for the effects of other control options. Whichever we use, the elasticity of demand for CFC-113 is higher than that for CFC-11
or -12, at least over the whole range of price increases considered here. Arc elasticities based on a price increase of 500 percent range from 0.10 to 0.16. These elasticities are still small when compared to those for other commodities traded in the economy.

Three simple differences, then, play the largest role in explaining differences in the results for Palmer et al. and those for this update. First, the use of CFC-11 and -12 in applications where control options were available did not grow as fast as Palmer et al. had anticipated, leading to a need to reduce the estimated effects of these options on CFC-11 and -12 use. Second, uncertainty about the use of the unexplained portion of CFC-12 production leads to great uncertainty...
about the effects of control options for applications that might explain
this use. By considering the portion of CFC-12 that might be used in
retail food refrigeration applications, this Note significantly
increases the potential importance of control options relevant to this
option. Finally, this Note considers many more control options than
Palmer et al. considered. Only one of these, carbon adsorption in the
recovery and recycle of CFC-113, is considered quantitatively. But lack
of detailed information need not lead us to conclude that other options
might not be important. Examination of these other options increases
the opportunities to reduce the uses of CFC-11, -12, and -113 at social
costs that fall within the range examined here and in Palmer et al.
Despite all the specific changes in implications for individual
chemicals, both Palmer et al. and the analysis shown here point to low
demand elasticities for all three of these chemicals.

Our summary results strongly suggest the potential leverage of the
options for which we have not developed quantitative results. They
clearly deserve more careful attention in the future. A better
understanding of where unexplained portions of CFC-12 are used will help
quantify more clearly options relevant to CFC-12. Reductions beyond
those possible with the options considered here, quantitative or not,
will require the use of much more costly options. If such reductions
are deemed necessary, however, we will need more information on them.

The reduction of PODs, of course, is a transnational problem. The
results developed here apply only to the United States and, as Appendix
C emphasizes, are unlikely to reflect opportunities available. The cost
of options to reduce the use of PODs outside the United States needs
additional attention.

The real purpose for developing results like those presented here
is to use them to compare the social costs of using alternative
policies, if need be, to reduce global ozone depletion in the future.
We currently plan to use the results presented here to look at policies
that spread reductions in U.S. use of these chemicals across time in
different ways. As better information becomes available on the costs of
options elsewhere, we can take a broader, global perspective.
Appendix A

POTENTIAL PROBLEMS IN COMPARING ALTERNATIVE POLICIES TO REDUCE POD USE

The demand schedules defined in this Note have an explicit interpretation. They represent opportunities to reduce use of potential ozone depleters that are currently known and that are implemented to minimize the social cost of reducing the use of any particular chemical by any particular amount. It is likely that many policies would not induce the kinds of reductions shown in these schedules. Other policies could easily induce reduction options that we do not yet know about.\(^1\) As a result, the results reported in this Note must be used with caution in comparing alternative policies. This appendix reviews some basic issues that must be considered in using results like those in the text to compare alternative policies.

Suppose, on whatever grounds, that policymakers decide to promote technical options of the kind discussed in the text to reduce POD use. How do they identify the technical options available or assure that options they choose are in fact implemented in the private economy? These problems of administering a regulatory policy draw important differences between policies based on command-and-control and those based on the price system. They also have important implications for the analysis of regulatory alternatives. Environmental policymakers, in the United States and elsewhere, typically use command-and-control programs to implement policy. In such programs, regulators identify the specific measures that must be undertaken and then monitor performance to assure that the private economy implements these measures. This allows policymakers to target the effects of their decisions and

\(^1\)In the discussion below, "options" always refer to specific actions in the private sector like implementing recycle and recovering of CFC-113, substituting pentane for CFC-12, or substituting away from polystyrene sheet to materials based on wood fiber. "Policies" refer to specific government programs that set up mandatory controls, impose taxes, or create entitlements.
mitigate the effects of those decisions on parties who would be hurt most if forced to reduce their use of substances or activities that may endanger the environment. It may also give policymakers a greater sense of control and predictability because they actively participate in the choice of technical options and focus their attention on achieving specific quantity changes in activities that they believe may threaten the environment.

Environmental policymakers make much less use of the price system to help them implement policy. Price-oriented programs typically tax activities that may endanger the environment or create entitlements to rights to engage in potentially dangerous activities. These entitlements can be bought and sold, subject to varying regulatory restrictions, by companies and individuals who engage in these activities. In these programs, policymakers rely on incentives to encourage actors in the private sector to discover and implement ways to reduce potentially dangerous activities. Where taxes are used, policymakers may not even attempt to achieve any particular level of reduction in activities that may endanger the environment. A tax can reflect the perceived incremental social harm associated with an activity; so long as the tax forces actors in the private economy to recognize this potential harm, their decisions will determine the socially desirable level of the activity. In this case, policymakers need only choose the "right" tax rate and assure that the tax is in fact paid. Creating entitlements requires policymakers to choose and regulate the total level of the dangerous activity and to assure that only companies with entitlements engage in it. But, as in the case of a tax policy, entitlement programs free policymakers of the responsibility of telling individuals and companies precisely what to do and then assuring that they do it.

When only social cost-benefit analysis is used to judge alternatives, command-and-control programs can never perform better than price-oriented programs unless the administrative cost of monitoring an activity where tax payments or entitlements are required is high. This is true in part because price-oriented policies by definition differentiate among consumers and suppliers with different willingness to pay for products and inputs. Consumers the least willing to pay for
foam products switch to alternatives first when foam producers must pay a tax or buy an entitlement to use PODs in foam blowing. Similarly, laborers with the least concern about alternative blowing agents consent to work with these alternatives at the lowest wages when taxes or entitlements drive up the cost of blowing agents based on PODs. These are precisely the kinds of private decisions favored by social cost-benefit analysis, and price-oriented programs promote them without requiring any special knowledge on the part of regulators. Price-oriented programs also outperform command-and-control programs because they create incentives in industry to discover and implement a broad range of subtle adjustments and accommodations that command-and-control methods simply cannot discover or enforce easily. To be successful, price-oriented regulators must assure that effective enforcement creates the right incentives, but they need no special knowledge of technology or consumption patterns in the private economy beyond that required to enforce taxes or entitlements.

Despite these apparent advantages of price-oriented systems, environmental policymakers continue to rely on command-and-control methods. Where taxes and entitlements truly encourage individuals and companies to cut back activities that may endanger the environment, they clearly contribute to solving the problem at hand. But where they simply force individuals and companies to pay a fee that they cannot avoid in any reasonable way, taxes and entitlements can be seen more as fiscal instruments that raise revenue or redistribute wealth than as valid instruments of environmental policy. For example, finding substitutes for CFC-12 in home refrigerators is so difficult and the cost of this CFC is such a small portion of the cost of a refrigerator that tax and entitlement programs are highly unlikely to change the use of CFC-12 in home refrigerators. Why burden the owners of home refrigerators—who will surely end up paying for new taxes or entitlements—with an environmental program that simply cannot change their behavior? Those who defend the use of social cost-benefit analysis would reply that such fees are just transfers among individuals, not real costs to the economy. Policymakers who typically favor the command-and-control programs that avoid such transfers apparently care about more than just the implications of social cost-benefit analysis.
These observations strongly suggest that social cost-benefit analysis by itself is unlikely to provide all of the answers that environmental policymakers require before choosing between various kinds of strategies. With that very important caveat in mind, however, we can ask how best to use the demand schedules discussed above to compare alternative regulatory strategies.

Two ideas are important to using these demand schedules. First, different policies must be represented by demand schedules that reflect different options. That is because different government policies make different technical options and responses available and only the options available under a particular regulatory policy should be considered when analyzing that policy.

Command-and-control regulators can consider only technical options that policymakers know currently exist, options that they can hope to learn about, and options that by whatever means the policymakers can bring into existence in the future. Further, unless the users of these technologies pass their costs forward in higher product prices, the demand schedules cannot reflect the mitigating effects of demand response; for example, strategies that subsidize POD-reducing options can reduce costs to industry but increase social cost by preventing consumers from reacting where they can to avoid the real costs of the POD-reducing technology. Finally, they cannot include options whose use is too difficult to enforce; the most obvious examples are technical options based on improvements in operating practices that regulators would have to monitor frequently to assure compliance.

Price-oriented regulators, on the other hand, can include a much broader set of options in the demand schedules they use. In fact, this can present an analytic problem because price-oriented policies are designed to generate information in their implementation that

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2In the discussion that follows, it may be easiest to think of the "inverted" demand schedule above in which reductions in production and use appear on the horizontal axis and the total level of reduction grows as price rises. Including more technical options and responses in such a schedule allows more reduction at any price, suggesting that adding options and responses increases the elasticity of the demand schedule in question.
policymakers and their analysts cannot have when estimating demand schedules. That is, analysts must assume something about the private sector's ability and willingness to innovate to reduce POD use. If the analyst assumes that the private sector will innovate at all, he also implicitly assumes that price-oriented policies can reduce POD use at a lower social cost than command-and-control policies. Price-oriented policies can also accommodate options based on improved operating practices and other activities that regulators cannot monitor easily. And they also benefit from the effects of consumer response to price increases induced by taxes and entitlements. Only options where the collection of taxes or enforcement of entitlement use is difficult should be excluded from these schedules. As a result, only if these options account for a large portion of POD saving and can be effectively monitored in a command-and-control program can such a program hope to match or surpass the options a price-oriented program can exploit.

The second idea to keep in mind when using demand schedules is that they play different roles in analyzing command-and-control and price-oriented regulatory strategies. For command-and-control strategies, they basically order the options available under this regime to help regulators determine a sequence of specific options to use to achieve any reduction in POD emissions. For price-oriented strategies, they have a more behavioral role. They help policymakers estimate how much a given tax rate might reduce POD use, or what tax or entitlement price should be associated with any total restriction on POD use. That is, although demand schedules simply help command-and-control regulators order their thoughts, they help price-oriented regulators do things that they cannot do in any other way.

The behavioral role of demand schedules used to analyze price-oriented policies may prove useful to regulators even if they anticipate using only command-and-control policies. Such demand schedules allow regulators to set a benchmark; regulators can use them to measure the social cost of reducing a given amount of POD use if the least socially costly price-oriented program were used. Policymakers can then compare the social cost of this alternative with the cost of various command-and-control programs to determine whether these programs offer enough to make them worth the amount they add to the social cost of any reduction.
This is a comparison that allows policy decisions to be made without reference to any knowledge about the social benefits of the POD reduction.

In the end, this form of cost-effectiveness is probably the best form of analysis to pursue with the information at hand. Without good information on the benefits of restricting the production and use of PODs, this approach still allows us to compare the social costs of achieving any given level of reduction in different ways. The alternatives to consider can go far beyond the somewhat stark price-versus-command dichotomy emphasized above. The potential for stratospheric ozone depletion can clearly be reduced by a given amount using different technical options to restrict any particular POD in a given year. But it can also be done by reducing the production and use of different PODs or of given PODs in different years. We do not attempt to examine such alternatives here in detail, but the framework and data developed here can be applied to a wide range of questions phrased as this form of cost-effectiveness analysis.
Appendix B

MODELS AND DATA USED TO QUANTIFY TECHNICAL CONTROL OPTIONS

We used the methodology developed in Palmer et al. (1980), Appendixes D and E, to estimate the prices at which foam producers and solvent users voluntarily switch between production processes. Palmer et al. (1980) define that methodology in detail. This appendix provides a brief review and the updated data used to calculate these prices.

FLEXIBLE SLABSTOCK FOAM

Palmer et al. (1980, pp. 53-58, 267-270) treated both slabstock and molded flexible foams. New technical options have been developed recently to displace CFC-11 in molded foam production. Unfortunately, we do not have good data on this technical advance. Hence, only the data for slabstock foams have been updated.

In this analysis, we develop a cost function to define the cost of producing a given quantity of foam under four different arrangements. Case 1, the "base case," assumes that half of the auxiliary blowing agent is CFC-11 and the remainder is methylene chloride. It also assumes that no recovery and recycle is used. Interviews with industry sources suggest that this approximates the typical circumstances in industry today. Case 2 assumes that recovery and recycle equipment is purchased and used. Case 3 assumes no recycle and recovery, but allows the share of methylene chloride to rise to 75 percent, about as high as it can reasonably rise according to interviews with industry sources. Case 4 assumes that methylene chloride accounts for 75 percent of the auxiliary blowing agent and that recycle and recovery is under way.

For Cases 1 and 3, the cost function looks like the following:

\[ TC = (P_c C + P_m M) f + (P_a A + P_m M) (1 - f) \alpha \]  \hspace{1cm} (B.1)

where \( P_c \) is the price of CFC-11, \( C \) is the quantity of CFC-11 demanded at
quantity of nonblowing materials demanded, \( f \) is the share of CFC-11 as an auxiliary blowing agent, \( P_a \) is the price of the alternative (methylene chloride), \( A \) is the quantity of the alternative demanded at full capacity, and \( \alpha \) is an adjustment factor to show how the use of the alternative affects productivity.

For Cases 2 and 4, the cost function looks like the following:

\[
TC = [P_c C (1 - e) + b C e + P_m M] f + [P_a A (1 - e) + b A e + P_m M](1 - f) \alpha + O_r + \lambda K_r
\]

(B.2)

where \( e \) is the efficiency of the recover and recycle system, \( b \) is its operating cost per unit of blowing agent, \( O_r \) is its annual operating cost, \( \lambda \) is the capital cost recovery factor, and \( K_r \) is the investment cost of recovery and recycle equipment. The second equation shows that recovery and recycle equipment reduces the CFC-11 and methylene chloride that must be added to the process each year at a cost that has several factors.

Cases 1 and 3 differ in the values assigned to \( f \) and \( \alpha \); Cases 2 and 4 differ in the same way.

Once all of the relevant values are substituted into these equations, each of these cost functions can be expressed as a linear function of the price of CFC-11. For example, (B.1) can be rewritten as

\[
TC = [P_m M f + (P_a A + P_m M)(1 - f) \alpha] + [C f] P_c
\]

(B.1')

These linear expressions can then be compared with one another, as explained in Sec. II, to determine which of the four arrangements above offers the lowest full annualized cost of producing foam. Table 3.1 presents the CFC-11 prices at which it becomes worthwhile to change from one arrangement to another.

Table B.1 presents the data used to quantify these expressions. These are drawn from Palmer et al. (1980, pp. 53-58, 267-270) and from recent discussions with industry to review the importance of changes since 1980. The following items are essentially the same as they were in Palmer et al.: \( C \), share of market, \( A \), \( K_r \), and \( e \). Updated values of
Table B.1

DATA INPUTS FOR FLEXIBLE SLABSTOCK FOAM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Small Plant</th>
<th>Medium Plant</th>
<th>Large Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual plant use of CFC-11, if 100% CFC-11, lb/yr, C</td>
<td>150,000</td>
<td>225,000</td>
<td>1,200,000</td>
</tr>
<tr>
<td>Share of market</td>
<td>0.19</td>
<td>0.28</td>
<td>0.53</td>
</tr>
<tr>
<td>1984 price of CFC-11, $/lb, P&lt;sub&gt;c&lt;/sub&gt;</td>
<td>0.51</td>
<td>0.51</td>
<td>0.51</td>
</tr>
<tr>
<td>Price of methylene chloride, $/lb, P&lt;sub&gt;a&lt;/sub&gt;</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>Annual cost of nonblowing agents, $/yr, P&lt;sub&gt;m&lt;/sub&gt;, M</td>
<td>1,430,000</td>
<td>2,140,000</td>
<td>1,140,000</td>
</tr>
<tr>
<td>Annual plant use of meth chlor if converted, lb/yr, A</td>
<td>0.85&lt;sup&gt;a&lt;/sup&gt;C</td>
<td>0.85&lt;sup&gt;a&lt;/sup&gt;C</td>
<td>0.85&lt;sup&gt;a&lt;/sup&gt;C</td>
</tr>
<tr>
<td>Capital costs of recovery equipment, $, K&lt;sub&gt;r&lt;/sub&gt;</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Operating costs per lb of CFC of recovery equipment, $/lb, b</td>
<td>0.0175</td>
<td>0.0175</td>
<td>0.0175</td>
</tr>
<tr>
<td>Other annual operating costs of recovery equipment, $/yr, O&lt;sub&gt;r&lt;/sub&gt;</td>
<td>95,000</td>
<td>95,000</td>
<td>95,000</td>
</tr>
<tr>
<td>Discount factor, λ (10 yr life, r = 0.15)</td>
<td>0.19925</td>
<td>0.19925</td>
<td>0.19925</td>
</tr>
<tr>
<td>Fraction of blowing agent recovered, e</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Material cost weighting factor w/o conversion, α&lt;sub&gt;0&lt;/sub&gt;</td>
<td>1.01</td>
<td>1.01</td>
<td>1.01</td>
</tr>
<tr>
<td>Material cost weighting factor with conversion, α&lt;sub&gt;c&lt;/sub&gt;</td>
<td>1.07</td>
<td>1.023</td>
<td>1.01</td>
</tr>
<tr>
<td>Fraction of foam blown with CFC w/o conversion, f&lt;sub&gt;0&lt;/sub&gt;</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Fraction of foam blown with CFC with conversion, f&lt;sub&gt;c&lt;/sub&gt;</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>
P\textsubscript{c} and P\textsubscript{a} are drawn from the International Trade Commission and various issues of Chemical Marketing Reporter. The following items were revised on the basis of recent interviews with industry to reflect updated views of costs and cost structures: \( P_m \), \( M \), \( b \), and \( O_r \). The value of \( \lambda \) reflects a value of the real pretax cost of capital equal to 0.15 rather than 0.20; a value of 0.15 is more in line with current costs and investment tax arrangements than 0.20. The values of \( \alpha \) have been revised down from 1.125 on the basis of sensitivity analyses for specific types of plants. The sensitivity analyses sought to achieve a greater degree of correspondence between the results of this cost analysis and observed patterns in industry. The values of \( f \) reflect a shift toward use of methylene chloride since Palmer et al. was written.

**EXTRUDED POLYSTYRENE SHEET**

The analysis of PS sheet is analogous to that for flexible foam above. The analysis considers three arrangements whose total, annualized costs can be expressed using equations like those for flexible foam. A minor change is required in the characterization of materials used for PS sheet because its production with CFC-12 and pentane involves different amounts of materials. We define \( M_C \) as the quantity of materials relevant to CFC-12 and \( M_A \) as the quantity of materials relevant to the alternative, pentane; we substitute these for \( M \) in the equations as appropriate. Then the three arrangements can be defined as follows. In Case 1, the base case, \( f = 1 \), so that no alternative gas, in this case pentane, is used. Hence, Eq. (B.1) becomes

\[
TC = P_c C + P_m M_C
\]

(B.3)

In Case 2, no alternative gas is used, but recovery and recycle equipment is added. From Eq. (B.2), we find

\[
TC = P_c C (1 - e) + b C e + P_m M_C + O_r + \lambda K_r
\]

(B.4)

Case 3 allows total conversion to pentane to that recovery and recycle is no longer a concern. Such conversion involved a capital investment
(K_a) and new operating costs (O_a), which can be related to total, annualized costs as follows:

\[ TC = P_a A + P_m M_A + O_a + \lambda K_a \]  \hspace{1cm} (B.5)

With appropriate data, these cost functions can be expressed as linear functions of the price of CFC-12 and switch prices calculated. Table B.2 provides the data used to quantify these equations. These data do not reflect any new discussions in the industry. They simply update data in Palmer et al. (pp. 112-119) for changes in prices and the cost of capital. The following values are the same as those in Palmer et al.: C, share of market, A, M_c, M_A, e, \( \alpha \), and f. P_c, P_a, and P_m are updated using information from the International Trade Commission and Chemical Marketing Reporter. K_r is the same as the value used in Table B.1, and h is updated from 1976 to 1984, using the average hourly earnings per worker (nonseasonal) for chemicals and related products, reported in the Survey of Current Business, to provide an index of rising labor costs. O_r is updated from 1976 to 1984 using the producer price index for fuels and related products and power, reported in the Survey of Current Business. \( \lambda \) is revised downward to reflect a real pretax cost of capital of 0.15.

**SOLVENTS: CFC-113**

The treatment of CFC-113 here is somewhat different from that in Palmer et al. (1980, pp. 78-84, 271-277). The frame of analysis--types of drying and cleaning units--has changed and the technical options examined has expanded. The analysis now considers six unit types, small, medium, and large in size, and using either pure CFC-113 or CFC-113 in combination with something else. Palmer et al. (1980) considered a finer grid of distinctions by size but could not examine the importance of the "pure" versus "combination" distinction.\(^3\) The analysis also considers carbon adsorption for recovery of CFC-113 vapor losses.

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\(^3\)The unit sizes used here can be related to those in Palmer et al. Table E.1, p. 272, as follows: The small unit here is Case 2, medium unit is Case 4, and large unit is Case 8.
Table B.2
DATA INPUTS FOR THERMOFORMED POLYSTYRENE SHEET

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Small Plant</th>
<th>Medium Plant</th>
<th>Large Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual plant use of CFC-12, lb/yr, C</td>
<td>350,000</td>
<td>500,000</td>
<td>750,000</td>
</tr>
<tr>
<td>Share of market</td>
<td>0.25</td>
<td>0.50</td>
<td>0.25</td>
</tr>
<tr>
<td>1984 price of CFC-12, $/lb, P_C</td>
<td>0.67</td>
<td>0.67</td>
<td>0.67</td>
</tr>
<tr>
<td>Price of pentane, $/lb, P_a</td>
<td>0.17</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>Price of nonblowing materials, $/lb, P_m</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Annual plant use of pentane if totally converted, lb/yr, A</td>
<td>350,000</td>
<td>500,000</td>
<td>750,000</td>
</tr>
<tr>
<td>Annual plant use of nonblowing materials with CFC-12, lb/yr, M_C</td>
<td>4,487,000</td>
<td>6,410,000</td>
<td>9,615,000</td>
</tr>
<tr>
<td>Annual plant use of nonblowing material with pentane, lb/yr, M_A</td>
<td>4,936,000</td>
<td>7,051,000</td>
<td>10,577,000</td>
</tr>
<tr>
<td>Capital costs of recovery equipment, $, K_r</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Operating costs per lb of CFC of recovery equipment, $/lb, b</td>
<td>0.0175</td>
<td>0.0175</td>
<td>0.0175</td>
</tr>
<tr>
<td>Other annual operating costs of recovery equipment, $/yr O_r</td>
<td>95,000</td>
<td>95,000</td>
<td>95,000</td>
</tr>
<tr>
<td>Discount factor, λ (10 yr life, r = 0.15)</td>
<td>0.19925</td>
<td>0.19925</td>
<td>0.19925</td>
</tr>
<tr>
<td>Fraction of blowing agent recovered, e</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Material cost weighting factor, α</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Fraction of foam blown with CFC, f</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Despite these changes, the basic methods used have not changed much. For each type of unit, we examine seven alternatives or cases, not all mutually exclusive:

1. Continuation of the status quo,
2. Use of more conservative equipment to reduce vapor loss,
3. Use of recovery and recycle equipment to reduce vapor loss,
4. Joint use of more conservative and recovery and recycle equipment,
5. Use of in-house distillation to reduce waste loss,
6. Use of external reclamation services to reduce waste loss,
7. Switching to an alternative solvent.

The structure of our cost models, which appears to be reasonable, allows us to treat vapor and waste losses separately, as they were in Palmer et al. (1980, pp. 271-277). We construct cost functions like those above to compare Cases 1 through 4 and then Cases 1 and 5. External reclamation and switching to an alternative solvent are treated differently. We consider reclamation and switching first and then we will return to the other options.

Reclamation and Switching

We assume that there are important sources of heterogeneity in cleaning and drying applications of CFC-113 that are not captured in the formal analysis of cost functions. Some units are located near external reclamation services and hence can take advantage of these services at a lower cost than other units. Similarly, some solvent applications are more amenable to the use of an alternative solvent than others. We assume that as the price of CFC-113 rises, more and more units will find external reclamation and switching attractive on cost grounds. Hence, we assume that CFC-113 use will fall at a certain rate as its price rises, causing more owners of units to reduce their waste losses through external reclamation or to cut their use to zero by moving to another solvent. Empirical data are not readily available to tell us how fast this might occur. As the text indicates, the rate we pick is more
important for switching than for reclamation because our analysis is more sensitive to the choice of the first rate. Based on very rough subjective judgment, we assume that CFC-113 use falls 1 percent for every 1 percent rise in price as a result of movements to alternative solvents; use falls one-half a percent for every percent rise in price as more users find it worthwhile to ship their waste to a reclaimer. The effect of changes in price does not occur for switching until a certain threshold price is reached. The threshold price represents the price increase required to cover the cost of new capital equipment that makes a switch possible. We use the same concepts as those used in Palmer et al. (1980, p. 81) to define thresholds for specific units. No investments are required for external reclamation; hence, use reductions start immediately if the price of CFC-113 rises. Cuts in the size of the CFC-113 market caused by switching to alternative solvents and external reclamation reduce the number of units that can be affected by other actions, but not the costs at which those actions become cost-effective.

Other Reduction Options

Within the market for CFC-113 that remains after switching and external reclamation have occurred, the other actions that can be taken continue to be be taken. The prices at which these actions become cost-effective can be calculated using the same kinds of cost functions used for the foams above. The primary differences are that uses associated with replacing vapor and waste losses must be carefully distinguished and material costs no longer play a role.

For the first, base case, then, total, annual cost can be represented by an equation much like Eq. (B.3):

$$ TC = P_c V_0 + (P_c + C_w) W_0 $$  \hspace{1cm} (B.6)

where $V_0$ is initial vapor loss per year, $W_0$ is initial waste loss per year, and $C_w$ is the cost of disposing of waste. Case 2 requires an investment ($K_c$) and new operating costs ($O_C$) that reduce vapor loss by a factor $\delta$: 
\[ TC = P_c V_0 \delta + \lambda_c K_c + OE_c + (P_c + C_w) W_0 \]  \hspace{1cm} (B.7)

Similarly, using carbon adsorption equipment to recover and recycle solvent cuts vapor losses by a factor \((1 - \beta)\), but requires new investment \((K_a)\) and operating costs \((OE_a)\), as well as the cost of reconstituting a combined solvent following its recovery \((f_a)\):

\[ TC = P_c V_0 (1 - \beta) + \lambda_a K_a + OE_a + (P_c + C_w) W_0 + f_a \]  \hspace{1cm} (B.8)

Combining these two options, in Case 4, leads to joint effects on vapor losses and all of the new costs of both:

\[ TC = P_c V_0 (1 - \beta) + \lambda_c K_c + \lambda_a K_a + OE_c + OE_a + (P_c + C_w) W_0 + f_a \]  \hspace{1cm} (B.9)

Case 5, using in-house distillation equipment, has full annual costs that look much like those for carbon adsorption and for similar reasons. Vapor losses fall by a factor \((1 - \gamma)\) at the cost of new investment \((K_d)\), operating expenses \((OE_d)\), and reconstitution of combined solvent following distillation \((f_d)\):

\[ TC = P_c V_0 + W_0 (P_c + C_w)(1 - \gamma) + \lambda_d K_d + OE_d + f_d \]  \hspace{1cm} (B.10)

Each of these cost functions is linear in the price of CFC-113. By substituting the relevant quantitative data, we can use these functions to calculate price ranges over which each of these options is cost-effective. These prices are reported in the text.

The data used to quantify these cost functions are shown in Table B.3. They are based in part on data from Palmer et al. (1980) and in part on new data from industry. The following variables are treated
### Table B.3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Small Plant</th>
<th>Medium Plant</th>
<th>Large Plant</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Pure Combin</td>
<td>Pure Combin</td>
<td>Pure Combin</td>
</tr>
<tr>
<td>Market share</td>
<td>.24</td>
<td>.15</td>
<td>.11</td>
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<td>Annual vapor loss, lb/yr, $V_0$</td>
<td>1931</td>
<td>6610</td>
<td>30670</td>
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<tr>
<td>Annual waste loss, lb/yr, $W_0$</td>
<td>971</td>
<td>1869</td>
<td>4369</td>
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<tr>
<td>Waste disposal cost, $/yr, $C_{w}$</td>
<td>538</td>
<td>1217</td>
<td>2846</td>
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<tr>
<td>Vapor loss saving in cons. equip., $\delta$</td>
<td>.57</td>
<td>.49</td>
<td>.14</td>
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<tr>
<td>Reuse efficiency for carb. adsorb., $\beta$</td>
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<td>same</td>
<td></td>
</tr>
<tr>
<td>Efficiency of in-house dist., $\eta_i$</td>
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<td>same</td>
<td></td>
</tr>
<tr>
<td>Efficiency of external recl., $\eta_n$, $\eta_j$</td>
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<td>same</td>
<td></td>
</tr>
<tr>
<td>Discount factor, cons. equip., $\lambda_c$</td>
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<td>same</td>
<td></td>
</tr>
<tr>
<td>Discount factor, carbon adsorb., $\lambda_a$</td>
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<td>same</td>
<td></td>
</tr>
<tr>
<td>Discount factor, in-house distilling, $\lambda_d$</td>
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<td></td>
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<tr>
<td>Capital cost for conserv. equip., $$/unit K_c$</td>
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<td>224800</td>
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<tr>
<td>Capital cost for carbon adsorp. $$/unit K_a$</td>
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<td>21000</td>
<td>87500</td>
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<tr>
<td>Capital equip for in-house dist., $$/unit K_d$</td>
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<td>Operating cost for cons. equip., $OE_c$</td>
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<td></td>
</tr>
<tr>
<td>Operating cost for carbon adsorp., $OE_a$</td>
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<td></td>
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<tr>
<td>Operating cost for in-house dist., $OE_d$</td>
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<tr>
<td>Added cost for carbon adsorp., $$/ lb, $f_a$</td>
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<td>9340</td>
<td>0 9340</td>
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<tr>
<td>Added cost for in-house dist., $$/ lb, $f_d$</td>
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<td>2670</td>
<td>0 2670</td>
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<tr>
<td>Transport cost for ext. reclam, $$/lb, $a$</td>
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<td>same</td>
<td></td>
</tr>
</tbody>
</table>
just as Palmer et al. treated them: market share, \( V_0, W_0, \delta, \gamma, OE_c, \)
\( OE_d, \) and \( \alpha. \) \( C_w W_0 \) is based on Palmer et al., but updated to reflect a
disposal cost of $300 a barrel. \( \beta, \lambda_a, K_a, OE_a, \) and \( f_a \) are relevant to
the new option of carbon absorption of vapor losses. Their values are
based on information in Mooz et al. (1982). \( K_a \) and \( f_a \) are updated from
1980 to 1984 with price indexes. \( K_a \) is updated using the Bureau of
Labor Statistics PPI 1166.04, producer price index for chemical industry
machinery. \( F_a \) is updated using average hourly earnings per worker
(nonseasonal) for chemicals and related products reported in the Survey
of Current Business. \( \lambda_c \) and \( \lambda_d \) are updated to reflect a real pretax
cost of capital of 0.15. \( K_c \) uses data from Palmer et al., updated from
1976 to 1984 using BLS PPI 1166.04. \( K_d \) uses data from Mooz et al.,
updated from 1980 to 1984 using BLS PPI 1166.04.
Appendix C

DIFFICULTIES IN USING U.S. RESULTS TO LOOK ABROAD

The results reported here draw heavily on information about technical options that use technologies available not only in the United States, but in most other parts of the world. Similarly, the United States has no special claim on the technologies that underlie alternatives that allow product substitution. And innovation that generates new technological opportunities in the United States or elsewhere should similarly benefit all parts of the world with access to this new knowledge. These considerations suggest that the kind of information developed in this Note for the United States could easily be transferred to other areas as well. Unfortunately, the problem is not so simple. Differences in prices, regulations, and markets can make some options that work in the United States irrelevant in other parts of the world. Similarly, options not mentioned here may be extremely important elsewhere. This appendix discusses these differences briefly as a form of caveat to the reader tempted to use results reported here outside the appropriate context of the United States.

DIFFERENCES IN PRICES AND THE COST OF CAPITAL

Prices of PODs, the products or processes in which they are used, and cofactors used to make those products are all important to opportunities to reduce the use of these PODs.

Consider product substitution. In the United States, the prices of packaging materials based on CFC-12 and wood fiber are so close in many parts of the United States that demand for CFC-12-based products is highly sensitive to price. This need not be the case in other parts of the world where wood is more or less expensive. Because wood is a lower value commodity per pound than CFC-12 or plastic resin, its price is likely to be more sensitive to transportation costs and hence location.
for CFC-11, -12, and -113. Although these substances are traded in a global market, suggesting that prices in one country must at least be related to prices in another for any chemical, transportation costs, duties, taxes, and regulations can lead to significant differences. We have not attempted to measure these differences because our study is limited to the United States. But we would expect to find them if we look more closely at other countries.

Differences in the costs (and productivity) of cofactors like labor are much better known. These costs are quite important to certain aspects of reducing the use of CFC-113 and recovering CFC-12 from mobile air conditioners. They also play a role in foam making. They could potentially be important to options not considered here, primarily because the high cost of U.S. labor makes them too costly. An example is removal of rigid foam insulation from buildings.

One of the most important differences may be in the cost of capital in different countries. Recall that decisions to recover and recycle, to buy more conservative equipment, to use in-house distillation, and often even to switch to a substitute chemical depend on investments, whose costs must be justified by future savings of operating costs. The cost of capital plays a vital role in determining whether such investments are worthwhile. Some might argue that in the current world of international finance, all industrial borrowers face the same costs of capital around the world. Local investment climate--what international investors often speak of in terms of "country risk"--easily creates differences from one country to another. But even setting aside this sometimes intangible source of differences, local taxes and duties routinely create large differences in the cost of capital from one country to another. For example, King and Fullerton (1984) reports that effective tax rates on investment in machinery in Sweden, the United Kingdom, the United States, and West Germany are respectively 0.2, -36.8, 17.6, and 44.5 percent. Among four nations typically thought of as being heavily industrialized market economies and comparable in technology, POD users in the United Kingdom would invest to reduce their use of PODs at much lower prices than our results would suggest--and may have already--whereas users in West Germany would require much higher prices than those in the United States. The
diversity of tax rates, with their implications for the cost of capital and willingness to invest, is likely to be still greater as we look at more diverse countries.

DIFFERENCES IN REGULATION

The substances we suggest as substitutes for PODs have a number of negative properties that may lead other countries to regulate them differently from the way the United States regulates them.

For example, some governments are much more concerned about fire hazards than U.S. officials typically are. The Japanese prohibit the use of hydrocarbon propellants in aerosols because of the additional fire hazard they create; this may suggest that they would not look favorably on using pentane in foam blowing. At the very least, they are likely to require more costly safeguards in its use as a blowing agent than those required in the United States. West Europeans also appear to be more stringent about the location of aerosol canning plants that use hydrocarbons; this concern could also be reflected in their treatment of pentane as a foam blowing agent.

West Europeans also show greater sensitivity to the possible carcinogenicity of methylene chloride than U.S. officials do. This leads to a marked difference in foam blowing practices between the United States and Europe. European foam blowers typically do not use methylene chloride despite its cost competitiveness with CFC-11, in part because it may pose a threat to health. This would limit the applicability of this substitution option in Europe or at least significantly raise its perceived social cost.

Similar problems are likely to arise with the use of CFC-113 and methyl chloroform. A major opportunity for reducing their use in the United States is to substitute toward other chemicals, many of them chlorinated solvents that may present serious health hazards and disposal problems. Although we have no direct evidence of it, we would expect other countries to view those problems differently. Indirect evidence comes from the alleged widespread use of carbon tetrachloride as a solvent in the Third World, evidence of lower concerns about health effects in this part of the world.
OTHER DIFFERENCES

Differences in use and production patterns are likely to lead to large differences in the relative importance of options considered here and in the effectiveness of any one of them in reducing potential risks to stratospheric ozone. The most obvious case is the absence of any discussion of aerosols in this Note. Reduced use of CFCs in aerosols probably provides the least costly way to reduce substantially the threat to the ozone layer from emissions outside the United States. Widespread use of carbon tetrachloride as a solvent outside the United States is another example; it deserves attention that would not be appropriate here. More generally, mobile air conditioning is likely to be less important outside the United States. Air conditioning in general is not important in parts of Europe that are heavy users of CFCs. In sum, these differences in use and production patterns make it clear that the effectiveness of individual measures will differ significantly outside the United States. And the summary results of this study should not be transferred elsewhere.

Although the technologies that underlie the choices discussed here would probably be usable anywhere in the world, then, the decisions to use them remain behavioral, not technological. And the factors that affect behavior--prices and regulations--can differ substantially from one country to another. At the very least, readers should exercise caution in using information about the incremental social cost of a particular decision in the United States in a different setting. More generally, the patterns of use and production in the United States are likely to differ profoundly from those elsewhere. Conclusions about the effectiveness of individual decisions or about the cost and effectiveness of a program like one undertaken in the United States to reduce the use of PODs are highly unlikely to be useful in another context.
REFERENCES


