Technical Options for Reducing Chlorofluorocarbon Emissions

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Technical Options for Reducing Chlorofluorocarbon Emissions


March 1982

Prepared for
The U.S. Environmental Protection Agency
PREFACE

In 1974 it was theorized in some quarters of the scientific community that atmospheric emissions of chlorofluorocarbons (CFCs) reacted with stratospheric ozone in a way that threatened to deplete it. This ozone layer protects the earth from harmful radiation. As a result of this theorized threat, the use of CFC as an aerosol-can propellant was essentially banned in 1978.

Following the aerosol ban, the U.S. Environmental Protection Agency (EPA) sponsored a wider investigation into nonaerosol applications of CFCs. One part of this study was conducted by The Rand Corporation between 1977 and 1980: an examination of the economic effects of regulating the nonaerosol uses of CFCs. Subsequently, EPA, judging that further research into the technical options available for reducing CFC emissions was desirable, funded the present study under Contract No. 68-01-6231.

The present study examines about 100 technical options in detail and discusses what would be involved in implementing each, together with expected emissions changes. In addition to providing a depth of detail heretofore lacking, it updates several estimates from the earlier Rand work—an important function in this fast-changing field.

The work should provide inputs to policymakers in the environmental protection area. It should also be of interest to industry, for it puts a large number of options into perspective, with regard both to their emissions reducing potential and to their ease or difficulty of implementation.

Related research is contained in several other Rand publications. The earlier study was reported in Adele R. Palmer et al., Economic Implications of Regulating Chlorofluorocarbon Emissions from Non aerosol Applications (R-2524-EPA), and summarized in an executive briefing (R-2575-EPA). Additional documents reporting portions of the earlier study include William E. Mooz and Timothy Quinn, Flexible Urethane Foams and Chlorofluorocarbon Emissions (N-1472-EPA), and Kathleen A. Wolf, Regulating Chlorofluorocarbon Emissions: Effects on Chemical Production (N-1483-EPA). A Rand study now under way addresses certain economic aspects of regulating CFCs. Finally, Adele R. Palmer and Timothy Quinn, Economic Impact Assessment of a Chlorofluorocarbon Production Cap (N-1656-EPA), discusses one method of limiting CFC use; and Adele R. Palmer and Timothy Quinn, Allocating Chlorofluorocarbon Permits: Who Gains, Who Loses, and What Is the Cost? (R-2806-EPA), treats one form of economic regulation.
SUMMARY

In 1974 certain scientists postulated a theory that the stratospheric ozone layer might be depleted through reactions with chlorofluorocarbon (CFC) emissions. Depleted ozone would increase the ultraviolet radiation reaching the earth's surface, and could change the climate and have serious effects on animal, plant, and human life. Responding to this theory, the Environmental Protection Agency (EPA) essentially banned aerosol uses of CFC in 1978 and began a series of studies of the nonaerosol uses of CFC, which represented about half of the total use of CFC in the United States before the ban.

One of the studies commissioned by EPA was performed by The Rand Corporation during the 1978-1980 period and examined the economic effects of regulating the nonaerosol uses of CFC. The study identified a number of technical options available to reduce CFC emissions and used these as inputs to the economic portion of the study.

On completion of that work, EPA commissioned Rand to make more detailed studies of the technical options available for reducing CFC emissions. As a result, the present study examines about 100 options in a wide range of product areas that use CFC. We were able to rank these options by their emissions reducing potential and also, in a rough way, by the difficulty of implementing them. Most of the technical options either accounted for very modest emissions reductions, were very difficult to implement, or were some combination of both. If we screen out those options that reduce emissions by less than five million pounds per year and those that result in extreme dislocations (such as retooling an entire industry or inventing a process to produce an acceptable substitute for the CFC), there are nine remaining. These are as follows:

- **Mobile Air Conditioning**
  - Improve service techniques
  - Reduce charge (a current trend)

- **Solvents**
  - Improve equipment and operating practices
  - Use carbon adsorption recovery for pure CFC-113
  - Use external waste reclamation

- **Flexible Urethane Foam Slabstock**
  - Extend the use of methylene chloride as a CFC substitute

- **Rigid Insulating Foam**
  - Use product substitutes in construction

- **Extruded Polystyrene Sheet**
  - Extend the use of pentane as a CFC substitute

- **Retail Food Refrigeration**
  - Substitute R-502 for R-12 in new units

Taken together, these options have the potential of reducing emissions by about one-third, when 1976 CFC use is the basis of the analysis.

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1 Adele R. Palmer et al., Economic Implications of Regulating Chlorofluorocarbon Emissions from Nonaerosol Applications, R-2524-EPA, June 1980.
Some of these options have already partially been implemented, attesting to their cost effectiveness in selected applications. For example, we see improvements in the use of solvents that cut down on the consumption (and emissions) of expensive CFC-113 and a gradual trend toward the use of more methylene chloride in the manufacture of flexible foams. We also see increased interest in waste solvent reclamation and a ready market for reclaimed solvent because of its lower cost. Finally, we see that automotive air conditioning systems are using reduced charges.

Other options listed above may be more controversial. Substituting other forms of insulation for rigid urethane or extruded polystyrene board implies the death of an industry but not of the ability to effectively insulate. Substituting pentane for CFC-12 in the manufacture of extruded polystyrene sheet implies very difficult and costly decisions for the segment of that industry using CFC, since the use of pentane requires a totally different manufacturing plant. Even the substitution of methylene chloride for CFC in flexible foam manufacture would force some companies to modify or relocate their plants or to buy new equipment. Again, consumers would probably be unaware of some of these changes, and their needs would continue to be met.

Pursuit of emissions reductions greater than those achievable through the nine options listed above requires that technical options other than those be used. This implies that options with low emissions reduction potential be implemented, or that options with large dislocations be used. The worse cases, of course, are those where the potential dislocation is very large and the emissions reduction potential is very small. An example of this is the recovery of the CFC remaining in home refrigerators and freezers at disposal. Each appliance contains less than half a pound of refrigerant in the cooling system, and the cost and difficulty of collecting and removing the CFC from millions of appliances each year is extremely large.

With regard to the product areas, it is notable that we include no technical options in the list above that address the specialty uses of CFC, home appliances, chillers, or room air conditioners, and there is only one option listed for retail food refrigeration. Other than the single option just mentioned, the remaining options fall in those product areas that consume and emit large amounts of CFC. These product areas—solvents, flexible and rigid foams, and mobile air conditioning—are those in which the emissions reduction potential is sizable and the dislocations are not so large as to render the technical options unworkable.
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Chapter 1

INTRODUCTION

Chlorofluorocarbons (CFCs) as a class of chemicals were discovered in the 1930s. It was quickly recognized that the physical and thermodynamic properties of some of these compounds made them ideal fluids for use in refrigeration—they were nonflammable, nontoxic, and extremely stable. Thus, they replaced other less desirable refrigeration fluids and fostered the development of safe, long-lasting refrigerators and refrigeration units. Today, almost all refrigeration and air conditioning devices operate with CFC as their working fluids.

It was not long before other desirable characteristics of CFCs caused their use to be expanded. For example, their very high molecular weight makes them excellent thermal insulators, and thus they are used to make insulation for houses, refrigerators, industrial tanks, and the like. Their high density makes them useful in separating minerals of different densities, by floating one mineral and allowing the other to sink. Certain CFCs have solvent properties that are ideal for cleaning electronic components, and, in addition, can be combined with alcohols or other solvents to tailor-make solvents for very specific applications.

The boiling points of CFCs are advantageous in several ways. One CFC is used in a process to make flexible foams—a basic component of furniture. The open cells in the foam are created partly by boiling a CFC that is mixed in with the foam ingredients. Another CFC is liquified under pressure and used variously as a propellant in aerosol spray cans, a pressure source for portable fog horns, or to create pressure to unclog sink drains.

These compounds have very many special characteristics making them valuable to the economy in diverse ways.

Strangely, the very desirable high chemical stability of the CFCs was the origin of concern about them. In the mid 1970s, several investigators\(^1\) expressed concern about these chemicals, since no matter how they were used, eventually they were released to the environment. Molina and Rowland hypothesized that the stability of CFCs allowed them to eventually reach the upper atmosphere. Then, it was hypothesized, these broke down because of impinging radiation, releasing chlorine. The chlorine, in turn, it was hypothesized, combined with stratospheric ozone in a way that would deplete the ozone layer that protects the earth from harmful radiation.

Concern about depletion of the protective ozone led to federal action in the United States to ban aerosol uses of CFCs in 1978. At that time, aerosol uses represented about fifty percent of CFC use. At the same time, the Environmental Protection Agency (EPA) implemented studies of nonaerosol CFC uses in preparation for possible future regulation. Rand conducted one study (Palmer et al., 1980) of the economic implications of regulating the nonaerosol CFC uses in which a variety of technical options to reduce CFC use or emissions were identified. Following that work, this study was commissioned by EPA to sharpen the perceptions of these technical options and to provide more detail about them.

Specifically, EPA requested a “chemical control options analysis” for each of the major

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\(^1\)See Siofarski and Cicerone (1974); Molina and Rowland (1974); Crutzen (1974); Turco and Whitten (1975); and NASA (1977).
CFC-using product areas. This analysis was to pinpoint CFC use or emissions reduction methods in four categories defined by EPA as:

- control technologies,
- work practices,
- chemical substitutes, and
- product substitutes.

Then, each identified technical option was to be analyzed in detail. The control technologies category refers mainly to the technical option of collecting emitted CFC for reuse. An example would be collecting the emitted CFC vapors from a factory that makes flexible foams or insulation and then processing them for reuse.

Work practices identify those options involving, mainly, how people handle CFC. For example, it has been a common practice for those who service automobile air conditioners to vent the CFC to the atmosphere before recharging the system. A technical option would be to stop this practice.

The chemical substitutes category refers to substituting another chemical for the CFC. Aerosol cans originally used CFCs as the propellant. At present, hydrocarbon propellants are used instead, or, in some instances, carbon dioxide.

Product substitutes include products that can be substituted for the CFC-bearing one. A roll-on deodorant is a product substitute for CFC-propelled aerosol deodorant; furniture cushions made with metal springs and cotton batting are substitutes for flexible foam ones manufactured with CFC.

Many technical options fit into more than one of these categories. For example, requiring that a CFC vapor collection device be used during servicing of a refrigerator fits into the work practices category and also the control technology category. Where such options occur in our analysis, they have been identified.

OBJECTIVES

Our objectives were, then, to examine each of the major product areas in which CFCs are used and to evaluate the emissions reducing potential of each technical option. But, since some options were more difficult to implement than others and caused dislocations of different degrees and types, we also attempted to describe the consequences of adopting each emissions reducing option. Almost without exception, those who use CFCs do so because of the CFCs' superior technical characteristics, which act to minimize their costs. This implies that any action to reduce their use of CFCs will raise their costs in some fashion. We could not, in the scope of this study, attempt to accurately estimate the change in costs for each option. There are too many, and the distribution of the costs is too diverse. Instead, we attempted to identify the required technical changes, who must make them, and how serious they are. The objective was to understand how each technical option works, how much CFC use would be reduced by adopting it, how difficult it would be to implement, and what segments of society would bear the brunt of the dislocation if the option were implemented.

For several reasons, we have attempted to deemphasize the use of quantitative results in our summaries. One reason deals with the timing of CFC emissions. CFC emissions may be equal to CFC use in some applications, but our previous work showed that for several important uses, particularly refrigeration, air conditioning, and insulation, emissions occurred many years after use. Consequently, estimating the effect of a change implemented today
required estimating CFC use in the particular application between the date of implementation and the date, far in the future, when the emissions occur. For many uses, such projections are difficult to make and are of questionable accuracy.

Another reason for de-emphasizing quantitative analysis concerned the interaction of the technical options with one another. We found that adopting one technical option often affected the potential of another, and therefore the estimated emissions reduction potential of each often depended on what was happening elsewhere.

Finally, we knew that despite our best efforts, and even with the full cooperation of those we contacted, the exact amount of CFC in industry-wide applications could not be pinpointed. Nonetheless, we feel that our results remain useful and we hope that our work may minimize the efforts of others attempting to rank options that for all intents are of equal effect.

As with the qualitative treatment of the emissions reducing potentials, we similarly are qualitative about the degree of difficulty of implementation. Some of the reasons for this have already been discussed, but there are more important ones. In several instances, an option would require the complete restructuring of an entire product line, resulting in retooling large factories and abandoning existing equipment. Estimates of the cost of so doing were solicited from the manufacturers involved and were taken at face value. But we know that such estimates were ball park figures and may be biased because of industry's general objection to the possibility of CFC regulation. The task of producing an accurate estimate would take a long time and be costly; even then it probably would provide no better information for a study of this type. We recognize that the task of retooling is a large one. We rate this to be a very large dislocation, and more severe than a case where a few companies or a few plants were required to make expensive changes, but where most of the companies or plants were not.

**SOURCES OF DATA**

Direct industry contact was the source of almost all information used in this study. Palmer et al. (1980) identified virtually all of the technical options for reducing emissions, and the additional data required for the refinement of our perception of these options came from those who understand them the best. As will become evident, inputs from industry required analysis, cross-checking, and integration into the results of this study. We are sure that some of the findings will surprise those who supplied data: Individual perspectives and circumstances are necessarily limited, usually fitting into a larger picture that we attempt to illustrate.

In this same way there were surprises for us. In some cases when we inquired as to why a certain product appeared to be marketable when a competing product appeared to have superior properties, we received rhetorical answers. Often, when more information became available and was analyzed, we found that the peculiarities of the market were such that there was a firm niche for the apparently less economical or less attractive product. Similarly, some in the industry held positions regarding CFC use that appeared to be against their own economic interests. This paradox was left unresolved in the first study. Further research usually confirmed what an economist would hypothesize: Firms tend to act to maximize profits if they want to be successful. But sometimes it was difficult to ferret out all of the elements that contribute to the viewpoints of those in industry. Of course, we found some isolated cases where imperfect knowledge of the market or technical options available prevented optimal decisionmaking.
NOMENCLATURE

There are some standard conventions in the CFC-using industries that we have adopted. The abbreviation CFC refers to chlorofluorocarbons and designates all CFCs that contain carbon, chlorine, and fluorine. There are some similar compounds that do not contain any chlorine (and hence may not be as injurious to the atmospheric ozone), and these are designated FC, for fluorocarbon. CFCs used as refrigerants have traditionally been prefixed with the letter R, and we, too, use this convention. Thus, the reader should be aware that CFC-12 and R-12 are identical materials, but that in the discussions of refrigeration or air conditioning the R prefix will be used.

CFCs are identified by number according to a standard system. The number describes the number of atoms of carbon, hydrogen, and fluorine in the CFC molecule. To use the system, first add 90 to the CFC number. This will produce a three digit number—the first digit represents the number of carbon atoms, the second represents the number of hydrogen atoms, and the third the number of fluorine atoms. This system applies only to pure CFCs. There are some blends that have CFC numbers, but which do not fit the system. We identify these where they are discussed.

OZONE DEPLETION POTENTIAL

CFCs differ in their hypothesized potential to damage the ozone layer. It is becoming common to describe emissions in terms of their CFC-11 equivalent, and we use this practice. Table 1.1 is constructed from information supplied to us by EPA. From this table, it is easy to see that if a product area used a CFC with a relatively high ozone damage potential, a viable technical option would be to switch to a less damaging CFC. This will become apparent in the text, particularly in the discussion of CFC-22.

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<tr>
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</tr>
<tr>
<td>CFC-113</td>
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<tr>
<td>CFC-114</td>
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<tr>
<td>CFC-115</td>
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<tr>
<td>CFC-502</td>
<td>0.13</td>
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<tr>
<td>CFC-22</td>
<td>0.05</td>
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*CFC-502 is a blend of 48.8 percent CFC-22 and 51.2 percent CFC-115.*
METRICS

We have adopted five categories of CFC use/emissions. The emissions, in millions of pounds per year, are as follows:

- Very small (VS) <1
- Small (S) 1-5
- Medium (M) 6-10
- Large (L) 11-20
- Very large (VL) >20

We have categorized the degree of cost or dislocation involved in implementing the technical option in the same way. These are:

- Small dislocation (S)
- Moderate dislocation (M)
- Large dislocation (L)
- Extremely difficult (VL)

Whereas the emissions categories are defined by approximate levels of CFC emissions, the categories describing dislocations do not have such guidance. This is because the dislocations range from effects on individual manufacturers, to effects on entire industries, to effects on consumers; and since this was a technical study, the synthesis of these various effects into a single metric was not part of its charter. Instead, we have subjectively ranked the dislocations so that they can be used as a guide. The most severe dislocation in our ranking refers to the retooling of an entire industry, such as would be required if mobile air conditioners were required to change from R-12 to R-22, or to the invention of a new benign CFC to replace one presently in use, or to such difficult tasks as requiring the collection of CFC from the insulation in the walls of buildings that are being demolished. The least severe dislocation is one where moderate changes in equipment, work practices, or chemical substitutes can achieve lower use or emissions of CFC at relatively modest costs. In some cases, identified by us in the text, these changes are partially under way at present.

Our evaluation of the emissions reducing potential of the technical options was based on 1976 emissions data. These data were chosen because of their complete presentation in Rand's earlier work, and the fact that they had undergone industry scrutiny with regard to emissions reduction. They are the most recent consistent data for all aspects of CFC use.

Because some emissions of CFC do not occur until many years later, we adopted a simple strategy for ranking the technical options. We simply posed the question "What would 1976 emissions have been if the technical option in question had been implemented enough in advance of 1976 that the entire stock of CFC bearing goods had turned over by 1976?" This approach allowed us to compare the ultimate effect of all options on the same basis. It avoided the pitfall of underrating an option that would have a relatively small effect today but a very large effect in the long run. Important time-dependent effects, however, are described in the main text.

Last, since the various types of CFC have different postulated effects on the ozone layer, we have compared the various options in terms of their CFC-11 equivalent.
COSTS

In a number of cases we have made simple cost estimates based on the information supplied to us by those we interviewed. In these cost estimates we adopted a simple method of annualizing capital costs from standard U.S. utility practice. This method uses a capital charge rate. The capital charge rate is a percentage figure that, when multiplied by the capital investment, determines the annual charges resulting from the invested capital. The capital charge rate includes the cost of money (which in turn includes inflation), depreciation, income and local taxes, and other cost elements related to capital investment. Contemporary capital charge rates in use run about 30 percent, and we have used this figure in our analyses. For those who wish to test alternative values, the cost estimates are simple enough that this can easily be done.

ORGANIZATION OF THE REPORT

This report is organized by product areas. A reader interested in a particular product area will find all of the analyses performed in that area discussed in the chapter dealing with it. Within each chapter we elaborate on the four principal methods of emissions reduction: control technologies, work practices, chemical substitutes, and product substitutes.
Chapter 2

CHLOROFLUOROCARBON USE IN RIGID FOAMS

I. Introduction and Summary

Rigid plastic foams are cellular materials familiar to most people: They are used to make egg cartons, fast food trays, meat trays in supermarkets, inexpensive ice chests, and light, disposable coffee cups. A lesser known, but even larger, application of rigid plastic foams is as an insulation material in construction, appliances, and industry. This insulation property can be enhanced by filling the cells with a chlorofluorocarbon (CFC). Thus, rigid plastic foams compete with, or even replace, earlier products that may have been heavier, less efficient, less rigid, more costly to install, or simply more expensive.

Rigid plastic foams can achieve their cellular structure in a variety of ways. For the purposes of this study, only two are of consequence: (1) the volatilization of a low boiling point nonreactive liquid (called a blowing agent) that is added to the liquid plastic ingredients that eventually form the cell walls, and to a lesser extent (2) the liberation of gas from the reactants.

For a number of reasons, the volatilization of CFC has become the preferred method of manufacture for most of the rigid plastic foams. CFCs produce a foam with superior physical properties, including insulation and product integrity; they often give the product economic and safety advantages, too.

PRODUCTS ANALYZED AND THEIR EMISSIONS CHARACTERISTICS

The diversity of rigid plastic foam types and uses is illustrated in Fig. 2.1, and the consumption of CFCs in these applications in 1976 is shown in Table 2.1. Construction uses of rigid urethane foams and packaging uses of extruded polystyrene (PS) sheet are the two largest consumers of CFC, and a substantial portion of this chapter is devoted to these two products.

Emissions of CFC from rigid foams occur during manufacture, during use, and on disposal. Rand's previous work showed that manufacturing emissions are generally small for most rigid urethane foam products but are larger for the nonurethane products, particularly extruded polystyrene sheet. Emissions during normal use are small for all foams and the manufacturers continue to improve the foams' CFC retention, since the efficiency of the product often depends upon it. Disposal of the foams seems to represent the largest emissions source, but since many of these foams—particularly those used to insulate buildings and those with other long-lived applications—will be in service for 20 to 100 years, the emissions may not occur for a long time.

We deal with this problem in our analysis by concentrating on CFC use, on the theory that if use is reduced, eventually emissions will be less. The base year for our estimates is 1976.
Fig. 2.1—Major types and applications of CFC blown closed cell foams

TECHNICAL OPTIONS PERCEIVED IN PREVIOUS RESEARCH

In Rand's previous report to EPA (Palmer et al., 1980), we concluded that options to reduce CFC emissions in closed cell rigid foams were quite limited.

In the area of urethane foams and extruded PS board, we observed that:

1. Alternative blowing agents were not available, because other non-CFC blowing agents would compromise thermal properties in insulation applications and physical strength.

2. Recovery of manufacturing emissions appeared generally infeasible, with the possible exception of laminated boardstock and slabstock, and other stationary sources of
Table 2.1
CFC CONSUMPTION IN RIGID FOAMS, 1976

<table>
<thead>
<tr>
<th>Application</th>
<th>CFC-11</th>
<th>CFC-12</th>
<th>All Others</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid Urethane</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td>20.2</td>
<td>Small⁴</td>
<td>0</td>
<td>20.2</td>
</tr>
<tr>
<td>Refrigeration</td>
<td>Almost 7.4</td>
<td>Small</td>
<td>0</td>
<td>7.4</td>
</tr>
<tr>
<td>Transportation</td>
<td>Almost 5.6</td>
<td>Some</td>
<td>0</td>
<td>5.6</td>
</tr>
<tr>
<td>Noninsulation</td>
<td>Almost 3.8</td>
<td>Some</td>
<td>0</td>
<td>3.8</td>
</tr>
<tr>
<td>Total</td>
<td>35.5</td>
<td>1.5⁴</td>
<td>0</td>
<td>37.0</td>
</tr>
<tr>
<td>Nonurethane</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extruded PS board</td>
<td>0</td>
<td>4.2</td>
<td>0</td>
<td>4.2</td>
</tr>
<tr>
<td>Extruded PS sheet</td>
<td>0</td>
<td>13.1</td>
<td>0</td>
<td>13.1</td>
</tr>
<tr>
<td>Extruded polyolefins</td>
<td>0</td>
<td>2.3</td>
<td>~2.2</td>
<td>4.5</td>
</tr>
<tr>
<td>Expanded PS bead</td>
<td>0</td>
<td>.9</td>
<td>0</td>
<td>0.9</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>20.5</td>
<td>2.2</td>
<td>22.7</td>
</tr>
</tbody>
</table>

⁴Earlier Rand research (Palmer et al., 1980), based in part upon Midwest Research Institute (1976) work for the EPA, found that froth-foaming used about 12 percent CFC-11 and 4.5 percent CFC-12 by foam weight, compared with about 12 percent CFC-11 in other urethane products. (New data indicate up to 16 percent CFC-11 by weight in some rigid urethane foams.) Consumption of CFC-12, because of froth-foaming in transportation insulation and marine flotation applications, is significant, totaling about 1.5 million pounds.

CFC emissions. While physical capture and recycle was possible, it seemed unlikely to be economical.

3. Cladding of rigid urethane foam was a delay strategy, reducing short-run emissions at the expense of higher emissions at future disposal.

4. Collection of foam at product disposal was technically feasible but not economical in most applications.

In noninsulating foams, such as extruded polystyrene sheet, extruded polyolefin, and other prompt emitters, two options appeared promising: (1) Pentane could be a satisfactory substitute blowing agent in most extruded PS sheet, and (2) recovery of CFC-12 seemed technically possible but had not been tried and may or may not be economical.

COMPARISON OF PRESENT AND PREVIOUS ANALYSIS

We were asked by EPA to focus on CFC control options in four areas: control technology, work practices, chemical substitutes, and product substitutes. Particular attention was to be
paid to substitute blowing agents, half-lives of various foam formulations, extruded polystyrene sheet, and thermal conductivity properties of CFC blown rigid foam.

Rigid urethane foams have found an important use in insulation of homes, offices, and industrial facilities. Some 20 million pounds of CFC-11 were estimated to have been used in 1976. Our present research confirms our earlier perceptions about chemical substitutes (no alternative blowing agents exist), work practices, and control technology (emissions recovery at manufacture and at disposal is impractical and uneconomical).

On the other hand, our perceptions about product substitutes have changed. We find that for the majority of rigid urethane foams, particularly in construction uses, insulating product and insulating systems alternatives exist. Typical alternatives include fiberglass batts in wider walls, thicker sheathing of another insulating material, or less insulation (with increased energy costs and reduced annual capital charges). These alternatives can compete with rigid urethane foam insulation in most construction applications, with only small price increases to consumers. This conclusion is based on our examination of and discovery of product substitutes in virtually all the construction applications areas for rigid urethane foams. We conclude that the area of product substitutes presents an important CFC emissions reduction option—one that could be implemented without major economic or physical dislocation to the U.S. economy.

Extruded polystyrene sheet is used extensively in packaging food products. Manufacturing used 13 million pounds of CFC-12 (10 million pounds CFC-11 equivalent) in 1976. Our present analysis determined that the earlier research was sound and still applies today. In the area of chemical substitutes, we found that pentane is a satisfactory substitute blowing agent. In the areas of work practice and control technology, we confirmed that recovery of CFC-12 is technically possible, appears to have favorable economics, and is about to be tested at a manufacturing facility. Recovery of as much as 50 percent of the CFC used might be possible. We found that product substitutes, such as wood fiber products, are plentiful but for performance reasons are less desirable in many applications. In a limited group of product applications, one clearly feasible CFC emissions reduction option is product substitutes. Extruded PS sheet and wood fiber have many uses (such as egg cartons and food service packages and trays); they even compete side by side in the same supermarket.

Only the chemical substitutes option of pentane has the possibility of bringing about a large reduction in CFC use. We estimate the dislocation of enforcing this option as small, because of the presence of facilities for manufacturing pentane blown extruded PS sheet and the marketing of this product for virtually all applications, competing successfully on price and performance against the CFC blown version.

Both of the other options—recovery of CFC-12 and product substitutes—hold small to moderate opportunities for CFC reduction with small dislocations. Recovery of some CFC-12 is thought to be economical today, and wood fiber products compete, in both price and physical performance, claiming a significant share of the packaging market.

Our findings across the entire rigid foam field can be summarized succinctly: We have confirmed the earlier Rand conclusions with respect to chemical substitutes, work practices, and control technology issues, and we have changed our perception of product substitutes. Generally, we found that suitable alternative products, or systems using alternative products using little or no CFC, exist, which could compete on cost and performance bases in many applications. In contrast to earlier conclusions, we now expect substantial demand shifts away from CFC products in many rigid foam applications, especially with increasing CFC prices.

Cost increases for CFCs could raise the cost of certain rigid foam products. In a competi-
tive market, this would produce price increases in rigid foams and reductions in the use of those products. If special cost advantages and market power (e.g., from patents) in production of rigid foams allowed them to compete in price with above-competitive markups, then an increase in the cost of CFCs would not necessarily increase the price or reduce the use of rigid foams. We have no evidence of anything other than a competitive market organization and will presume throughout the remainder of this report that competitiveness is the correct assumption.¹

Significant dislocations are probable for manufacturers of certain rigid foam products when demand shifts, but the aggregate effect on the economy will be small.

¹Additional work by Rand on this subject is reported in Palmer and Quinn (1981), p. 33.
II. Rigid Urethane and Isocyanurate Foams: Construction Applications

In the present study, we have focused on product substitutes and have tried to differentiate between products with substitutes and those without. This examination has caused us to change our perception from that of the previous study. We find that many rigid foam products, particularly urethane used in construction applications, are in a tightly competitive business, where small increases in material costs, such as CFC and thus product price, would significantly shift demand away from CFC blown rigid foam.

In the previous Rand study, we found the CFC demand schedule to be inelastic, with the result that "there is virtually no chance that substitution to nonfoam insulations could be induced by higher CFC prices within the price range considered" (p. 115). This conclusion derived partially from industry statements that no product substitutes existed for their insulation products, and partially from an analysis of the effect of higher fuel costs. During the course of subsequent interviews, industry statements (such as "in each case the ... products are unique with no other products that can be directly substituted in many applications") continue to support the idea that demand for the product is inelastic. This is true only in the narrow sense of direct substitutes. In the broader sense, there are products—alternative insulating systems, and even energy itself—that compete and are thus broad substitutes for one another.

Table 2.1 showed that 37 million pounds of CFC were used in rigid polyurethanes and isocyanurate foams. Within this broad product area we examine the options for reducing CFC use in construction (stationary and mobile refrigeration, and noninsulating uses of foam, are the subjects of following sections).

In construction uses, which consumed about 20 million pounds of CFC, insulation boardstock's share was over 35 percent or over seven million pounds. We focus here on boardstock because its use is projected to grow at a faster rate than other products. We also discuss spray foam, which consumed about 40 percent of CFC used in construction.

Two distinct chemical processes, isocyanurate and urethane, are currently competitive in the manufacture of rigid insulation foams. We discovered no substantial difference between them in terms of CFC consumption. Isocyanurate and urethane foams are identical in CFC diffusion rate, half-life, thermal conductivity, and cost. Choices between the two are based on the differences in physical strength, fire resistance, or installation technique, and have little consideration for CFC usage.

ALTERNATIVE BLOWING AGENTS

Water and CO₂ were the original blowing agents for rigid urethane foams. Foam blown with CO₂ may again be possible, but its thermal characteristics and density probably will make such a product economically unmarketable. A major difficulty with CO₂ is its low

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2 Extruded PS boardstock and expanded PS bead board are also competitive but will be discussed later in this chapter. Significant differences exist between products made with these two processes and the foams being discussed in this section.
molecular weight (relative to CFC) and high thermal conductivity. Another difficulty is that it is soluble in polyurethane and rapidly diffuses out of the foam leaving a low-pressure (less than 1 atm) gas behind. (Air does not rapidly enter this low-pressure space from outside because of its low diffusion rate through the polymer.) To achieve the structural strength of the CFC blown foam, CO₂ blown foam must be denser. Foam blown with CO₂ in the two pound density range is similar to CFC blown foam of 1.7 pounds per cubic foot. Other physical characteristics make CO₂ foam inferior to CFC foam: It is more brittle, has more open cells, and has less compressive strength. Foam with acceptable strength requires a density greater than two pounds per cubic foot. Furthermore, and perhaps most important, is the relative insulation capability of these foams. Zwolinsky (1975) and other researchers confirm that the insulating value of CO₂ foam is about half that of CFC foam.

CO₂ is the only known alternative blowing agent currently available. Later in this chapter we will discuss the tightly competitive position of rigid urethane foam and our conclusion that foam produced with CO₂ is uncompetitive in any product line or application requiring superior insulating characteristics. Perhaps the only exception is in certain packaging applications where insulation, strength, and consistency are not critical factors. Here CO₂ blown foam might have an economic justification. Since packaging is such a small part of the urethane foam market, and since there are alternative non-CFC blown foams, we did not pursue this application.

Methylen chloride (and some other high molecular weight chlorinated solvents) might have good insulating properties, but it is a solvent for the plastic polymer and therefore is not a candidate for substitution. CFC-123, CFC-141b, or CFC-133a might be replacements for CFC-11 as blowing agents.³ Foam has been made in the laboratory with CFC-123 and CFC-141b. The foam appeared to have properties similar to foam blown with CFC-11, except for a ten percent degradation of thermal insulating performance (with CFC-141b). CFC-133a has been dropped from consideration primarily because it is embryotoxic. CFC-123 has been dropped primarily because no commercial manufacturing process has been found. CFC-141b seems the most likely prospect but is made currently only with a noncommercial process. Efforts to find a catalyst or separation technique necessary for commercial manufacture have failed. We were told that costs to manufacture CFC-141b will be substantially higher than those for CFC-11, even if the customers could adapt their CFC-11 foam blowing processes to CFC-141b. Given the strong competition faced in most urethane foam applications, we conclude that even if CFC-141b were available, it would not be economically competitive except possibly in a few market applications for rigid urethane foams.

HALF-LIVES AND THERMAL CONDUCTIVITY

High molecular weight CFC foam blowing agents are known to result in very low thermal conductivities, and that is the most valuable property of insulating foams. Retention of the CFC in the foam is desirable in present foam applications, and the preservation of low conductivity will be vital to the viability of any chemical substitutes for the CFC blowing agent.

Retention of gases in foams is often discussed in terms of "half-life"—the time required for the gas content to fall to one-half its original value. It is important to note that this

³According to DuPont (1980a).
half-life depends not only on the polymer material but also on the foam sample size and shape, boundary conditions, temperature, and detailed chemical makeup. Changes in gas composition and amount in the foam result from diffusion and dissolution processes that are complicated and, except when dealing with slab geometries, are not described by the exponential time dependence often associated with the use of the half-life concept.

Theoretical models of the diffusion of CFCs in foam have been based on simple geometries to obtain qualitative statements about the diffusion process at work. Specific quantitative diffusion estimates are not obtainable by these theoretical models; thus, diffusion constants of a new-materials combination are not easy to estimate. Diffusion theory has been used in conjunction with test data to find the diffusion constants. Because the diffusion constants can vary over orders of magnitude for relatively small changes in gas and polymer type, extrapolation of earlier gas retention data to a new-materials combination is unwise. DuPont, in recognition of this problem, has developed an accelerated test procedure.4

Early work on foam conductivity and CFC retention by Norton (1967) neglected the solubility of CFC in the solid phase of the foam. More recent literature suggests that the solubility has a significant effect and that foam effective life is longer than previously estimated. Dow and DuPont in informal estimates suggest half-lives in the range of 75 to 150 years for one-inch unclad foam. What is important to the foam purchaser, however, is the variation in conductivity with time, and that depends not only on CFC retention but also on air diffusion into the foam, as well as time-dependent erosion/decay of the foam structural properties. So CFC escape is only part of the problem with the foam's thermal conductivity. The expanded use of impermeable barriers to diffusion is economical because it prevents air diffusion into the foam as well as loss of CFC and helps maintain a high insulation rating until final disposal.

Our interviews and literature search on this project indicate that relatively little CFC diffuses out of these foams, the cell wall thickness and foam density being the determining factors. Standard foam densities are around 1.7 pounds per cubic foot. The commercial range where insulation is an important measure of performance is 1.6 to 2.4 pounds per cubic foot. For light foams of about one pound density, diffusion is significant.

The Jim Walter Research Corporation has tested the variation of insulating capability over time (Sherman, 1979). Impermeable facing such as foil is important in reducing the degradation of the insulation conductivity factor, K.6 If the double faced foil is removed, within six months the K factor degrades from K = 0.14 to K = 0.17. Clearly, foil protects the foam from the adverse effects of gas permeation. Degradation of foam insulation capability immediately after manufacture is about 15 percent. Initial K is about 0.12 Btu-inch/hr ft²·°F. A reasonably stationary K value of about 0.14 is reached after one month. Jim Walter researchers could not determine a half-life after extensive testing. In fact, no finite half-life could be found within the limits of measurement accuracy. However, as noted earlier, Dow and DuPont report a 75 to 150 year diffusion half-life for CFC. The relationship between CFC diffusion and K factor degradation is not clear. There is some speculation still on whether the degradation is caused more by the diffusion of CFC out of the cells or by the diffusion of air into the cells.

Thus, current estimates of CFC half-life cover a broad range of from 50 to 100 years. Here, the economic significance to the user is negligible. Chemical manufacturers and foam producers have no economic incentive to refine measurements of the half-life. They are more

4 This procedure takes only two to three months.
5 Btu · inch/hr · ft²·°F.
concerned, as are users, with K-factor degradation over the life of the product (of the order of 50 years or less) where all measurements indicate that the degradation (except for that just after manufacture) can be controlled economically by cladding the foam with an impermeable barrier for construction applications. (In refrigeration applications, discussed in Sec. III, impermeable barriers in the form of liners and cabinets are used.)

One must assume for the purpose of CFC policy analysis that eventually all CFC will be released to the atmosphere. Physical and biological processes go to work at disposal of rigid plastic foams, inevitably leading to the release of CFC from the cells. More accurate measurements of CFC diffusion coupled with models of product disposal and destruction may ultimately be needed if the timing of CFC release to the atmosphere from rigid foams is to be more accurately predicted.

PRODUCT SUBSTITUTES

Rigid urethane and isocyanurate foam boardstock and some cut slabstock are used primarily in residential, commercial, and industrial insulation. The primary use of boardstock is for sheathing. Residential sheathing dominates the market, but the market is similar for commercial and industrial buildings. Residential and commercial sheathing and roofing and certain pipe and storage tank insulation have product alternatives or alternative insulating systems with little price or performance differences. Other products, made with little or no CFC, may be ready substitutes for CFC blown rigid urethane foam.

The following describes the various application areas and the competing products that fill these particular application areas. In some areas, suitable competitive products (or systems and products) are available with little or no increase in cost. In others, quite the contrary is true. Competing products include other CFC blown foams (e.g., extruded PS board) as well as non-CFC foams (e.g., fiberglass, fiberboard, and expanded PS (EPS) board). CFC blown rigid foams are competitive because of their advantages in thermal insulation, physical strength, and weight. Thermal resistance is measured by R (the inverse of K, with units of hr·ft²·F/Btu·inch). Urethane and isocyanurate have about R = 7 per inch; fiberglass board R = 4 per inch; extruded PS board R = 5 per inch; EPS board R = 4 per inch; and fiberglass batts R = 3 per inch (all approximate).

Below-Grade Insulation*

Currently, there is an even split between installing below-grade insulation inside or outside the cellar walls. Insulation of basements and slabs can be done with extruded PS board, EPS board, urethane, or isocyanurate foams. Porosity is an important factor in this application, because high porosity means that the insulation can easily take up water, which is often present, particularly outside in the ground. Extruded PS board is the least porous and EPS board the most porous. Water reduces insulating value by providing a conductive path through the insulation. However, water's effect on R value is quite variable among urethane foam, extruded PS board, and EPS board. The alternating cycles of freezing and thawing shorten the life of insulation containing water.

*Below grade is a construction term that refers to the area beneath the surface of the ground. In this discussion, it refers to basement or slab insulation.
Insulation installation methods and their costs—particularly when vapor barriers are installed to prevent water infiltration—can make each of the rigid foams competitive as below-grade insulators. Another factor affecting choice of insulation is the amount of water pressure on the product below grade. Transportation costs are also an important factor. Each product is competitive or potentially competitive, depending on local conditions and installation methods.

Fiberglass can compete below grade on inside installations, but not at all on the exterior because of its porosity and tendency to compact, which destroy its insulating effectiveness. It is competitive particularly in below-grade retrofits, which clearly can be done only from the inside. On an insulation value or R basis, fiberglass is cheapest (i.e., 15¢ per square foot compared with 40¢ for urethane R-11). However, when viewed as a complete insulation system, installation methods and costs must be considered; specifically, adding studs to support dry wall and adding dry wall for aesthetics and fire protection add to the cost of a fiberglass installation and make CFC blown foam and EPS foam competitive.

Dry wall is needed for fire protection over most fiberglass and some rigid foams (urethane, extruded PS board, and EPS board). Thermax, a trade name isocyanurate foam product from Celotex Corporation, does not need the dry wall for code-required fire protection in some applications, giving it a slight economic advantage. If aesthetic considerations require dry wall anyway, another insulation might be preferred.

The choice among these different products is made based on the fact that (1) each product has different aesthetic characteristics, and (2) each site and building design have different transportation and installation costs. All the products mentioned do compete currently. The removal of one product would affect the product mix.

**Sheathing and Wall Insulation**

For sheathing and wall insulation, we find competition between fiberglass batts, fiberboard, urethane, isocyanurate, extruded PS board, and EPS board.

Fiberglass virtually always has the advantage as insulation between the studs in the walls. In regions where extremely heavy insulation is required, rigid urethane foams are used between the studs. Pour-in-place, spray, slab, or cut boardstock occasionally may be used because they have a higher R value.

Wall insulation has many variations: In some areas, higher R levels are needed than can be achieved with R-11 fiberglass in a 2 × 4 wall. A 2 × 8 stud can be used instead with fiberglass R-19 batt. If more insulation is needed, one-inch urethane sheathing (R ~ 8 per inch) can be added to achieve R-27 insulation. However, any general shift to 2 × 6 construction nationally would require a capital equipment changeover to increase production of 2 × 6 inch studs (to replace the 2 × 4 studs) and new wider windows and door casings.

Frame construction using 2 × 4 studs can be insulated to R-19 by using fiberglass batts (R-11) in the studs and then by sheathing with approximately one inch of urethane or isocyanurate (R ~ 8 per inch) or two inches of EPS board (R ~ 4 per inch) or one and one-half inches of extruded PS board (R ~ 5 per inch). Wall thickness is not so great for one inch sheathing of urethane as to require special and therefore more expensive door and window jambs, casings, and the like. The older traditional sheathing was fiberglass board or fiber-

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2Plastic foams are sometimes combustible and may release toxic fumes. Fire codes require special fire barriers in most installations where plastic foams are used.
board, which could not meet the higher R values required now without using a greater thickness. They have been displaced by foam sheathing.

The builder must choose how to achieve a particular insulating level, given the various wall types and insulation types. Labor, material, and transportation costs are contributors to the total cost. And there may be quality, value, or architectural factors affecting his choice. Furthermore, each home in each tract might require an individual choice, depending on the local environmental and market conditions at the time. In addition, if building codes do not specify a required R level, the amount of insulation itself is a variable, a function of energy and financing costs. EPS board, fiberglass board, and extruded PS board are competitive with each other and with all other insulations, the choice being made case by case.

Generally, our impressions from the foam industry are that, if CFC blown insulation products are removed from the market, current insulation standards of R-19 walls could be achieved by using 2×6 inch studs or a thicker EPS board sheathing. Changeover costs and dislocations in the lumber industry for studs, window and door casings, and jambs to supply the market using 2×6 frame construction may be important. (We did not interview anyone in the lumber industry nor did we research the impact of possible energy or building code changes.) We do not know whether long-run construction costs would change much, but transient shortages until the lumber industry is converted might make costs higher in the short and intermediate term. Homes using 2×6 studs are reputed to be slightly more expensive presently than homes using 2×4 studs, but when completely installed with insulation they may cost very little more.

As energy costs have risen and insulation has become more desired, the foam sheathing market has expanded, as it is the most economical way to achieve better insulation with 2×4 construction. Any price increases or quantity constraints on the CFC blown foam suppliers would both reduce insulation and increase housing costs, but the long-term increases may not be prohibitive. In a market with as many competitive products as construction insulation, the long-term dislocation to the overall industry by a change in CFC price or availability is not likely to be large.

Roofing

In roof and ceiling applications, differentiation must be made between residential and commercial/industrial. Generally, residential roofing is more steeply pitched and has attic space and ceilings that can be insulated. Commercial/industrial roofing is usually only slightly sloped and insulation is done on or just below the roof.

In the colder states, R-38 is a standard residential insulation requirement. In California, R-19 has been chosen as a more appropriate standard. Vaulted or open beam ceilings are popular in California, and in this type of residential construction, the economic competition is between the 2×6 studded faise roof with R-19 fiberglass batts and a plywood exterior roof or one of rigid boardstock (urethane extruded PS board, or EPS board) directly over the ceiling. Some roofers install directly over foam; others require plywood on top, but most important is the savings on the installation of studs. Either way, the rigid foams are very competitive with fiberglass because it is unnecessary to install a second studded roof. Thicker foam, as would be necessary using EPS or extruded PS foam, requires longer roofing nails, and these PS foams may create other unusual installation requirements (relating to fire protection, for example) that could drive up the installation costs. Nevertheless, EPS board and extruded PS board do compete in roofing systems insulation applications.
Rigid foams have not made inroads into the ceiling insulation market held by fiberglass batts (or rock wool)\(^9\) because space is not constraining, there are no structural or safety requirements, and, for equal amounts of insulation, fiberglass and rock wool are the least expensive. If additional insulation levels are required, rigid foam insulation sheathing can be nailed below the rafters with gypsum dry wall faced below the insulation.

The commercial and industrial roofing market is divided into reroofing and new roofing. Two general types of roofs are available: a built-up roof with layers of hot asphalt tar and felt, and a one-ply roof with a single membrane of rubber or plastic waterproofing. Today, built-up roofs are insulated with perlite board, fiberglass, fiberglass board, or any of the rigid foams. Particular installation techniques must be used for the polystyrene foam insulation.

The trend is toward the one-ply or membrane roof on new roofs and on reroofing (currently 10 to 15 percent of the market). This newer style one-ply roof is insulated with the same mix of products as built-up roofs, including urethane or isocyanurate boards, spray-on urethane foams, perlite board, fiberboard, and, because of the one-ply roofing installation process, EPS board and extruded PS board. We find that reroofing is increasingly being done in one-ply because of weight and labor advantages.

About 30 percent of the commercial/industrial market is perlite, 20 percent fiberglass, eight percent fiberboard, and 40 percent rigid foams, including spray-on urethane. Polystyrenes (extruded PS board or EPS) are not always acceptable in built-up roofs because most application methods cause the plastic to melt from the hot tar or to dissolve from solvents in the hot tar. Furthermore, in one-ply roofs, the natural temperature buildup from the sun may damage the polystyrenes. The old standby of roof insulation was fiberboard or perlite board. Weight (eight pounds per cubic foot), installation expense, and insulating capability (approximately R = 3 per inch) all combine to make it currently inferior to urethane, isocyanurate, and PS foams in most applications. Urethane and polystyrenes can only be used on roofs where fire protection has been supplied by a code-rated fire barrier such as perlite, plywood, or concrete. Isocyanurate foam has the edge where the fire barrier is not in place, because it often qualifies without needing an added fire barrier.

We find that any of these rigid insulation materials can have a one-ply roof or built-up roof applied, depending upon installation techniques, building and fire codes, and specific individual roofing needs or characteristics. However, since most polystyrenes require more care in application of roofing insulation, the rigid urethane and isocyanurate foams command perhaps a 20 percent higher price than in sheathing or below-grade applications, where the PS foams require no special handling.

Sprayed-on urethane foam insulation has a significant part of the reroofing market. One-ply roofing is usually applied on top. The savings here is in labor, during both installation and preparation. The spray-on foam has advantages when the surface to be reroofed is uneven with lots of curves, pipes, or ducts. The labor involved in cutting rigid boardstock or slabstock, urethane, EPS board, or extruded PS board to unusual shapes can shift the choice to spray-on urethane foam. Furthermore, reroofing often has serious weight constraints. As the allowable load is approached, a lightweight replacement roof competes well with a heavier one that might require removal of the previous roof.

On the other hand, cut slabstock can have the advantage: Flat roofs can be converted to gently sloped roofs by cutting the slabstock urethane (or EPS board) in a tapered shape. It

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\(^9\)Rock wool is similar in insulating value to fiberglass batts (R = 3 per inch) and consists of loosely packed fibers that are installed by blowing the material onto the ceiling with a hose.
also has the edge in applications where surfaces to be insulated have no sinks, valleys, or sags, and few air conditioning ducts.

Floors

In insulating floors, fiberglass batts have the advantage, because floor joists are usually 2 × 6 or larger and can accommodate R = 19 per inch fiberglass batts. If more insulation is required, rigid plastic foams can be nailed below the floor joists. Occasionally, the architect designs the crawl space as a plenum to carry heated or cooled air throughout the building. In such a case urethane, extruded PS board, or EPS board are made water-vapor-tight and placed on grade.

General Applications

The inroads into the insulating market made by the rigid plastic foams are just beginning. Those companies we interviewed said that not one of the large tract builders in the United States uses foams. We can conclude from this that at present initial costs of using foams are higher than the cost of fiberglass substitutes. Specialty home builders often advertise the energy efficiency aspects of their homes. This is where most rigid insulation foam is used. Only 20 percent of homes built today and four percent of the apartments use plastic foam insulation. If energy prices rise or if interest rates drop, we expect that more insulation will be demanded. As labor and transportation costs change, so will the economics of insulation, with product shifts toward and within the rigid foam insulation industry.

Foam manufacturers feel that chemical technology, costs, and demand are rapidly changing. Since the industry is highly competitive, changes must be accommodated within a very short time.

Clearly, in every application, strong competition exists between the newer insulating plastic rigid foams and the older materials such as fiberglass, insulating boards, and so forth. The older products have been losing out. New installation methods (such as one-ply roofs, sprayed-in-place foam, and studless basement insulation) are labor-saving enough to displace the older and often cheaper material. Demands for high R ratings even within older constructions have increased the demand for foam insulation.

Profit margins of suppliers vary from one product area to another. Where a product has strong advantages, that is, from transportation, insulation, aesthetic, or performance points of view, the margin is higher. For example, in reroofing insulation, all rigid foams have unique areas of the market where they have a strong position. In floor or ceiling insulation, fiberglass batts have the strongest position.

Modest increases in chemical costs, driven perhaps by CFC cost increases, would not displace rigid plastic foam insulation from the strong markets. In areas where foam insulation is a weaker competitor, such as in floor or ceiling insulation, traditional fiberglass or rock wool will remain dominant.

Not only does rigid foam compete with other insulation, it also competes with energy and housing financing costs. Because of the competition and the relative ease of a new manufacturer entering the business, profit margins are small. Any product cost increase brought about by CFC price increases will affect the nature of the balance between the competition. Foam manufacturers will either go out of business as the profit disappears or will try to raise their product's price.

If prices of rigid foam insulations rise, we know that insulation levels would drop, hous-
ing costs would rise, building techniques would shift (for example, to a wider wall or away from vaulted ceilings), and substitutes for CFC insulation would increase in use. We can only predict that some of each of these phenomena will occur. Without an elaborate model, one cannot predict the specific reduction in average insulation, the level of increase of housing prices, or the degree shift to other insulation products. Nor can one easily predict any specific changes in construction procedures and capital changes in the manufacturing of lumber, window or door casings, jambs, or hardware.

SUMMARY

No satisfactory substitute blowing agent is available at this time. Chemical manufacturers have been unsuccessful in their attempts to develop economical manufacturing processes for potential alternative CFCs (such as CFC-123 and CFC-141b) with significantly less ozone depleting potential. Current findings confirm previous reports. (Emissions reduction options are summarized in Table 2.2.)

<table>
<thead>
<tr>
<th>Tactic</th>
<th>Annual Amount (1976 Basis)</th>
<th>Level of Dislocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substitute blowing agent</td>
<td>Very Large</td>
<td>Very Difficult a</td>
</tr>
<tr>
<td>Disposal emission control</td>
<td>Very Large</td>
<td>Very Difficult</td>
</tr>
<tr>
<td>Recovery and recycle of manufacturing emissions</td>
<td>Small</td>
<td>High</td>
</tr>
<tr>
<td>Substitute product construction</td>
<td>Large</td>
<td>Small-Moderate</td>
</tr>
<tr>
<td>Substitute product refrigeration and transportation</td>
<td>Medium</td>
<td>Moderate-High</td>
</tr>
<tr>
<td>Disposal emissions control (transportation)</td>
<td>Small</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

aModerate if a suitable substitute is invented; very difficult at present.

Several research reports have shown half-lives of CFC-11 in rigid urethane foams to be quite long. The earlier Rand study estimated a half-life of 50 to 60 years for a standard clad-on-one-side, two-inch-thick boardstock. Now, preliminary evidence indicates even longer
half-lives in rigid foams. Most important, however, is that the issue of half-life of CFC within the foam does not appear to be relevant unless further data show that half-lives are substantially less than the 75 years now reported.

Most roofs have life expectancies in the ten- to 30-year frame; construction insulation in houses has an 80-year life expectancy. For the most part, one can assume no release of CFC until destruction or disposal. A model of release upon disposal would be needed to determine release of CFC banked in rigid urethane foams.

The issue of thermal conductivity of rigid urethane foams is important, primarily because conductivity provides rigid urethane much of its competitive edge. Degradation of insulating R value has been shown to be more a result of diffusion of air into the closed cells than of CFC diffusion out of the cells. Cladding with an impervious barrier such as aluminum is economical in that it sustains the R value.

Our present research reveals no significant changes from our earlier estimates of half-life or thermal conductivity. On the other hand, some significant differences are important to note in the area of product substitutes. In Palmer et al. (1980), Rand concluded that rigid urethanes, for the most part, enjoyed a wide competitive edge in insulating applications. This would imply that a change (even a large one) in retail price of the product would not cause significant shifts in demand for the various products. Our perceptions are now different for construction applications. We find that for the majority of rigid foam products, or applications of the product, the competition is strong. Price increases would shift consumers to product substitutes.

Emissions control technology is a technical option. Economic incentives do exist to hold manufacturing emissions down. The emissions can be captured and recycled, but we have found no evidence that recovery is presently economical for any of the rigid urethane foams.

Further improvements in work practices are unlikely to reduce emissions significantly for rigid urethane foams. Collection of emissions at disposal is remotely conceivable but clearly uneconomical in virtually every product application because of the small amount of remaining CFC at disposal, the transportation costs, dismantling costs, and CFC collection equipment costs.

Nothing during the course of research under this contract has changed our perceptions in the work practices or control technology areas.

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2DuPont indicates that they have an accelerated test procedure and have found a half-life of 75 years in one-inch-thick slabstock.
III. Rigid Urethane and Isocyanurate Foams: Refrigeration Applications

STATIONARY REFRIGERATORS AND FREEZERS

Foam insulation is used in the vast majority of home refrigerators, home freezers, and retail food display cases. It has displaced glass fiber from all but one-quarter (G.E.) to one-third (Whirlpool) of refrigerators, and that market share is expected to decrease further (to about one-tenth) in coming years because of the emphasis being put on energy efficiency.

In retail food display cases, the fraction using foam insulation is almost 100 percent—both Hussman and Tyler use foam almost exclusively—and only the smaller producers now use fiberglass insulation. Low-production-volume cases are insulated with slabstock foam, but as time goes by, foam-in-place foam is used increasingly. Although such foam requires a substantial investment in tooling, it reduces labor, provides better insulation, and avoids the problem of heat leaks and drips.

The long-term retention of thermal-conductivity properties in these foams has been a subject of some debate. After testing, G.E. concluded that there is no detectable deterioration of conductivity after nine years of use. Fiberglass, on the other hand, is subject to local sagging and moisture leaks, which can result in serious losses of insulation effectiveness. The low-conductivity properties of CFC blown foam are a result of the high molecular weight of the CFC blowing agent.

In refrigeration applications, the physical properties of the foam are of great importance. The resistance of the foam to breakage and abrasion must be sufficient to prevent damage to the foam under sometimes heavy shock loading in transport. The foam supports the inner liner and evaporator; breakage of the foam here could result in progressive failure from the intrusion of water. Foam also supplies some structural support and permits, in a few cases (retail food display cases), a somewhat thinner gauge of metal for the outer casing, or a lighter plastic inner liner for refrigerators. Using other insulators would require substantial redesign and retooling to compensate in these areas as well.

The properties described above are important enough to justify a price premium of $50 to $100 per appliance, which generally can be recovered in about three years by the purchaser, depending on the local price of electrical power. Market acceptance of foam insulation has been high. Only a small and decreasing part (20 to 30 percent) of production uses fiberglass insulation, which is available mostly in older, smaller models of refrigerators and freezers. The industry is in a slow changeover to foam insulation; as new models are introduced to replace older ones, fiberglass use will be further reduced.

This trend has been reinforced by proposed stricter regulations on energy consumption. The future course of such regulation is naturally uncertain, but if it continues it will be very difficult to satisfy without either using CFC blowing agents for foam or producing a less desirable product—one with less usable inside space for given outer dimensions, and with a higher price.

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10 This is based on current catalog prices, and energy requirements of freezers with identical inside and outside dimensions, having foam and fiberglass insulation.
Product Substitutes

Formerly, fiberglass insulation was used exclusively (and to some extent it still is used) for insulation of household refrigerators and freezers, and it could be used again. A return to fiberglass insulation for the retail food refrigeration industry would require at least one year for redesign, five or six years to implement, and about $10 million for each line of cabinet. We learned in our interviews that a change might cost the entire industry over $100 million. A return to fiberglass for the household refrigeration industry might be less traumatic, because they now produce a few fiberglass insulated models. But because this industry is much larger, it would require retooling of the major lines at a very significant cost. The redesign to incorporate more insulation thickness would require several years of development before introduction of the new line.

We attempt a rough cost comparison of foam insulation and fiberglass insulation, under the assumption that the capital costs for a large automated foaming installation have already been invested (as they are for the major manufacturers). Manufacturers were understandably unwilling to reveal details of their costs, so our estimates are uncertain and were derived from a factory tour rather than from a detailed study. We estimate materials and labor costs for refrigerators having the same internal and external dimensions, whether foam or fiberglass insulated; as a result, the fiberglass unit would require a higher energy cost in the long term.

The assumptions used in this comparison are as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation volume</td>
<td>10 ft$^3$</td>
</tr>
<tr>
<td>Foam density</td>
<td>1.5 lb/ft$^3$</td>
</tr>
<tr>
<td>Foam materials cost</td>
<td>68¢/lb</td>
</tr>
<tr>
<td>(both components, including blowing agent)</td>
<td></td>
</tr>
<tr>
<td>Fiberglass density</td>
<td>0.6 lb/ft$^3$</td>
</tr>
<tr>
<td>Fiberglass materials cost</td>
<td>50¢/lb</td>
</tr>
<tr>
<td>Labor increment for fiberglass</td>
<td>0.5 manhour/unit</td>
</tr>
<tr>
<td>above requirement for foam.</td>
<td></td>
</tr>
<tr>
<td>Includes fiberglass storage,</td>
<td></td>
</tr>
<tr>
<td>handling in factory</td>
<td></td>
</tr>
<tr>
<td>installation, and additional</td>
<td></td>
</tr>
<tr>
<td>labor in installing liner,</td>
<td></td>
</tr>
<tr>
<td>supports, and finish trim</td>
<td></td>
</tr>
<tr>
<td>Direct labor cost</td>
<td>$10/hr</td>
</tr>
<tr>
<td>Overhead factor for supervision, fringe benefits</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The labor estimate is doubtlessly the most uncertain part of this comparison. We observed two fiberglass lines; from these we estimated that 20 people were associated with the fiberglass installation (including handling, actual installation of the liner, and closure) with

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$^{11}$The foaming installation at G.E., Louisville, was estimated to cost over two million dollars. This cost was thought to be higher than some because of the great emphasis placed on reproducible high quality in the design of the system.
an estimated average cycle time of about one minute. We allowed 50 percent for breaks, and so estimated one-half a manhour per unit.

Our estimates of insulation costs per unit produced are as follows:

<table>
<thead>
<tr>
<th>Item</th>
<th>Fiberglass</th>
<th>Foam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>$3.00</td>
<td>$10.20</td>
</tr>
<tr>
<td>Incremental labor</td>
<td>7.50</td>
<td>--</td>
</tr>
<tr>
<td>Total</td>
<td>$10.50</td>
<td>$10.20</td>
</tr>
</tbody>
</table>

Fiberglass seems to have essentially the same marginal cost as foam, and the cost of fiberglass installation is dominated by labor. If the comparison accounted also for the costs of the foaming machine, a machine amortization cost would be necessary, of about one dollar per unit; the exact cost would depend on the machine life, capacity, and capital cost.

These estimates support the claim by manufacturers that a mandated change away from foam insulation would increase costs if it were also required that the insulation values remain the same.

Of the foam material costs, we estimate that about ten percent, or about one dollar per appliance, is due to the CFC-11 used as blowing agent.\(^\text{12}\) Increasing CFC costs—even to double or triple—would probably not reduce CFC-11 use in refrigerator insulation, because it is a small component of cost and contributes much to the product quality and value on the market.

Stopping the use of CFC foamed insulation in refrigerators probably would require a direct intervention or prohibition. The principal alternative, as suggested above, is fiberglass insulation. Recall that more remote possibilities include the use of CO\(_2\) blown foam and the use of expanded PS boardstock. So far, CO\(_2\) blown foam has had poor mechanical strength and cannot approach the insulating value of CFC blown foam. Current foaming machines would require very substantial change, possibly replacement. Foam boardstock, in addition to its fundamentally poorer insulating value, would be more difficult to install than fiberglass. A combination of EPS board and fiberglass might be preferred, but new manufacturing processes would have to be developed if these substitute insulations were used.

If use of CFC foamed insulation were prohibited, not only would the foaming equipment—representing some tens of millions of dollars of investment industry-wide—have to be abandoned, but most of the product lines, which are not suitable for fiberglass substitution, would have to be completely redesigned and retooled (because of inner liner support, even if the higher heat load could be accepted). Even the largest industries would find it difficult to introduce more than one new line a year, because of the availability of staff; and the first new line could not be introduced for several years, because a substantial amount of product design and testing would be required to ensure acceptable performance. Major companies have as many as eight to 12 distinct models that would require redesign and retooling.

**Recovery of CFC at Manufacture**

It was estimated that about ten percent of the CFC-11 used in insulating refrigerators, freezers, and retail food cases is lost at the time of foaming. Configurations of foaming equip-

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\(^{12}\) The costs of CFC-11, polyol, and isocyanurate components of the foam mixture were taken as $45$, $62$, and $83$/lb, respectively.
ment vary widely, from highly automated multiple foaming machines in high-volume production applications to single-station, essentially manually operated stations on a factory floor. In either case, the emitted CFC comes out of the volume to be insulated, along with expelled air. The difficulty of collecting the CFC is associated with the difficulty of collecting that air before it is too diluted. Any detailed study of collection alternatives would require consideration of the configuration of the foaming machine. In the absence of any study, we cite an estimate of $100,000 for CFC recovering equipment in use at a rework area for air conditioners.13

Recovery of CFC During Use

Very little CFC is lost from refrigeration foam during use, as it is contained on all sides by metal walls or structural plastics. Recovery during use is therefore not of any interest.

Recovery of CFC at Disposal

Refrigerators and freezers have long lives—ten to 15 years or more—and following ordinary use meet a variety of fates. In Los Angeles, which we think typical of urban areas, disposed of units are collected by the retailer who sold the replacement, given to a salvager who removes the compressor, motor, and copper tubing for their scrap value (venting any remaining refrigerant), and then transported to a landfill dump. There the boxes are crushed by a large compactor, which releases the majority of the CFC in the foam as the foam structure is broken up.

In other areas, boxes are dumped without compaction and are buried essentially intact. In these cases, the CFC would escape only after rust-out of the box. In still other cases, the boxes are left to decay in barns, fields, streams, culverts, and the like.

Unfortunately, we cannot foresee an economically feasible way to effect CFC recovery at disposal. To make it worthwhile to collect disposed of boxes at central areas for recovery would require about $20 worth of specialized transportation charges for each box, which may contain only 1½ pounds of CFC—worth one dollar.

Destruction of CFC in the Foam: A Future Possibility

If (or when) it becomes economical to salvage the sheet steel in the cabinet of a refrigerator—about 100 pounds—it may be possible to destroy the CFC-11 in the foam (along with the foam and the plastic liner) when the whole cabinet is melted (at about 2,500°F—more than the melting point of steel). A complex mixture of pyrolysis products from the paint, plastics, foam, and CFC would result, and some would clearly be noxious and corrosive—Cl₂ and F₂ from the CFC-11—but the possibility of controlling these secondary emissions by scrubbing or dilution certainly exists, although it may be expensive, depending on the makeup of the pyrolysis gas. Detailed planning for such a long-term possibility is inappropriate—it is uncertain whether recycling of steel will become economical, because before it became economical, much less steel would probably be used in appliances.

13Personal communication to The Rand Corporation from General Electric, Louisville, April 1, 1981.
MOBILE REFRIGERATORS AND FREEZERS

Refrigerated trucks, trailers, and ship containers are examples of mobile refrigerators and freezers. Insulation in these applications saves significant energy. Froth-foamed urethane has taken over the majority of this market because of its physical properties and its price. Spray-on urethane foam and pour-in-place foam capture a smaller market share and are suitable alternatives for certain mobile refrigeration units.

Just as in stationary refrigerators, the expanding foam adheres to the walls and provides structural strength. The walls act as a cladding to restrain the movement of air and moisture into the foam so it maintains its superior insulating ability.

Froth-foam uses about four percent by weight of CFC-12 as a frothing agent to expand the chemicals even before the heat of reaction vaporizes the CFC-11. This expansion is useful in filling the entire cavity and in reducing the pressure needed to constrain the foaming process. A lighter foam (approximately two pounds per cubic foot) is better achieved with the froth process than with a pour-in-place process. The frothing process uses slightly more CFC than pour-in-place because of the CFC-12.

One technical option is to reduce CFC-12 use in froth-foaming by using a less ozone depleting agent. Industry has not yet found any suitable substitutes.

Alternative insulations do exist but are significantly inferior to urethane foam. Fiberglass batts collapse from road vibrations and become ineffective insulators. Rigid fiberglass board is heavy, and EPS board would require new fabrication methods. All alternatives add weight, reduce space available for the product, and are less-effective insulators. Mobile refrigeration units have a unique need for rigid urethane insulating foams because of the extra costs associated with weight and volume in transportation.

EPS board as a product substitute cannot be ruled out. It would require new methods for manufacturing and would slightly reduce the space in the mobile refrigeration unit if the same level of insulation were to be achieved. We do not have enough information on whether the changes required would be moderate or significant: Industry would suffer moderate dislocations if production systems had to be converted.

Another option is to redesign only the jigs necessary to restrain the internal and external forms making up the trailers, ship containers, and rail cars so they will handle the higher pressure of the pour-in-place urethane foam. The manufacturing process might be redesigned both in the jigs to restrain the walls and in the pouring process to eliminate voids during foam expansion.

Either of these changes may be economical today because a savings of about four percent in chemical weight of CFC-12 would result.

Capturing and recycling CFC-12 is unlikely to prove economical even though most of the CFC-12 used is emitted during manufacture of the foam. Technology exists for CFC-12 recovery but a system has yet to be installed. The small amount of CFC-12 emitted would most likely not justify the equipment.

Both CFC-11 and CFC-12 are emitted during manufacture. Earlier Rand research (Palmer et al., 1980) estimated that, on average, 11 percent of the CFC was emitted during manufacture of urethane foam. Total releases from froth-foam are thought to be much higher, perhaps about 18 percent of the CFC used. Capture and recycle of CFC-11 would be most economical in continuous boardstock or slabstock manufacture and least in intermittent or diffuse foaming operations. The largest immediate releasers of CFC are froth-foamers; these manufacturers are diverse and operate intermittently. Spray-on foam operations are mobile, and the large capital required for recovery is probably not justified. Stationary operations,
such as production of laminated boardstock, have low levels of release associated with urethane foam manufacture, and the volume and value of CFC available for recovery simply would not justify the capital expense, and may not even cover the marginal expenses for operating recovery equipment. Hence, we dismiss capture and recycle as a technical option for mobile refrigeration.

Collection of insulated trailer bodies, rail cars, ship containers, etc., for centralized disposal and recycle of approximately 40 pounds of CFC-11 is a technical option that cannot be dismissed. No extensive economic feasibility study of this possibility has been made to our knowledge. The economics of recovery or destruction of CFC at this point would benefit from the recovery of the scrap metal that could be recycled (much of which is the aluminum used in fabrication of all these mobile refrigeration units). Since ownership is more consolidated (than is the case for private refrigerators, homes, etc.), and since the unit is mobile throughout its life and large, with significant recyclable components, this option seems potentially attractive.

SUMMARY

No satisfactory substitute blowing agent is available at this time. Chemical manufacturers have been unsuccessful in their attempts to develop economical manufacturing processes for potential alternative CFCs (such as CFC-123 and CFC-141b) with significantly less ozone depleting potential. Current findings confirm previous reports. (Emissions reduction options are shown in Table 2.2, Sec. II.)

Several research reports have shown half-lives of CFC-11 in rigid urethane foams to be quite long. Earlier, Rand (Palmer et al., 1980) estimated a half-life of 50 to 60 years for a standard clad-on-one-side two-inch-thick boardstock. Now, preliminary evidence indicates even longer half-lives in rigid foams. Most important, however, is that the issue of half-life of CFC within the foam does not appear to be relevant unless further data show that half-lives are substantially less than the 75 years now reported. Most refrigerators and truck and trailer bodies have life expectancies in the ten- to 30-year frame. For the most part, one can assume no release of CFC until disposal. A model of release upon disposal would be needed to determine release of CFC banked in rigid urethane foams.

The issue of thermal conductivity of rigid urethane foams is important, primarily because conductivity provides rigid urethane much of its competitive edge. Degradation of insulating R value has been shown to be more a result of diffusion of air into the closed cells than of CFC diffusion out of the cells. Cladding with an impervious barrier such as aluminum is economical in that it sustains the R value.

Our present research reveals no significant changes from our earlier estimates of half-life or thermal conductivity. In Rand's previous study, it was concluded that rigid urethanes enjoy a wide competitive edge in insulating applications. This would imply that a change in price of the foam product would not cause significant shifts in demand in the various applications. Our present study supports this finding in the area of refrigeration applications.

Emissions control technology is a technical option. Economic incentives do exist to hold manufacturing emissions down. These emissions can be captured and recycled, but we have found no evidence that recovery is presently economical for any of the rigid urethane foams.

\[\text{DuPont indicates that they have an accelerated test procedure and have found a half-life of 75 years in one-inch-thick slabstock.}\]
Further improvements in work practices are unlikely to reduce emissions significantly for rigid urethane foams. Collection of emissions at disposal is remotely conceivable but clearly uneconomical in virtually every product application because of the small amount of CFC remaining at disposal, the transportation costs, dismantling costs, and CFC collection equipment costs. The disposal emissions option cannot be ruled out entirely for all products. The only promising candidate for emissions reduction is in the area of transportation insulation, since ownership is centralized and units are mobile.

Nothing during the course of research under this contract has changed our perceptions in the work practices or control technology areas.
IV. Nonurethane Rigid Foams

Nonurethane foams consumed an estimated 23 million pounds of CFC in 1976. Here, we focus on extruded PS sheet (primarily used in packaging), which used over 50 percent and extruded PS board (construction insulation), which used almost 20 percent of the CFCs consumed in manufacture of nonurethane foams in 1976.

EXTRUDED PS BOARD

Substitute blowing agents were not thought to exist at the time of Rand's earlier study (Palmer et al., 1980). Since then, DuPont has reported that CFC-124 and CFC-134a should prove technically feasible as substitute blowing agents for extruded PS board if difficult manufacturing and toxicity questions are resolved. Methyl chloride is a possible substitute blowing agent in Dow's extruded PS board, although the resultant product has approximately 20 percent less insulation value.

It is not known how an extruded PS board blown with methyl chloride could compete against EPS board. On the basis of our interviews, we believe that this substitute blowing agent is not economically feasible, because the resultant product would not be able to compete against some of the product substitutes, particularly expanded EPS board made without CFC.

Dow Chemical has estimated the half-life and diffusion of CFC in extruded PS board, but the information is proprietary. The earlier Rand study concluded that the half-life was 50 years for unclad and 200 for clad extruded PS board. Additional interviews helped us confirm the reasonableness of the 50-year estimate. With this long half-life, we do not find the half-life or diffusion issues important in long range policy analysis.

Thermal conductivity is decreased (aged R value higher) by containing the CFC-12 within the cells in extruded PS board. Extruded PS board blown with methyl chloride and EPS board (also known as molded beadboard) blown with pentane are about 25 percent poorer insulators than extruded PS board blown with CFC-12.

Recall that extruded PS board is used primarily for insulation in all areas of construction: foundations, below-grade interior sheathing, and roofing. Rigid urethane foams, EPS, fiberboards, fiberglass, and even energy all compete in these product areas.

Previously in this chapter we described product substitutes for rigid urethane foam in construction. These substitutes apply to extruded PS board as well. In most applications, some alternative method of insulation is available. Wide use of these alternatives may require different designs (e.g., 2×6 studs instead of 2×4 studs in wall construction), may require different installation methods (e.g., longer nails, vapor barriers, or greater care in handling), and may require production changes in related products (e.g., pre-made window and door casings and jambs).

After examining most of the product applications case by case, we concluded that adequate product or system substitutes exist, even substitutes using no CFC (such as fiberboard, EPS board, or energy) for most extruded PS board applications and, as mentioned earlier, for most rigid urethane board applications.

This general conclusion covers the majority of uses for the product, but, in certain isolated cases (such as in below-grade applications where the material is subject to freezing and
thawing) extruded PS board has clear advantages due to its very low permeability, and no suitable alternative may exist.

The chief competitors of extruded PS board are rigid urethane boardstock and EPS board (along with energy, costs of financing, and traditional insulating systems such as fiberglass). It is hard to assess the specific market changes that might come from CFC regulation. Generally, though, we can indicate the direction of the market shift.

For this exercise, we assume that CFCs are implicitly raised in price either by tax, production limits, or permit systems, and we further assume that the price rise is made in accordance with CFC-12 having only 0.79 the damage potential of CFC-11. We know that extruded PS board has approximately ten percent CFC-12 by weight, that rigid urethanes have about 11 percent CFC-11 by weight, and that EPS board has no CFC. Furthermore, we find close product competition for insulation applications among these three foams. Given these assumptions, we would expect to see an increase in the use of EPS board with a CFC price increase and would expect to see a decrease in the use of rigid urethane boardstock.

Whether extruded PS board demand would increase or decrease is uncertain: When competing against rigid urethane, extruded PS board will be less expensive. It uses less CFC per pound of insulation and uses CFC-12 (with less ozone damage potential) and so would have a smaller tax or relative price rise compared with foams using CFC-11. Even though it has a lower R value, its other chemical costs are cheaper. More relevant is the fact that it competes in most construction insulation markets today. If CFC faces an explicit or implicit tax, extruded PS board would be in a better market position than rigid urethane boardstock.

Extruded PS board also competes at the present time with EPS board. The former is stronger and has a better R factor. If the cost of CFC-12 increases, extruded PS board will cost more and will lose market shares to EPS board. An unknown factor in the competition is that extruded PS board has manufacturing and physical advantages over EPS board, independent of its superior CFC-induced insulating value. The extrusion process is continuous, with increasing economies of scale. The process produces a stronger product with low moisture permeability and has a lower labor cost component. On the other hand, resultant centralized production facility would lead to higher transportation costs. Therefore, it is hard to judge how the extrusion process would fare in the market if extruded PS board were made only with a non-CFC blowing agent such as methyl chloride.

We did find product substitutes or alternative insulation systems in most application areas for extruded PS board, however. Some substitutes, such as EPS board, use no CFC. We conclude, therefore, that adequate substitutes or systems are available, with installed price and overall performance that could displace a CFC-blown extruded PS board in most applications.

In control technology and work practice areas, we were unable to determine what emissions control prospects exist. We know, from Rand’s earlier study, that approximately ten percent of the CFC-12 used is released during manufacturing. Dow Chemical reports to have “looked at recovery but it was not promising.” We assume that to mean that they examined the entire process, including recycle of scrap and emissions from the extrusion process. Emissions control upon product disposal, again, as in rigid urethane foam, appears uneconomical because of the large labor, transportation, and monitoring costs of collecting the used product. Thus we judge that no control or work practice technologies appear likely for reducing CFC-12 emissions in extruded PS board. A summary of emissions reduction options for extruded PS board is shown in Table 2.3.
### Table 2.3
**Emissions Reduction Options: Extruded PS Board**

<table>
<thead>
<tr>
<th>Tactic</th>
<th>Annual Amount (1976 Basis)</th>
<th>Level of Dislocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substitute blowing agent</td>
<td>Small</td>
<td>Moderate&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Product substitutes</td>
<td>Small</td>
<td>Small-Moderate</td>
</tr>
<tr>
<td>Control technology: recovery of manufacturing emissions</td>
<td>Very Small</td>
<td>Moderate</td>
</tr>
<tr>
<td>Disposal emissions control</td>
<td>Small</td>
<td>Moderate-High</td>
</tr>
</tbody>
</table>

<sup>3</sup>Small if a process to make an adequate substitute is found.

### EXTRUDED PS SHEET

Rand's earlier study reported that 13 million pounds of CFC-12 were emitted from the production of extruded PS sheet in 1976. Three factors provide the opportunity for large emission reductions at small to moderate dislocation in the manufacturing and use of extruded PS sheet.

Substitute blowing agents could virtually eliminate CFC use and emissions. Product substitutes could replace extruded PS sheet in almost every application with some amount of performance degradation. Collection and recycle of CFC-12 used in manufacturing is the third technical option; it could cut emissions approximately in half.

Extruded PS sheet currently uses either pentane or CFC-12 as blowing agents in its manufacture. Thus, the issue of alternative blowing agents for this foam product is relatively clear. In recent years the shift has been toward the CFC production process. In the early 1970s about 50 percent was CFC blown. By the late 1970s, CFC had increased its market share well above 60 percent.

This shift toward CFC is a result of a slight economic margin in favor of the CFC blown product, mainly because it can be made lighter and therefore is less plastic-material consumptive, and because pentane poses serious fire hazards, and fire hazard protection and insurance costs are incurred. An important factor working against pentane is air quality regulations, which can require collection and destruction of pentane vapors in pentane blown extrusion production.

Claims that pentane is inferior as a blowing agent in extruded PS sheet are based on the allegations that pentane produces higher scrap rates, higher densities resulting in from five to 25 percent more weight per product, and lower structural strength products. These criticisms were not denied by one pentane user. These deficiencies appear to be irrelevant to the issue of whether or not pentane blown products are viable economically, since a number of major manufacturers do use pentane and their pentane products compete in virtually all applications of extruded PS sheet. We must conclude that the overall economics of production are very close.

In high temperature applications, the CFC blown product is preferred, because the CFC
has a less plasticizing effect than pentane in the blown extruded PS sheet. But generally, the pentane blown sheet competes in each application with a CFC blown sheet.

While pentane is commonly used as a blowing agent, individual plants currently using CFC are unlikely to find pentane a suitable substitute without substantial plant modification or total plant rebuilding to reduce the fire hazards associated with its use. Building a new plant would require capital costs on the order of a million dollars. In addition to plant engineering and construction costs, the necessary skills to operate under the fire hazardous environment would have to be learned or transferred, at significant costs. While there is no proprietary technology involved with designing and constructing an extruded PS sheet line that uses pentane, the work place procedures and the trouble-shooting during the startup may be costly.

Other possible blowing agents are the CFC-12 substitutes such as CFC-124 and CFC-134a. As mentioned earlier, efforts to invent a commercial manufacturing process for CFC-124 have ceased. Development work is continuing on CFC-134a, although no commercial process yet exists. Given the likelihood of substantially higher costs for CFC-134a even when produced, we do not feel that a CFC substitute blowing agent is economically viable for extruded PS sheet. CFC-22 works well in extrusion but, because it is a solvent in polystyrene, cannot make a foam sheet with the necessary rigidity.

Our interviews confirmed that the half-life of CFC-12 in extruded PS sheet is rather short, about six months. Thermal conductivity is not a major physical asset in most extruded PS products.

A chemical control technology—collecting and recycling CFC-12 emissions—is available and economical at today's prices. Rand's early study noted that industry reported likely prospects for an economically viable system that might recover 50 percent. Recent interviews have confirmed this prospect. The recoverable percentage is unknown at present, partly because the procedure has never been tried commercially. One system has been designed and is reported to be under construction.

A typical extrusion line may experience a 15 percent emission rate of CFC during the regrinding of scrap, an 11 percent rate at the thermoformer, about 30 percent from the extruder, leaving about 40 percent in the finished product. The difficulty and cost of collecting CFC vapors at each location is still unclear. A device to collect vapors at the extruder has so far defied invention. The decision to collect CFC-12 at any point in the manufacturing process must be made point by point, given the costs of the collector and the amount of CFC-12 collectible.

In addition to collection and recycle, fine tuning of the feedback control systems regulating the CFC and other chemicals and regulating the thermoforming are work practice options that could theoretically reduce emissions significantly.

Measurements of emissions have indicated up to 40 percent loss of CFC input in the extrusion process. One report pointed out that this is indicative of a bad extrusion process, lack of proper equipment, and poor chemical process management. Losses at the extrusion should theoretically be zero, but practically can be kept to five percent. The best technology in equipment and control systems (i.e., improved process management) combined with collection of scrap vapors might reduce typical emissions by some 30 percent. The economic balance between fine tuning costs, feedback control costs, capital equipment costs, and CFC-12 collection and recycle is unknown.

Overheating in thermoforming can burst the cells and release CFC. To achieve the same

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performance more polystyrene and CFC must be put through the system. Feedback control systems and new designs in thermoforming have always been areas for improvement. Under an ideal system, no CFC is released in thermoforming. Practically, the ideal system does not exist and is costly to even approach. It may prove more economical to capture CFC vapors at this point of the process than to design and operate improved thermoformers.

We understand that the CFC blown product is probably slightly cheaper and has slightly superior physical characteristics if the CFC line is run under the best of operating conditions. The average production line using CFC may not be managed optimally, nor may the particular equipment be capable of achieving the ideal production process. These add to costs and emissions, which might be why the pentane blown product is competitive.

Because of the varied applications for extruded PS sheet, product substitutes are not a clear emissions reducing option. Clearly, in some applications product substitutes exist that can meet the physical and price performance of extruded PS sheet. However, in other areas the physical demands of the application virtually require the plastic foam.

Wood fiber products have long been used in food service applications. One major manufacturer started with the fiber business and now has expanded into extruded PS sheet. Certain markets have been shifting, demand for fiber product has been dropping, and plastic foam has been increasing because of its fundamental physical advantages. No clear cut price (or energy) advantages seem to exist for either product. Costs of manufacture are very similar; transportation costs are marginally better for wood fibers. The primary criterion determining which sells in which market is physical performance.

The meat and fish tray market has quickly gone to extruded PS sheet because the plastic is hydrophobic (absorbs no moisture). An absorbent pad can pick up some meat juices. Fiber trays become moisture filled, lose strength, and are unsightly, and in freezing can adhere to the meat. A thin plastic film could be bonded to a wood fiber tray to improve its competitiveness, but even so the plastic foam tray has distinct advantages and would be difficult to displace from its market.

In the fresh produce market, the respiration of wood fiber trays is used to advantage. Both products are viable here but the wood fiber product has the advantages. In the egg carton market, both products compete equally. Here we can claim that adequate product substitutes do exist with little dislocation. One manufacturer claims that the extruded PS sheet egg carton has the edge with longer shelf life and fewer breakages, but we have not confirmed this. Another claims that design, whether fiber or foam, is the factor on controlling breakage. Both products compete in the market for disposable plates and dishes used in fast food eating places and hospitals. Fiber trays have advantages where the food is heated in a microwave oven, since fiber has better temperature resistance. Polystyrene foam is better in cold applications.

In addition to performance factors, economic factors that influence the final product cost to the consumer also drive the demand in each application in each area of the country. Wood fiber production is more capital-intensive. For items with short production runs, the business tends to prefer extruded PS foam sheet. Round items are more efficiently made with wood fiber, since no scrap is involved. Small items tend to be more efficiently made in plastic; larger items are more economically made in wood fiber. Direct energy costs of wood fiber are higher, although the petroleum feedstock and the energy to make plastics may be large and even exceed the wood fiber process. Transportation costs and delivery time are other factors that vary regionally.

With all the competition between extruded PS sheet and wood fibers, no blanket conclusions on product substitutes can be made. Each application and geographic location has dif-
different product substitutes, some easy with small dislocation, others hard with moderate dislocations. Because product substitutes do exist, the dislocations involved in shifting away from extruded PS sheet would range from small to moderate.

To summarize, pentane is being used commercially today as a substitute blowing agent in extruded PS sheet. It competes on economic and physical performance measures against the product blown with CFC-12. We learned that the CFC process has a slight advantage economically, if the production process is skillfully designed, constructed, and operated. (We do not know the relationship between capital charges or operating costs with CFC or pentane manufacturers.) We do not have enough information to determine how high CFC prices would have to rise to make it economically advantageous to shift to pentane. Substantial capital costs are necessary to convert or rebuild a production line using CFC to one using pentane.

The CFC half-life is short and the diffusion rate is relatively quick for extruded PS sheet. Extruded PS sheet emits virtually all the CFC-12 within the year after manufacture. No new information was uncovered during this research to change our perceptions of these issues.

Product substitutes for extruded PS sheet are plentiful but not currently preferred in some applications. Woodfiber products currently compete with the plastic foam. Important product characteristics differentiate the various application areas and the substitutability of the nonplastic foam products. Thus, product substitution is clearly a feasible CFC emission reduction option in a limited group of product applications.

The previous Rand report discussed the prospect of control technologies to recover CFC-12 during and after manufacture of extruded PS sheet. Engineering designs and cost analyses are reported to now show that recovery is economical for perhaps 50 percent of the CFC-12 used in the production process. The exact amount of CFC recaptured, the cost savings, and the particular production facilities that might economically install a recapture system are unknown at this time. We understand that at least one manufacturer of extruded PS sheet is testing a variety of the system components in anticipation of installing a recovery system. Emissions reduction options for extruded PS sheet are given in Table 2.4.

### Table 2.4

<table>
<thead>
<tr>
<th>Tactic</th>
<th>Annual Amount (1976 Basis)</th>
<th>Level of Dislocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substitute blowing agent</td>
<td>Large</td>
<td>Small&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Product substitutes</td>
<td>Medium</td>
<td>Moderate</td>
</tr>
<tr>
<td>Control technology: capture and recycle</td>
<td>Small-Medium</td>
<td>Small-Moderate</td>
</tr>
</tbody>
</table>

<sup>a</sup>Small nationwide, but severe for some individual enterprises.
OTHER NONURETHANE RIGID FOAMS

Other products (specifically the extruded polyolefins) that use CFC in their manufacture were not studied further. The previous Rand study found that virtually all the CFC used was released in the first year after manufacture and found that no suitable alternative blowing agent was available. Thermal conductivity is not an issue with these foams. Product substitutes do exist but the competitive strength of the CFC product is unknown. Limited evidence collected during this study confirmed these conclusions.
Chapter 3

SPECIALTY USES OF CHLOROFLUOROCARBONS

I. Introduction and Summary

We have investigated the use of chlorofluorocarbons (CFCs) in liquid food freezing (LFF), as a sterilant-diluent, and as a separation medium in coal cleaning. In 1976 no significant emissions occurred from coal cleaning, whereas about six million pounds were emitted from food freezers and 13 million pounds from sterilizers. Emissions during LFF were expected to increase substantially during the following years because of expanded use of CFCs in the freezing of meat products, but this has failed to occur. LFF uses cold liquid CFC-12 as a direct immersion fluid for the freezing of vegetables, fruits, and seafood. Coal cleaning employs CFC-11 as an ambient temperature separation medium, whereas sterilant usage employs CFC-12 as a diluent of ethylene oxide gas.

The emissions in LFF and sterilization are prompt, whereas those from CFC cleaned coal may be delayed for a few months. In LFF, the emissions occur through dragout of freezeant on product and vapor losses from the freezing unit. In coal cleaning, CFC emissions occur from the float liquid retained on the cleaned coal and on the refuse. In sterilization, emissions occur when the 12 percent CFC-12/88 percent ethylene oxide sterilizing gas (12/88) is vented to the atmosphere after use.

In a previous study (Palmer et al., 1980), Rand identified several feasible technical options for reducing CFC emissions in these use areas. In LFF, the most important was to not overload the freezer units. Sterilant emissions were thought to be reducible through increased use of nondiluted ethylene oxide or carbon dioxide diluent, recycling of the sterilant gas, or use of low pressure/longer sterilization cycle units. The reduction of coal cleaning losses was not considered.

The present investigation has sharpened these perceptions. In LFF, increasing the use of surge bins or other rate-leveling devices and increasing freezer cooling capacity should reduce overloading somewhat. This may be most applicable in operations where several processes draw on the same refrigeration system. LFF emissions may also be reduced by carbon adsorption recovery systems. No such systems are currently in place, but at least one is under development and undergoing the critical adaptation for use with CFC-12. Cryogenic freezing of food products with either liquid nitrogen or carbon dioxide is technically feasible, although high energy-related costs have driven the former from serious consideration. Carbon dioxide freezing is often more expensive than CFC freezing, increasing the cost of hamburger, for example, by about 1¢ per pound. Mechanical (air blast) freezing is a good substitute process for producers considering replacement of their CFC equipment or expansion of their freezing capacity. It is generally a cost effective approach to freezing vegetables and meat, although there is some concern over a degradation of flavor. The substitution of CFC-22 and CFC-115 freezeants for CFC-12 was considered but found to be impractical. CFC-22 would create severe food certification problems and CFC-115 is expensive relative to the air blast alternative and may be difficult to use technically.

In large industrial sterilization, CFC-12 emissions may be reduced by at least 70 percent
per cycle by recycling and reconstituting the 12/88 sterilant gas. At least one self-contained unit is commercially available now, and another system employing tank storage followed by reclamation and reconstitution to acceptable sterilization standards is under development. The use of pure ethylene oxide by large industrial operators could reduce CFC emissions further but at an increased risk of flammability. Substitution of other diluent gases for CFC-12, notably CFC-22 and CO₂, is technically feasible. However, the mixtures of these gases with ethylene oxide will fractionate, creating a need for large expansion chambers. In addition, the lower ethylene oxide content of these gas systems more than doubles sterilization times. High energy gamma or electron radiation sources may also be used to sterilize a small fraction of goods presently sterilized by CFCs, but the application is limited because many of the polymers used in medical goods cannot tolerate the radiation.

CFC-11 emissions from coal cleaning operations are projected to reach about five million pounds per year by the mid-1990s. The specific emission rate is very low in this process—only one-tenth pound of CFC per ton of raw coal—because carbon adsorption units are used to recycle the CFC and prevent economically unacceptable losses. (By comparison, current LFF units lose about 30 pounds of CFC per ton of food frozen.) The major alternative to this CFC process is the continued use of present methods such as hydrobeneficiation, although at the cost of unimproved sulfur, ash, and refuse slurry pond pollution. Of the pure halocarbons, only CFC-113 appears as a possible substitute, but our sources claim that its higher viscosity (60 percent greater than CFC-11) creates mechanical problems with present pumps and offers only a small improvement in ozone depletion potential.

In Table 3.1, we present our estimates of the potential emission reduction capability of each of the control options analyzed. As discussed in Chapter 1, we have evaluated this emission reduction in terms of CFC-11 equivalents and then semi-quantitatively categorized the results as small, medium, or large. The reduction estimates for coal cleaning are unique in this table because they have been made for an optimistic projected market rather than an existing one. Because the CFC-132b substitute option in coal cleaning is technically very difficult to introduce and the option of continued use of hydrobeneficiation would eliminate the sole CFC coal cleaning company, these options were excluded from Table 1.1 in Chapter 1. Table 1.1 does not include any of the other technical options from the specialty use category because the potential emissions reductions are all small.

Certain options in the LFF and sterilant categories would lead to relatively large dislocations upon their introduction. Air blast freezing would not be disruptive for producers considering expansion of freezing capacity but would be expensive if used only to replace existing equipment. Cryogenic freezing (with CO₂) would also lead to large dislocations if used to replace existing equipment. The introduction of alternative freezants would probably have great difficulty achieving FDA approval as well as require considerable freezer redesign. In the case of increased use of pure ethylene oxide sterilant or carbon dioxide diluent, users would experience moderate to large dislocations in the design requirements and costs of the gas containment systems.
<table>
<thead>
<tr>
<th>Technical Option</th>
<th>Potential Emissions Reduction&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFF</td>
<td></td>
</tr>
<tr>
<td>Rate-Leveling Devices/Enhanced Cooling</td>
<td>Very Small</td>
</tr>
<tr>
<td>Carbon Adsorption</td>
<td>Small</td>
</tr>
<tr>
<td>Air Blast Freezing&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Small</td>
</tr>
<tr>
<td>Cryogenic Freezing</td>
<td>Small</td>
</tr>
<tr>
<td>Alternative CFC Freezant&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Small</td>
</tr>
<tr>
<td>Coal Cleaning&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Substitute Float Medium</td>
<td></td>
</tr>
<tr>
<td>CPC-113</td>
<td>Small&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>CPC-132b</td>
<td>Medium</td>
</tr>
<tr>
<td>Hydrobeneficiation</td>
<td>Medium</td>
</tr>
<tr>
<td>Sterilants</td>
<td></td>
</tr>
<tr>
<td>Recycling of 12/88 Sterilant</td>
<td>Small</td>
</tr>
<tr>
<td>Pure Ethylene Oxide</td>
<td>Small</td>
</tr>
<tr>
<td>Substitute Diluent Gas&lt;sup&gt;f&lt;/sup&gt;</td>
<td>Small</td>
</tr>
<tr>
<td>Radiation</td>
<td>Very Small - Small</td>
</tr>
</tbody>
</table>

<sup>a</sup>Based on CFC-11 equivalents.

<sup>b</sup>Liquid carbon dioxide or nitrogen; energy demands and costs favor carbon dioxide, however.

<sup>c</sup>CFC-115 or CFC-22.

<sup>d</sup>Potential emissions reductions based upon capture of one-sixth of the current hydrobeneficiation market in the mid-1990s.

<sup>e</sup>CFC-113 provides for a smaller emission reduction than CFC-132b because CFC-113 is assumed to have a much higher ozone depletion factor.

<sup>f</sup>Carbon dioxide or CFC-22.
II. Liquid Food Freezing

INTRODUCTION

Liquid food freezing employs a ten-year-old process developed by DuPont in which food to be frozen is immersed directly in purified R-12 (CFC-12) at \(-22^\circ\)F. Foods frozen by this process include berries, fish, cob corn, onion rings, shrimp, and meat patties. The R-12 is vaporized as the food freezes and the vapors are condensed by overhead cooling tubes for recycle. Uncondensed vapor losses, dragout of freezant on frozen product, and machine cleaning losses are the principal sources of emission, leading to a total estimated emission rate of six million pounds per year (1976). Regardless of emission source, it is important to note that all CFC-12 used in LFF is ultimately emitted to the atmosphere.

Even a short time ago it was estimated that CFC use in LFF was likely to increase substantially. Forecasts of CFC consumption by 1985 provided by DuPont in 1977 to 1978 suggested that use could increase from six million to 18 million pounds primarily because of a large anticipated increase in the raw and cooked frozen meat market. However, the most recent information from DuPont (December 1990) indicates that this trend is not developing. CFC-12 use is steady or decreasing as evidenced by the recent lack of new equipment installation. Mechanical cold air blast methods are providing an alternative (discussed below), apparently because the unit operating cost of air blast methods used to freeze meat is about 50 percent less than the comparable figure for LFF. Similarly, mechanical freezing is now perceived by the quick frozen vegetable industry as the cheapest approach, so there is little potential for the expanded use of LFF in this sector.

As determined by Rand in our previous study, the major users of LFF are Green Giant (Le Sueur, Minnesota), General Foods (White Plains, New York), Booth Fisheries (Chicago), National Sea Products (Florida), Stayton Canning and Flavorland Foods (Oregon), Wilson Foods (Oklahoma), Heying Foods (Iowa), as well as a number of shrimp producers on the Gulf Coast.

Green Giant is a subsidiary of the Pillsbury Company (Minneapolis) and uses LFF to freeze cob corn, green beans, and peas. They chose the LFF process primarily to freeze cob corn but used it later to freeze green beans and peas in an attempt to reduce the idle time of the LFF equipment. In this capacity, the Pillsbury Company is the largest single domestic user of CFCs for LFF with 1980 CFC-12 purchases of 1,495,370 pounds, an amount equivalent to 25 percent of all the CFC-12 used for LFF in 1976 (Pillsbury, 1981). This use occurs during harvest only, over the period of June through September (peas, June-July; beans, July-August; corn, August-September). The CFC LFF systems represent 32 percent of Pillsbury’s total installed freezing capacity and were installed over the period of 1969-1973 at a cost of $45 million. While Pillsbury dominates in the use of CFC fast freezing to freeze cob corn, it is noteworthy that 55 percent of frozen cob corn is produced competitively by other methods.

THE LFF PROCESS

The use of CFCs in the fast freezing of food is exemplified in the quick freezing of cob corn. To provide background on the sources of CFC emissions, we present the details of the LFF process in this particular application.
Sweet corn is delivered to the plant over a period of 42 to 60 days, depending on weather conditions. With little delay it is washed and conveyed to a dehusking machine and then visually classified for either frozen cob or cut corn processing. After the ends of the cob are trimmed, the corn passes into a surge bin that provides a constant rate of feed to the subsequent LFF steps. When the harvest is short and delivery to the processor is rapid, the rate of flow of corn through early processing steps may exceed the capacity of the LFF units. The surge bin alleviates this problem by storing partially processed corn until there is a break in deliveries from the field and the LFF units have a chance to catch up. Without the surge bin, the corn continues on to the LFF unit and overloading may occur.

From the surge bin the corn passes into a blanching unit where steam raises its temperature to 140°F (to inactivate enzymes that would shorten shelf-life). Next, it passes through an evaporative cooler, dropping the surface temperature to 70-80°F, and then enters the LFF unit. The lower surface temperature reduces the cooling demand on the LFF unit and probably lowers the CFC emission rate.

The LFF units (either Lewis products or DuPont prototypes) are enclosed and each freezes about 15,000 to 25,000 pounds of product per hour. The corn enters on a knobbled conveyor belt that is steeply inclined and then falls into a pool of liquid CFC-12. It floats on this pool for a few seconds and then falls onto a metal mesh conveyor belt. Spray heads above the belt freeze the food product with liquid CFC-12. Below the belt is the collecting area and sump. The CFC-12 that is vaporized during freezing is condensed by a set of ammonia-cooled tubes located above the spray heads and returned to the sump for recycle. The residence time required for freezing is about nine minutes.

At the exit end of the LFF unit, no spray heads are present and the conveyor is inclined upward, thus providing for CFC drain-off from the corn. There are no extra condensing units or collecting vents at the exit in currently operating units. Upon leaving the LFF unit, the frozen corn passes on to the packaging operation.

EMISSIONS

Palmer et al. (1980) estimated that total emissions from LFF operations in 1976 were about six million pounds of CFC-12. These result primarily from the freezing of vegetables, fruit, meat, and seafood. Fruit and vegetable freezing accounts for 60 percent of the CFC use with most of the remainder equally divided between meat and seafood freezing. In the case of frozen corn, data are available that give the approximate emission rates of CFC per unit of product frozen over a six year period as well as the total consumption of CFC for each of these years (Table 3.2).

These data reveal a long-term trend toward a lower rate of CFC emission per ton of product frozen. This has occurred even though production has increased considerably over the past four years. The equipment upon which these figures are based, according to industry sources, has undergone some modification, starting in about 1977, to reduce CFC losses.

It is important to note that the fruit and vegetable industry is highly seasonal, which accounts for much of the variability in the historical CFC emission rates. The most important effect is the variable rate at which the crop matures and is delivered to the processor. If the rate is too high, the produce will overload the LFF freezers increasing the dragout and vapor losses. Some producers (such as Pillsbury) attempt to smooth out the delivery rates by staggering the time of spring planting. However, by the time harvest arrives, local variations in
Table 3.2

HISTORICAL USE AND EMISSION OF CFCs
IN THE LFF OF COB CORN
(In pounds)

<table>
<thead>
<tr>
<th>Year</th>
<th>Consumed</th>
<th>Emitted/Ton Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td>950,000</td>
<td>38.2</td>
</tr>
<tr>
<td>1976</td>
<td>780,000</td>
<td>43.4</td>
</tr>
<tr>
<td>1977</td>
<td>1,850,000</td>
<td>39.6</td>
</tr>
<tr>
<td>1978</td>
<td>1,336,000</td>
<td>27.2</td>
</tr>
<tr>
<td>1979</td>
<td>1,495,000</td>
<td>34.6</td>
</tr>
<tr>
<td>1980</td>
<td>1,495,000</td>
<td>27.0</td>
</tr>
</tbody>
</table>

weather may alter the expected maturation schedule and occasionally lead to a fluctuation in which most of the crop matures within a narrow span of time. This is reflected in harvest times for corn that vary from as little as 42 days to more than 60 days. To a minor degree, weather may also have an effect, altering the water content of the corn and cob size, leading to increased mass, increased cooling demand, and enhanced chances for overloading. Thus, given the same equipment, a producer cannot always achieve the lowest emission rate appearing in Table 3.2.

The losses appearing in Table 3.2 occur over the average operating time of 900 hours per season. Massive losses of freezant are extremely rare and represent only a negligible contribution to the data. Vapor losses, dragout losses, and cleaning losses are all included in these data; no breakdown of these losses is available. In the case of cob corn production, there is no time at which the entire charge of CFC is replaced with new material and the old charge emitted to the air.

CFC usage in the meat (beef and pork) and seafood (primarily peeled and deveined shrimp) industries amounted to one million pounds each in 1976. Emission rates for these industries are summarized in Table 3.3. These figures are valid for 1978 and do not reflect historical losses. However, seafood industry sources have stated that equipment modifications have been taking place over the last few years with a consequent drop in the emission rate. For example, one major shrimp producer now reports a loss rate of 40 pounds per ton of product frozen.

The variability in these loss rates is high when comparing various companies or various seasons. This is because the loss rate increases considerably when more product is frozen per unit of time, and this in turn depends on the rate of food delivery to the company and demand for the product. More perishable items, such as raw shrimp, must be processed immediately and are therefore more likely to lead to freezer overload (and higher CFC loss rates) than less perishable or preprocessed items, such as cooked shrimp, where the rate of flow to the CFC freezer can be smoothed out in earlier processing steps.
Table 3.3  
**EMISSION OF CFCs IN THE LFF OF BEEF, PORK, AND SHRIMP (1978)**  
(In pounds)  

<table>
<thead>
<tr>
<th>Product</th>
<th>Emitted/Ton Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shrimp (raw or cooked)</td>
<td>50.0</td>
</tr>
<tr>
<td>Beef patties (raw)</td>
<td>36.0</td>
</tr>
<tr>
<td>Pork patties (cooked)</td>
<td>60.0</td>
</tr>
</tbody>
</table>

CONTROL OF EMISSIONS

Several control methods may be considered for the reduction of CFC emissions from existing CFC food freezers:

- Use of surge bins to reduce overloading of the LFF units.
- Evaporative cooling of the product before freezing to reduce cooling demand on and evaporative losses from the CFC freezer (largely in place).
- Expansion of refrigeration capacity in large facilities where several processes, including the CFC condensers in the LFF units, draw on the same refrigeration system.
- Use of carbon adsorption to capture and recycle vaporized freecant.
- Substitution of an alternative freecant for CFC-12 (technically difficult).

In addition, CFC emissions could be reduced by replacing the LFF system with an alternative system, specifically

- Mechanical (air blast) freezing; or
- Cryogenic freezing employing liquid nitrogen or carbon dioxide.

Work Practices and Control Technologies

We have considered modifications of work practices and the introduction of new control methodologies that might reduce CFC emission rates in LFF. Improved work practices with present equipment cannot significantly reduce emissions, since the process is highly automated. However, new control technologies along with changes in work practices could be introduced to effect such reductions. These are discussed in the next two sections.

**Surge Bins/Evaporative Cooling.** The surge bin is a relatively simple device that can level the feed rate to the LFF unit. At Green Giant's Glencoe, Minnesota, facility, for example, the feed rate to the surge bin may vary by a factor of two or more. In one design, the surge bin is a flat container that is filled to various distances behind the withdrawal edge (depending on the feed rate of food to be frozen) by a variable backing shuttle conveyor. It works to smooth out fluctuating rates of delivery only over a period of several hours, so if harvesting rates are consistently high for days, even the surge bin will not prevent overloading. If overloading occurs frequently, the producer has to either increase his surge bin capacity (although space consideration is a limiting factor) or increase the capacity of the LFF unit itself (where capital investment is limiting).
Green Giant installed surge bins in the 1977 to 1978 season. Unfortunately, determining the magnitude of the emissions reduction attributable to this device is difficult to achieve by analysis of the type of data shown in Table 3.2; other modifications in the freezing operation as well as weather-driven variances in hours of idling time, shut-down, and vegetable heat content tend to obscure that information. However, historical CFC use data suggest that the major steps taken at Green Giant to reduce CFC emissions—introduction of surge bins and enhanced refrigeration capacity—have collectively reduced the CFC use ratio from 40 pounds per ton of product (average over the 1975 to 1977 seasons) to 30 pounds per ton (average over the 1978 to 1980 seasons). In other words, these steps have reduced CFC emissions per ton by 25 percent. This degree of CFC savings is peculiar to the Green Giant operation and location and only crudely suggestive of savings that might be obtained elsewhere. Other producers may have far more (or less) variable crop maturation and delivery rates, which would enhance (or depress) the effects of surge bins. In addition, other producers may have less non-LFF demand on their refrigeration systems and would gain little by increasing capacity.

The use of surge bins in the fast freezing of fruit seems technically feasible, provided the bin design spread the fruit and prevented bruising. However, useful implementation of this procedure is limited, since similar current practices accomplish the same end. For example, much of the fruit frozen on the West Coast is held in chill rooms for hours or even days, allowing the operators to withdraw fruit at a rate that prevents overloading of their freezers.

**Carbon Adsorption.** To our knowledge no food producer currently employs carbon adsorption to recover and recycle the CFC-12 vapors that escape from a CFC freezer. However, that technique is under active consideration at one of the major processing plants where the developers believe that it can recover at least 50 percent and perhaps as much as 90 percent of the vapors now being emitted. On the other hand, DuPont feels that a more realistic range is 30 to 60 percent. If no serious pitfalls were encountered and if carbon adsorption were used in all segments of the LFF industry, then, with 1976 use figures, this amounts to an emission reduction of between 3.0 and 5.4 million pounds of CFC-12 annually. The principal uncertainty of this process is the adaptation for use with CFC-12. Most previous experience has been with lower vapor pressure solvents and some critical engineering design and demonstration are required before feasibility is assured for LFF.

The design concept is similar to that used for vapor phase degreasers in the CFC solvent application. Lip vents would be installed at both the inlet and outlet ports of the machine. Some air flow would be established in these areas to draw the CFC vapors toward a carbon adsorption unit. Presumably at least two carbon beds would be employed so that one unit could be trapping vapors while the other was desorbing. The desorption would be accomplished by treating the carbon with steam. In many food processing operations, steam sources are already present with some excess capacity, so the introduction of carbon adsorption methods does not necessarily require the simultaneous investment in a new steam plant.

**Chemical Substitutes for CFC-12 Freezant.** Replacing CFC-12 with an alternative freezant in existing LFF equipment is another approach to emission reduction. Of all the currently available CFCs (11, 12, 22, 113, 114, and 115), only CFC-22 and CFC-115 have boiling points sufficiently low (at 1 atm) to provide the desired cooling (the others boil at 39°F or higher). The physical and toxicological properties of these compounds are shown in Table 3.2.

---

1This includes not only a scale-up of their ammonia refrigeration system (compressor, evaporator, etc.) but also emplacement of the maximum number of condensing tubes that can line the surface of the LFF freezer.
3.4. While CFC-22 presents a lower ozone threat than CFC-12 and with some equipment modification might be suitable for heat transfer, it has failed the Ames assay for mutagenicity\(^2\) and would be highly unlikely to gain FDA approval for LFF. Other short-term as well as long-term whole animal toxicity studies are soon forthcoming (conducted under the aegis of Imperial Chemical Industries for a consortium of European producers), but even if these fail to demonstrate a mutagenic response, FDA approval would still be difficult to obtain. Also, producers such as DuPont question whether they would find the cost and effort of approval worthwhile for such a limited market, particularly when the air blast alternative exists for many users.

Somewhat more favorable is the possibility of substituting CFC-115 for CFC-12. Its boiling point is low enough to freeze products; it has an ozone depletion factor that is about one-fourth that of CFC-12; its liquid density and viscosity are very similar to CFC-12, thus ensuring compatibility with existing LFF pumps; and its low surface tension suggests good contact with the article to be frozen. Of greatest importance, however, are its low toxicity, non-flammability, and existing FDA approval for its use as a food propellant.

However, these attributes are offset by three factors. First, it may be difficult to condense CFC-115 in existing CFC-12 freezers. Because the boiling point of CFC-115 is 16°F lower than that of CFC-12, the ammonia-filled condensers in present LFF units would operate on a smaller temperature difference, leading to poorer condensation efficiency and higher vapor losses, unless they were replaced or modified. Second, the lower boiling point of CFC-115 may make it freeze certain vegetables too quickly, causing the rupture of thin-skinned varieties. Third, the cost of CFC-115 is higher. Its current price is about three times that of CFC-12 and would lead to a large increase in unit operating cost. For example, for hamburger and a CFC loss rate of 36 pounds per ton of product, the use of CFC-115 in a year-round operation would lead to a cost increase of nearly 3x per pound of product (plus any costs incurred from modifying the refrigeration unit to condense CFC-115). This is significant because it would generally drive the unit operating cost above that for liquid nitrogen or carbon dioxide and severely diminish the competitiveness of LFF with these methods (see Table 3.5, bottom line and footnote).

Of the alternative CFCs (21, 31, 32, 123, 124, 125, 132b, 133a, 134a, 141b, 142b, 143a, and 152a), only CFC-32, 125, 134a, 143a, and 152a have boiling points in the range of CFC-12 or below. However, CFC-32, CFC-143a, and CFC-152a are flammable and are therefore unlikely substitutes. CFC-125 is an improbable substitute in view of the present absence and small near-term likelihood of developing a good commercial manufacturing process (DuPont, 1980b). CFC-134a with a boiling point of -16°F is a possibility but this too has no good manufacturing process, although work continues on developing one. In addition, toxicological testing has not been completed on this compound and even if favorable results were obtained, FDA approval would still have to be gained. Thus, no good alternative CFC for LFF appears to exist or to be on the horizon in the near term.

Air Blast and Cryogenic (Liquid Nitrogen and Carbon Dioxide) Freezing as Product Substitutes

Air blast freezing occurs when air is passed over refrigerated coils to reduce its temperature to -20°F or slightly less and is then directed upward through one or two mesh belts and

\(^2\)This is a sensitive biological test that examines a chemical for its ability to mutate a cell from a state where it cannot synthesize an essential nutrient (amino acid) to a state where it can.
Table 3.4

COMPARISON OF PHYSICAL PROPERTIES, TOXICITY, AND COSTS OF POTENTIAL FREEZANTS

<table>
<thead>
<tr>
<th>Property</th>
<th>CFC-12</th>
<th>CFC-22</th>
<th>CFC-115</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling point (°F)</td>
<td>-21.6</td>
<td>-41.4</td>
<td>-37.7</td>
</tr>
<tr>
<td>Density (liq, g/cc)</td>
<td>1.31</td>
<td>1.19</td>
<td>1.29</td>
</tr>
<tr>
<td>Density (sat'd vapor at b.p., g/l)</td>
<td>6.33</td>
<td>4.72</td>
<td>8.37</td>
</tr>
<tr>
<td>Specific heat (liq, cal/g/°C)</td>
<td>.232</td>
<td>.300</td>
<td>.285</td>
</tr>
<tr>
<td>Heat of vaporization (at b.p., Btu/lb)</td>
<td>71.0</td>
<td>100.4</td>
<td>54.2</td>
</tr>
<tr>
<td>Thermal conductivity (liq, Btu/hr/ft/°F)</td>
<td>.041</td>
<td>.051</td>
<td>.030</td>
</tr>
<tr>
<td>Viscosity (liq, cp.)</td>
<td>.21</td>
<td>.20</td>
<td>.19</td>
</tr>
<tr>
<td>Surface tension (dynes/cm)</td>
<td>9</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Ozone depletion factor</td>
<td>79</td>
<td>5</td>
<td>20</td>
</tr>
</tbody>
</table>

Toxicity

<table>
<thead>
<tr>
<th>TLV (ppm)</th>
<th>Other</th>
<th>FDA approval for LFF</th>
<th>Weak mutagen (positive Ames assay)</th>
<th>FDA approval for food propellant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td></td>
</tr>
</tbody>
</table>

Flammability

<table>
<thead>
<tr>
<th>Cost ($/lb, Oct. 1981)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(bulk, food grade)</td>
</tr>
<tr>
<td>0.75</td>
</tr>
<tr>
<td>(bulk)</td>
</tr>
<tr>
<td>1.15</td>
</tr>
<tr>
<td>(ton tank, food grade)</td>
</tr>
<tr>
<td>2.55</td>
</tr>
</tbody>
</table>

\*TLV is the threshold limit value, defined here as the maximum allowable time-weighted average concentration to which a human may be exposed over an eight-hour workday, 40-hour week.
### Table 3.5

**Comparison of Hamburger Freezing Cost (1980) Using Various Techniques**

<table>
<thead>
<tr>
<th>Number of Shifts</th>
<th>1</th>
<th>2</th>
<th>1</th>
<th>2</th>
<th>1</th>
<th>2</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
<td>Mechanical System</td>
<td>Liquid Nitrogen</td>
<td>Liquid Carbon Dioxide System</td>
<td>LFF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freezer capacity and production rate, lb/hr</td>
<td>6,000</td>
<td>6,000</td>
<td>6,000</td>
<td>6,000</td>
<td>6,000</td>
<td>6,000</td>
<td>6,000</td>
<td>6,000</td>
</tr>
<tr>
<td>Operating time, hr/yr</td>
<td>2,000</td>
<td>4,000</td>
<td>2,000</td>
<td>4,000</td>
<td>2,000</td>
<td>4,000</td>
<td>2,000</td>
<td>4,000</td>
</tr>
<tr>
<td>Annual production, millions lb/yr</td>
<td>12</td>
<td>24</td>
<td>12</td>
<td>24</td>
<td>12</td>
<td>24</td>
<td>12</td>
<td>24</td>
</tr>
<tr>
<td>Freezer usage:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LN₂ 1 lb/1b $0.5c/1b</td>
<td>--</td>
<td>--</td>
<td>0.7</td>
<td>0.7</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>CO₂ 1 lb/1b $3.5c/1b</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.8</td>
<td>0.8</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>CFC 1 lb/1b $50c/1b</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>.018</td>
<td>.018</td>
</tr>
<tr>
<td>Total investment (installed), $</td>
<td>600,000</td>
<td>600,000</td>
<td>240,000</td>
<td>240,000</td>
<td>250,000</td>
<td>250,000</td>
<td>550,000</td>
<td>550,000</td>
</tr>
<tr>
<td>Operating cost $/yr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Investment-related, fixed (straight-line)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depreciation $102</td>
<td>60,000</td>
<td>60,000</td>
<td>24,000</td>
<td>24,000</td>
<td>25,000</td>
<td>25,000</td>
<td>55,000</td>
<td>55,000</td>
</tr>
<tr>
<td>Interest $12% simple</td>
<td>36,000</td>
<td>36,000</td>
<td>14,400</td>
<td>14,400</td>
<td>15,000</td>
<td>15,000</td>
<td>53,000</td>
<td>53,000</td>
</tr>
<tr>
<td>Maintenance $4%</td>
<td>24,000</td>
<td>24,000</td>
<td>--</td>
<td>--</td>
<td>22,000</td>
<td>22,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance LN₂ and LO₂ 2%</td>
<td>--</td>
<td>--</td>
<td>24,000</td>
<td>24,000</td>
<td>25,000</td>
<td>25,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Variable costs:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power $5c/kwh</td>
<td>29,800</td>
<td>59,600</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>27,700</td>
<td>55,400</td>
</tr>
<tr>
<td>Operator labor $8/hr</td>
<td>16,000</td>
<td>32,000</td>
<td>16,000</td>
<td>32,000</td>
<td>16,000</td>
<td>32,000</td>
<td>16,000</td>
<td>32,000</td>
</tr>
<tr>
<td>Cleanup labor $4.10/hr, 15 hr/wk</td>
<td>3,200</td>
<td>3,200</td>
<td>3,200</td>
<td>3,200</td>
<td>3,200</td>
<td>3,200</td>
<td>3,200</td>
<td>3,200</td>
</tr>
<tr>
<td>Freezer cost $/yr</td>
<td>--</td>
<td>--</td>
<td>420,000</td>
<td>840,000</td>
<td>336,000</td>
<td>672,000</td>
<td>121,000</td>
<td>242,000</td>
</tr>
<tr>
<td>Yield loss %</td>
<td>.6</td>
<td>.6</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>.25</td>
<td>.25</td>
</tr>
<tr>
<td>$/yr 0.73c/lb</td>
<td>52,272</td>
<td>104,544</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>21,760</td>
<td>43,560</td>
</tr>
<tr>
<td>Total annual operating cost</td>
<td>221,272</td>
<td>319,344</td>
<td>501,600</td>
<td>903,600</td>
<td>420,200</td>
<td>772,200</td>
<td>299,700</td>
<td>486,160</td>
</tr>
<tr>
<td>Unit operating cost, c/lb</td>
<td>1.84b</td>
<td>1.33b</td>
<td>4.18</td>
<td>3.92</td>
<td>3.50</td>
<td>3.22</td>
<td>2.50</td>
<td>2.03b</td>
</tr>
</tbody>
</table>

**Conversion factors:**
- g/s = 1 lb/hr x 0.126; kg/yr = 1 lb/yr x 0.454; $/kg = $/lb x 2.2; c/kg = c/lb x 2.2.

**Sources:** Briley (1980), p. 30, and industry supplied estimates (corrected to a common accounting basis for comparison.

a If CFC-115 were used, the cost of the same mass of freezer would triple (see Table 3.4) and the unit operating cost would rise to about 4.5c/lb.

b If yield losses were zero, these figures would be 1.4c/lb and .90c/lb, respectively.
over product carried on the belts. The product is gently agitated in the flow of high velocity air. Air blast freezing is the preferred freezing system for peas, cut corn, lima beans, and carrots.

Cryogenic freezing takes place at a much lower temperature, $-320^\circ F$ for liquid nitrogen and $-109^\circ F$ for carbon dioxide. In the case of the former, product is exposed to liquid nitrogen where the latent heat of vaporization effects the freezing. In the case of the latter, liquid carbon dioxide (contained at 260 psig and $-10^\circ F$) is expanded to atmospheric pressure and the resulting snow is used to freeze the product (atmospheric pressure is less than the triple point of carbon dioxide and so it exists only in solid or vapor form).

The air blast (mechanical system), liquid nitrogen, carbon dioxide, and LFF (CFC-12) methods for the freezing of hamburger are compared in Table 3.5. Data are presented for a high volume, year-round operation for either a one or two shift day to exhibit the sensitivity of operating cost to this variable. Equipment costs and power and labor rates are given in 1980 dollars. Yield losses (mostly “freezer burn” losses) are included in the computations for air blast and LFF but have been excluded from the liquid nitrogen and carbon dioxide cases because of insufficient data.

The most important conclusion that can be made from these data is that air blast freezing has the lowest unit operating cost of all four (meat) freezing technologies for high volume operations, regardless of the number of shifts or the inclusion of yield losses. Similarly, liquid nitrogen and carbon dioxide freezing are both more expensive than either LFF or air blast; if yield losses were included for cryogenic freezing, the unit operating cost would be higher and the techniques rendered even more unfavorable.6

The 34 to 44 percent lower cost of air blast explains why LFF has not captured a growing share of the frozen meat market in the last few years and why air blast is the preferred method for the freezing of vegetables. Companies planning to expand their meat or vegetable freezing operations are thus being driven to air blast methods, even without the added incentive that would occur if CFC were to rise to a higher price. Of course, companies that already operate LFF equipment resist the changeover to air blast because of the required investment in new equipment as well as the expense of providing new work space. (For the same throughput, Green Giant has stated that the air blast equipment occupies more space than LFF equipment and will require the construction of a new building.)

Liquid nitrogen and carbon dioxide freezing are not only more expensive than air blast for high volume meat and vegetable processing operations but present other problems as well. According to Briley (1980), the energy requirements for producing liquid carbon dioxide and liquid nitrogen are, respectively, 4.5 times and 17.5 times those of the air blast method (see Table 3.6). Because of the very high energy consumption in producing liquid nitrogen, most cryogenic freezeplant users had switched from liquid nitrogen to carbon dioxide as early as 1975. In addition, until recently, increasing fuel costs have been raising the cost of transporting these cryogenic fluids to the users. Furthermore, if a large seasonal (e.g., vegetable) producer elects to use carbon dioxide freezing, there may be some difficulty in securing sufficient supply during the harvest. At a use rate of 1.3 pounds of CO$_2$ per pound of vegetable (corn) (for comparison the use rate is 1.8 pounds per pound for onion rings, 0.8 pound per pound for hamburger), a producer such as Pillsbury would require 67,000 tons of CO$_2$ per 50

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6 For lower volume, intermittent operations, the carbon dioxide system may be competitive with LFF because variable operating costs are lower, and the lower capital cost of the CO$_2$ system leads to a lower unit cost of production. However, we are primarily interested in existing, large volume LFF systems where there is potentially greater leverage for reducing CFC emissions.
day season or about 13 percent of the total domestic production of 10,000 tons per day during this period (or 40 percent of the daily output of Liquid Carbonics, the largest CO₂ producer). This would require that several suppliers be found; otherwise, Pillsbury would have to produce their own CO₂ or build tanks for off-season storage, which would drive up the unit operating costs of CO₂ freezing even further. Still other difficulties may be encountered if liquid nitrogen is used to freeze fruits and vegetables. Because the freezing temperature of this fluid is so low, the food often freezes too quickly and explodes or, in the particular case of corn, is shelled from the cob.

Table 3.6

<table>
<thead>
<tr>
<th>Method</th>
<th>Energy Use (KW/100 Btu of freezing capacity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Nitrogen</td>
<td>0.383</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>0.100</td>
</tr>
<tr>
<td>Mechanical</td>
<td>0.022</td>
</tr>
</tbody>
</table>

Using LFP to freeze raw or cooked shrimp leads to a lower operating cost than air blast. The reason for the reversal in costs is that the yield loss from dehydration in air blast frozen shrimp is relatively high, on the order of 1.5 percent (Palmer et al., 1980). Because the cost of shrimp is also high (currenty greater than 86 per pound), this yield loss may amount to 89 percent of the total annual operating cost and be the dominant factor in determining the unit operating cost. In the case of LFP, the corresponding yield loss is only about 0.25 percent, amounts to only 33 percent of the total annual operating cost, and leads to a lower unit operating cost. Furthermore, one shrimp producer claims that the air blast technique requires higher labor costs than LFP because considerably more labor is required to spread the wet shellfish before exposure to the air stream to prevent them from sticking together.

Thus, certain seafood and fruit applications aside, there is generally a strong cost incentive to select air blast freezing over other methods when expanding or replacing freezer capacity. The major counterargument to this has been the claim by food producers (some strawberry and frozen corn producers, for example), that the product frozen with LFP or cryogenic methods tastes and looks better, but strong statistical evidence is lacking. One major vegetable producer concedes, however, that taste quality aside, he would not now use any other method than air blast freezing.

Shrinkage or dehydration of the product when frozen by air blast has been a concern for years and has been the deciding factor for many companies to turn to LFP or cryogenic methods instead. However, Briley (1980) strongly states that such dehydration is minimal in air blast systems that are properly designed “and that it is not the major factor it is reported to be.” Rasmussen and Olson (1972) determined that dehydration of product occurs during the cooling phase (the stages of heat loss before freezing) and is significant only if the time spent in this phase is long. Modern air blast systems are in fact capable of keeping this time

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*Annual production of liquid CO₂ was 2,617,669 tons in 1980 (Bureau of the Census, 1981).
comparable to that obtained with LFF or cryogenic systems. For example, a hamburger meat patty can be frozen in five to eight minutes cryogenically or in six to eight minutes in a good mechanical system with quality and shrink differences that would be difficult to detect; at −35°F to −40°F there would be a minimum of freezer burn. (However, carbon dioxide freezing chemically gives a longer shelf life and better color to red meat.)

Although not yet in use, still another system might be considered as a possible substitute for LFF. This is a combination mechanical-cryogenic system using liquid carbon dioxide in which 70 to 90 percent of the carbon dioxide is recovered, compressed to 250 psig, condensed by a two stage ammonia refrigeration system at −10°F, and recycled. According to Briley (1980), the unit operating cost and capital cost would be close to those of air blast and the combination system would incorporate the best quality characteristics of both CO₂ and air blast.
III. Coal Cleaning

INTRODUCTION

Coal cleaning using CFC-11 is a new process used to separate coal from the gangue (refuse material) that accompanies it immediately after mining. It is a technique that floats coal on the surface of a dense liquid bath of CFC-11 while allowing the mineral matter, including pyritic sulfur, to sink to the bottom. The cleaned coal is sold primarily to utilities where its low sulfur and ash content reduce the need for stack clean-up and fly ash disposal facilities.

The sole developer of this CFC-coal beneficiation process is Otisca Industries Ltd. of Syracuse, New York. It is a small eight-year-old company of thirty employees but it projects a large incursion into the current coal cleaning market by the early 1990s. Otisca intends to market its process to the fifty or so producers that account for 80 percent of all the coal mined in this country and expects to capture greater than ten percent of the current hydrobeneficiation market in the early 1990s. While the corporation has concentrated on reducing the CFC emissions associated with processing a unit of coal, the size of the projected market suggests that a significant absolute amount of material might still be emitted. Thus, in the subsections below, we estimate these losses and discuss their origins and methods for control.

Otisca is presently operating two facilities, a two to 15 ton/hr development center in Florence, Pennsylvania (near Pittsburgh) and a 125 ton/hr plant in Ohio. The range of capacities given for the Florence facility reflects the effects of coal type and fineness on maximum flow-through; the lower throughputs hold for the finer coals. The Florence development center primarily produces cleaned coal for user testing.

THE PROCESS

The coal (with a specific gravity of approximately 1.2 to 1.5) is separated from the gangue by floating it on a bath of CFC-11 (specific gravity 1.5). Pyrite (specific gravity 4.9) and most of the other contaminants (specific gravity > 2) sink to the bottom of the bath. The coal is drawn off the surface of the float media via an inclined plane to allow drainage of solvent. The coal at this stage contains approximately 10 to 15 percent by weight of CFC-11. This is removed by vaporization in an indirect fired conductive evaporator at an energy cost of about 22,000 Btu/ raw ton of coal. If the input coal is not dry, the additional vaporization of water may raise this figure to 60,000 Btu/ raw ton.

The vaporized CFC-11 is collected and passed on to a carbon adsorption unit. Such units are usually designed to regenerate the carbon by driving off the adsorbed material with steam once the bed has reached a small fraction of its saturation capacity. However, Otisca has found that a target of about 50 ppm of CFC in the exhaust stream from the recovery unit must be achieved to keep this loss of nonrecoverable CFC from adversely affecting the economics of the process, and that such a level is not attainable with steam desorption. Therefore, Otisca uses an alternative system that subjects the carbon bed to a vacuum and drives off the adsorbed CFC with indirect heat. To further reduce CFC emissions, the exhaust stream from the recovery unit is mixed with the air used as oxidizer for the system's boiler.
The CPC in this stream is therefore thermally decomposed, presumably to carbon dioxide, hydrogen chloride, and hydrogen fluoride.

The entire separation system is enclosed and operates under a slight vacuum of about one inch of water to minimize CFC losses. The refuse stream is nearly completely dry and is disposed of in dry landfills.

The CFC coal cleaning process is aimed primarily at the treatment of bituminous Eastern coals. These coals generally have a higher sulfur content than Western coals and, because they lie in shallow seams, emerge from the mine with a higher proportion of gangue. Some low sulfur Western coals (such as those in the Gillette seam in Wyoming) do not require coal cleaning at all because the seam is so thick that the overburden can be removed at the mine site with no significant loss of coal. The Otisca process could be used with lignite and sub-bituminous coals but its efficiency declines with respect to sulfur and mineral removal. The process is most economical when applied to the cleaning of fine coals and to raw coals that contain montmorillonite clay.

EMISSIONS

Otisca states that CFC is lost from the float cycle in four principal ways. First, some CFC-11 remains on the coal after the evaporation step and passes out of the separation equipment with the product coal. The concentration of CFC in the product coal is about 50 ppm. CFC-11 is also lost in the refuse stream (about 25 percent by weight of the raw coal) where the concentration ranges from 40 to 100 ppm. Third, some fluid is lost through shaft seals although losses here have been nearly eliminated through the use of double oil seals. Finally, some CFC remains in the air stream after solvent recovery. Otisca attempts to keep the CFC concentration in this stream below 50 ppm. When combined with reasonable coal and air flow rates, these ppm loss figures may be used to calculate a total nonrecoverable CFC loss per ton of raw coal processed. Otisca's current estimate of this loss\(^*\) lies in the range of 0.1 pound CFC per ton of raw coal. This figure has undergone change as demonstration work has progressed—the anticipated loss was 0.05 pound CFC per ton in January 1978 (Fed. Reg., 1978b), and 0.5 pound per ton in April 1981 (Otisca, 1981)—and the possibility must still be considered that it may undergo further change as large-scale plants become operational.

The rate of CFC actually emitted to the atmosphere is less than the rate of CFC lost to recovery. This is because the CFC contained in the air stream after the carbon adsorption step is incinerated in the boiler flame. In addition, the CFC buried with the refuse may be slow in diffusing to the atmosphere, and the CFC remaining on the coal at the time of utilization by the power plant will be thermally decomposed during combustion. If the product coal is not utilized within three months, however, most of the initial 50 ppm CFC vaporizes and the coal will contain only 5 to 10 ppm at the time of combustion. This suggests that about 80 percent of the CFC initially present on the product and refuse streams may constitute an upper bound for emission, or about 0.08 pound of CFC per raw ton if each stream contains 50 ppm after separation and if use and burial are not immediate.

Otisca projects that its process will be cleaning five million tons of coal annually by 1985 (Fig. 3.1a), and remains hopeful that it might capture one-sixth of the 350 million tons per year of the hydrobeneficiation market, or about 60 million tons per year in the mid-1990s. In

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\(^*\)D. V. Keller, personal communication to The Rand Corporation, November 4, 1981.
1978, Otisca hoped that this level of penetration could be achieved before 1990 (Fig. 3.1a), but this has been delayed due to slow industrial acceptance, high interest rates, and concern over CFC emissions. Based on the most recent market projections of Otisca, the total CFC losses are shown in Fig. 3.1b for the period 1982 to 1985 using the most recent 0.1 pound CFC per ton of nonrecoverable CFC loss rate as well as the two earlier estimates. If Otisca does meet its optimistic forecast of capturing one-sixth of the hydrobeneficiation market in the 1990s and the 0.1 pound per ton loss rate is maintained, the nonrecoverable CFC loss rate may climb to six million pounds per year and the emission rate to about five million pounds per year. Some uncertainty may still be associated with these loss rates, and it is therefore incumbent upon Otisca and its operators to maintain this 0.1 pound per ton loss rate as commercialization proceeds or risk contributing several percent to overall CFC emissions in the 1990s.

CONTROL OF EMISSIONS

Methods for controlling the emission of CFC-11 from coal cleaning are several and include:

- Enclosure of the cleaning process and the use of negative pressures within to prevent solvent vapor losses (in place).
- Use of carbon adsorption to trap and recycle vapors (in place).
- Substitution of another CFC with a lower ozone depletion factor (technically difficult).
- Continued use of alternative processes, most notably hydrobeneficiation.

Control Technologies and Work Practices

Because even a small loss of CFC from the separation unit would be highly detrimental to the economics of this process, Otisca has paid close attention to reducing this loss to a very low level, principally by the use of negative air pressure above the float region and new non-steam-contact carbon adsorption systems. Indeed, the tenth pound loss of CFC-11 per ton of coal compares very favorably with similar processes, such as the liquid fast freezing of vegetables, where typical losses of 35 pounds of CFC-12 per ton of product are encountered. However, Otisca does feel that the operating experience it will gain on the present equipment over the next five or six years may allow it to further reduce its loss rate. Otisca reports that the emission of one-tenth pound of CFC-11 per ton of raw coal does not change significantly with a reduction in coal size. Presumably, slight alterations in process flow rates could be used to compensate for any small changes in loss rate.

Hydrogen fluoride and hydrogen chloride emissions and consequent scrubber corrosion at the steam plant are not encountered when CFC-cleaned coal is burned. Even though the product coal may contain up to 100 ppm of CFC immediately after the cleaning, much of the residual CFC evaporates from the coal during the subsequent handling and transport stages. The amount of CFC-11 remaining in the coal just before combustion is about 5 to 10 ppm, low enough to be well within air pollution standards and apparently low enough to avoid significant corrosion.

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*D. V. Keller, personal communication to The Rand Corporation, November 4, 1981.*
Fig. 3.1a—Annual tonnage of coal cleaned by Otisca process as projected in 1978 and 1981

Fig. 3.1b—Annual nonrecoverable CFC losses at three loss rates

Product Substitutes

One major competitor to the Otisca coal cleaning process is the present method of hydrobeneficiation. This process employs a water-magnetite suspension dense enough to float the coal and separate it from the gangue. The excess water on the coal is removed in a drying step. Some of the disadvantages of hydrobeneficiation relative to CFC beneficiation are that it is more energy consumptive (because of the high latent heat of vaporization of water), it is less efficient in removing pyritic sulfur particles at diameters below .02 inch, there is severe wear on the screens due to the abrasive action of the magnetite, and there is a high potential for water pollution from the slurry ponds employed in this method. Certain special coals, particularly those containing the montmorillonite clays, are not readily cleaned by hydrobeneficiation. Such clays interfere in the process by swelling in water, forming thixotropic solutions and slimes, thus greatly increasing the cost of operation. Otisca claims that because of the high energy and maintenance costs of hydrobeneficiation, its method is less expensive.

Chemical Substitutes

When separation media other than CFC-11 are considered as potential substitutes in the Otisca process, a prime consideration is finding fluids dense enough to float coal (the density of bituminous coal is 1.2 to 1.5 g/cc). In the case of single phase fluids, this condition generally restricts attention to the halogenated hydrocarbons, especially the chlorocarbons and CFCs. Suspensions similar to water-magnetite might be found that have sufficiently high densities but use of these will generally require significant changes in equipment and operating practices.

Non-CFC halocarbons, although having high enough densities, have not been successful substitutes in the past because of their tendency to combine with the coal, increasing the costs of solvent makeup and leading to increased halogen acid emissions upon combustion of the coal in steam power plants. Likewise the halocarbon contamination prevents the coal's use in the making of coke.

Of the presently available CFCs (11, 12, 22, 113, 114, 115, and 152a), only CFC-11 and CFC-113 seem matched to the process in terms of being liquids at ambient (70°F) temperature and pressure and having densities sufficiently high to float coal (the specific gravity of CFC-11 is 1.48 at 77°F, and the specific gravity of CFC-113 is 1.56 at 77°F). The heat required to vaporize these pure fluids at ambient temperature is similar even though the boiling point of CFC-113 (118°F) is 43°F higher than that of CFC-11. In fact, the lower latent heat of vaporization of CFC-113 (70.6 Btu/pound compared with 83.5 Btu/pound for CFC-11) more than makes up for the greater sensible heat requirement to raise it to its boiling point. However, this energy advantage of pure CFC-113 is offset in coal cleaning by the transfer of sensible heat from the CFC-113 fluid to the coal mass. In addition, Otisca claims the greater viscosity of CFC-113 (η113 = .68 cp; η11 = .43 cp) presents some difficulty and claims that the wetting properties of CFC-113 are somewhat inferior to those of CFC-11 in spite of similar surface tensions (18 dynes/cm for CFC-11 compared with 17.3 dynes/cm for CFC-113). Furthermore, the substitution of CFC-113 for CFC-11, even if technically feasible, provides only a modest potential for alleviating the ozone threat, since the ozone depletion factor of CFC-113 is 77 percent of that of CFC-11. With the introduction of CFC-113, CFC-11-equivalent emissions would be reduced below present early 1990 projections by 1.2 million pounds per year.
Of the alternative CFCs being investigated by DuPont (21, 31, 32, 123, 124, 125, 132b, 133a, 134a, 141b, 142b, and 143a), only CFC-123, CFC-132b, and CFC-141b have boiling points that allow them to be liquids under ambient conditions (82°, 116°, 90°F, respectively, while the next highest alternative CFC boiler is CFC-21 with a boiling point of 48°F). However, CFC-141b is flammable and has a density (1.25 at 10°F) that would not float bituminous coal, thus ruling it out as a substitute. CFC-123 is an unlikely substitute because no manufacturing process currently exists or is imminent. CFC-132b could be manufactured but at high cost. Its density is satisfactory (1.41 g/cc at 86°F), it is not flammable, its surface tension at 16 dynes/cm is favorable relative to either CFC-11 or CFC-113 at 18 dynes/cm, and its viscosity at .53 cp compares well with that of CFC-11 (.43 cp) and is better than CFC-113 (.68 cp). However, because its latent heat of vaporization is higher than either CFC-11 or CFC-113 at 97 Btu/pound and its boiling point is relatively high, its use as a coal cleaning medium would mean increased energy consumption in the solvent evaporation step. If ten percent of the weight of the coal emerging from the float tank were attributable to solvent, the use of CFC-132b would require about 24,000 Btu/ton of raw coal to evaporate this solvent or 5,300 Btu/raw ton over that required for CFC-11. Furthermore, CFC-132b may prove to be too soluble in coal to allow it to be a feasible substitute. Because the solubility characteristics of CFC-132b are quite similar to methylene chloride, and the chlorocarbons are known to be excessively soluble in coal, the same may be true for CFC-132b. The possible toxic effects of CFC-132b have not yet been assessed.

The ability of Otisca to consider substitute solvents depends on the level of nonrecoverable CFC losses. If the loss rate is high, the cost of replacing lost solvent may eliminate the price difference between CFC and hydrobenficiation, thus making the CFC process noncompetitive with hydrobeneficiation. In 1978, Otisca estimated this difference as $2.60 per raw ton of coal processed ($3.50/ton for hydrobenficiated coal compared with $1.00/ton for CFC beneficiated coal). At a loss rate of 0.1 pound per ton (as recently estimated for CFC-11 at the pilot plant level), a substitute solvent must therefore cost less than $25.00 a pound, a price below which CFC-113 (as well as CFC-11) should easily remain for the foreseeable future. However, if the Otisca loss rate cannot be held to the 0.1 pound per ton figure as the company scales up to larger units, the unit cost of substitutes considered for these units must be substantially less. If the loss rate were to climb to 1.0 pound per ton, then the price of CFC-113, for example, could rise only to $2.50 per pound or slightly less (i.e., triple) before the Otisca process became noncompetitive with hydrobeneficiation and CFC-113 were rendered a nonviable substitute. CFC-132b would be subject to a similar price constraint but since this compound is not presently manufactured, any assessment of its ability to satisfy the above cost restraint remains problematical.

NON-CFC EMISSIONS

The Otisca process is notable for its lack of significant emissions other than CFC vapors. Unlike its hydrobeneficiation competitor, it does not use refuse slurry ponds and thus eliminates water pollution from this source. It greatly reduces the dust emission from dryers and reduces the explosion hazards associated with the thermal drying of coal. Probably because of the good wetting properties of CFC-11, the Otisca process can also reduce the annual amount
of ash and sludge that must be disposed of by steam plant operators. Relative to that produced when hydrobeneficiated coal is burned, CFC beneficiated coal reduces ash and sludge wastes by 1,500 pounds and 4,000 pounds, respectively, for each 25 megawatt-hours/yr generated by the plant. Furthermore, the hydrobeneficiation process consumes significantly more energy because of the high latent heat of vaporization that must be supplied to dry the coal after the float (500,000 Btu/ton of raw coal relative to 22,000 Btu/ton in the CFC process).
IV. Use of CFCs as Diluents for Ethylene Oxide in Gas Sterilization

INTRODUCTION

Gas sterilization using ethylene oxide (EtO) is widely used throughout the health care system for sterilizing prepackaged, single-use medical supplies, and sterilizing for reuse a great variety of hospital goods that would be damaged by the high temperatures of steam autoclaving. Because pure ethylene oxide is highly flammable, safety considerations require that it be diluted with an inert gas before being used in certain applications. The most commonly used diluent is CFC-12 and the most widely used formulation consists of 12 percent ethylene oxide and 88 percent CFC-12. The 12/88 mixture still possesses a high degree of antimicrobial activity but is not combustible. Consequently, it can be used with safety in hospital and other institutional settings. Indeed, ethylene oxide is never used in the undiluted form in hospitals and similar environments. Pure ethylene oxide is used by some industrial sterilizers of prepackaged medical supplies but the 12/88 mixture is also used extensively in the industry.

Carbon dioxide is a less commonly used diluent for ethylene oxide. CFC-11 is also used as a diluent to a minor degree.

INDUSTRIAL STERILIZATION

Most industrial gas sterilization is carried out in fewer than 50 large (1,000 to 2,200 cubic feet) sterilizers and a greater number of smaller industrial units (40 to 1,000 cubic feet). Gaseous ethylene oxide is generally used industrially for the sterilization of disposable sterile kits containing items such as disposable hypodermic syringes and needles, microbiological laboratory supplies, and life support items such as electronic cardiac pacemakers, blood oxygenators, and dialysers, to name a few (Glaser, 1977). Phillips et al. (1978) list more than a hundred other items that can only be sterilized by EtO.

The sterilization process involves the following steps (Glaser, 1977):

1. Materials are manufactured, cleaned, packaged, and prepared for ethylene oxide sterilization.
2. Materials are placed in the chamber which is then tightly sealed.
3. Most of the air in the chamber is removed, creating a vacuum.
4. Ethylene oxide gas or gas mixtures are introduced into the sealed chamber and the proper conditions of temperature (e.g., about 140°F) and humidity (e.g., over 40 percent relative humidity) are established at somewhat elevated pressure.
5. The gas mixture is maintained over a period of two to six hours at the proper temperature and humidity to allow sterilization to take place.
6. The sterilizing gas is exhausted from the closed system, usually by venting to the atmosphere, and a vacuum is drawn to remove the gaseous contents of the chamber.
7. Filtered air enters the chamber and the goods are aerated, then the door is opened and the sterilized goods are removed.
Since ethylene oxide is quite soluble in certain plastics and elastomers, it is important to eliminate these residual traces, which could prove toxic to living tissue. This is accomplished by further storage of the goods in sterile air in aeration chambers that are held at temperatures around 120°F.

HOSPITAL/INSTITUTIONAL STERILIZATION

Some 6,000 or more hospitals and institutions in the United States have ethylene oxide sterilizers, the majority of which are small tabletop units. However, Glaser estimated that 1,000 to 2,000 large sterilizers (permanent installations with chamber volumes greater than four cubic feet) are also in use. According to a survey conducted by the American Hospital Association in 1977, the average hospital has 1.8 sterilizers, the number per hospital being a function of hospital size.

Ethylene oxide sterilizers are used also in many smaller medical and dental clinics and facilities. The National Institute of Occupational Safety and Health has estimated that more than 10,000 sterilizers are in use in the United States (Glaser, 1977).

The principal items sterilized with ethylene oxide in hospitals are those that are reused repeatedly, such as air powered surgical instruments, anesthesia equipment, cardiac catheters, endoscopes, and other equipment containing lenses, humidifiers and nebulizers, implantable body parts, electronic pacemakers, ophthalmic instruments, respiratory therapy equipment, thermometers, and equipment contaminated by use in isolation rooms. Hospital procedures for sterilization are similar to those used in industry, as described above.

QUANTITIES USED AS DILUENTS

Two recent estimates have been made of the quantities of CFCs that are used annually as diluents for ethylene oxide. DuPont estimated that 15 million pounds, or two percent of total U.S. production of CFCs, went into this end use in 1979. The Health Industry Manufacturers Association (HIMA) (1981) estimated that about 14 million pounds per year are currently employed in industry and hospitals as a diluent for ethylene oxide.

No accurate data are available on the split between industry and hospital usage. However, a rough breakdown can be provided by assuming that:

1. Equal amounts of CFCs as ethylene oxide diluents are used in industry and hospitals, and
2. The breakdown within the health care industry is proportional to the figures obtained by HIMA in the 1977 survey of its member firms (Phillips et al., 1978).

A breakdown based on these assumptions is shown in Table 3.7. Since almost all of the sterilant mixture is emitted promptly, the annual emission figures would be the same as the annual usage figures.
Table 3.7

**Approximate Breakdown of 1980 Ethylene Oxide and CFC Usage in Gas Sterilants**

<table>
<thead>
<tr>
<th>User</th>
<th>Ethylene Oxide</th>
<th>CFC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Millions lb</td>
<td>%</td>
</tr>
<tr>
<td>Industry</td>
<td>4.4</td>
<td>81</td>
</tr>
<tr>
<td>Pure ethylene oxide</td>
<td>3.2</td>
<td>(73)</td>
</tr>
<tr>
<td>EtO blends with CFC</td>
<td>1.0</td>
<td>(23)</td>
</tr>
<tr>
<td>EtO blends with CO₂</td>
<td>0.2</td>
<td>(4)</td>
</tr>
<tr>
<td>Hospital/institutional</td>
<td>1.0</td>
<td>19</td>
</tr>
<tr>
<td>Totals</td>
<td>5.4</td>
<td>100</td>
</tr>
</tbody>
</table>

**Chemical Control Options**

Several alternative strategies could reduce emissions of CFC-12 associated with sterilant use in future years. These include the following:

1. Recovery, reclamation, and recycling of the 12/88 mixture employed in industrial sterilization.
2. Increased use of pure ethylene oxide in industrial sterilization.
3. Substitution of CFC-22 for CFC-12 as an ethylene oxide diluent, on the grounds that the ozone depletion factor of CFC-22 (0.05) is considerably lower than that of CFC-12 (0.79).^8
4. Substitution of CO₂ for CFC-12 in industrial sterilization.
5. Use of sterilants other than those based on CFC-diluted ethylene oxide.

It is important to note that we have not included steam sterilization in this list. The principal reason for this is that steam sterilization alone would not allow articles to be packaged before sterilization, thus increasing the chances of contamination during the later packaging step. The high temperatures (121°C at 15 psig) necessary in a steam autoclave to effect sterilization would not always be compatible with the plastic packaging materials. Steam would not penetrate those materials that were so packaged. In addition, the plastics used in the medical items themselves (e.g., disposable needles) might be destroyed. Thus, a return to steam sterilization would force a return to the use of steam compatible materials, such as stainless steel needles, and on-site sterilization. Because this represents a great dislocation in the sterilization industry as well as in hospital operating practices, we have considered only those CFC reduction methods that still allow prepackaged sterilization to continue.

As in other CFC usage areas, it is difficult to categorize certain emission reduction methods: Improved work practices and improved control technology often go hand-in-hand. Thus,

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^8DuPont’s (1981) most recent estimates of these factors are 0.03 and 0.84, respectively.
we have arbitrarily categorized 12/88 recovery methods as improved work practices although new equipment will be required. Most other emission reduction methods involve substitution of other chemical sterilants or diluents for the 12/88 mixture. In some cases, the use of an alternative sterilant (e.g., EtO/CO₂) requires the simultaneous replacement of the sterilizer itself (product substitution). The technical feasibilities of these options are discussed below.

**Work Practices**

**Recovery of 12/88 Mixture.** At least two U.S. companies have ventured into the business of recovering for reuse the effluents from 12/88 sterilization in industry. One of these, Vacudyne Altair, of Chicago Heights, Illinois, has indicated that its equipment is just now being introduced into the industry. Its 12-88 Industrial Gas Reclamation System, according to a company-supplied information sheet, "is a self-contained unit which will recover for reuse the majority of the 12-88 gas used in a sterilizing chamber. The reclaimer removes the gas from the chamber, dries and condenses it, analyzes and rebles it to the original 12-88 spec, and returns it as a gas to the chamber for the next sterilization." This system is said to be almost completely automatic, requiring very little operator attention and adding only a little time to the sterilization cycle. A company representative has stated that about 70 percent recovery of sterilizer effluents could be obtained on each cycle. Their equipment is designed for large industrial users only, not for hospital use.

The Linde Division of Union Carbide Corporation is also in the process of developing a reclamation system for 12/88 but this has not yet reached commercial status. This system, as described by a company representative, promises nearly 100 percent recovery of the gas sterilant mixture. It involves installation of a large (e.g., 5,500 gal) storage tank at the customer's location. When the tank is full, Linde empties it, takes the contents away and reprocesses the gas to restore it to its original specifications, then returns it to the sterilizer under a "buy-back" arrangement. The economics of the system are said to be potentially attractive to industrial sterilizers who use more than about 20,000 pounds per month of the 12/88 mixture, but would probably not be economical to sterilizers who use less than 10,000 pounds per month.

Since there is currently little recovery and reuse of sterilization effluents, it is too early to accurately assess to what extent CFC emissions will eventually be reduced by this technology. However, it does appear that only industrial usage of CFC-12 will be affected in the near future, thus limiting the reduction potential to less than seven million pounds (see Table 3.6) (about five million pounds if the 70 percent efficient Altair system were used throughout).

**Chemical and Product Substitutes**

**Increased Use of Pure Ethylene Oxide.** In spite of the flammability of undiluted ethylene oxide, most industrial sterilizers use the gas in the pure form. In fact, according to HIMA's figures, over 70 percent of all industrial sterilizations with ethylene oxide are carried out using the pure gas (Table 3.6). Clearly, if suitable precautions are taken, sterilizations can be carried out safely by well-trained personnel using pure ethylene oxide rather than the noncombustible 12/88 mixture. There is a potential here for reducing CFC-12 emissions through switching from the diluted form to the pure form of ethylene oxide as the sterilizing agent. This would probably apply only to medium or large industrial sterilizers, however, rather than to hospital operations, since very stringent safety procedures can be followed
more readily in large industrial facilities than in hospitals, and more people are potentially at risk in hospitals. Because of the leverage represented by the ratio of 12 to 88, switching only 136,000 pounds of ethylene oxide from the diluted to the pure form of gas sterilization would reduce CFC-12 emissions by about one million pounds.

Replacing CFC-12 with CFC-22. According to DuPont, the flame retardant behavior of CFC-12 (when mixed with ethylene oxide) is due just to a physical blanketing effect. CFC-22 is said to have a similar property, although its partial halogenation makes it somewhat less effective than CFC-12 in this respect. Thus, it is possible that CFC-22 could be substituted for CFC-12 as an ethylene oxide diluent. DuPont has estimated that such a mixture would require about 90 to 92 percent CFC-22. This would be a somewhat slower sterilant combination than the conventional 12/88 mixture because of the smaller fraction of ethylene oxide in the mixture. The use of a CFC-22 ethylene oxide sterilant has an additional drawback in that it will fractionate when the gas is withdrawn from a pressurized container of the mixture, leaving behind a mixture rich in flammable ethylene oxide. Large industrial users could avoid this by first exhausting the entire contents of the cylinder into an expansion tank, but considerable volume would be required. (The 12/88 mixture acts more like an azeotrope and does not fractionate.) It is not yet known whether such a mixture of CFC-22 and ethylene oxide would be stable enough chemically under typical conditions of storage and use. DuPont has concluded that there is no market justification to develop an alternative to CFC-12 specifically for this use. They have pointed out that it would take up to ten years of testing and construction before an acceptable alternative could be put into commercial production. Nonetheless, given increased costs, implementation and FDA approval delays, and the availability of an existing substitute (see the next subsection), the use of CFC-22 as a diluent appears feasible although not necessarily the best option.

Replacing CFC-12 with CO₂. As shown in Table 3.6, about four percent of the ethylene oxide used in industrial sterilization is used in the form of blends with carbon dioxide. An unknown but probably small percentage of gas sterilizations in hospitals and other institutions also use ethylene oxide/carbon dioxide blends. Theoretically, emissions of CFCs might be reduced by replacing the CFC-12 diluent with CO₂. Different kinds of equipment and operating cycles are required for CO₂ blends, however. Thus the two types are not interchangeable. Mixtures of carbon dioxide and ethylene oxide (e.g., the 10:90 blend) are stored at much higher pressures than the 12/88 blend of ethylene oxide and CFC-12. This mixture is also subject to fractionation when the gas is released from the cylinder during use, leaving behind an ethylene oxide rich fraction (HIMA, 1981). As mentioned above for the CFC-22 diluent, this can be avoided by exhausting the gas into an expansion tank but this option is best suited to industrial users. Some form of fractionation control is mandatory, not only to avoid problems of flammability in the ethylene oxide rich gas but also to ensure a steady ethylene oxide concentration and reliable sterilization. Furthermore, if a sterilizer cannot withstand an increase of its operating pressure when switched from a CFC to a CO₂ diluted sterilant, the ethylene oxide/CO₂ mixture would require about two-and-one-half times the exposure time to sterilize the same goods. Thus, while CO₂/ethylene oxide mixtures are used in industry, their use could be expanded only after a greater investment in sterilizing equipment, particularly for increased capacity and fractionation control. The use of CO₂ blends in the hospital environment would be far more problematical.

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9 Certain other compounds, such as bromotrifluoromethane, function as flame retardants by the additional mechanism of chemically terminating the oxidation chain reactions. However, there is no evidence that this occurs with either CFC-12 or CFC-22.
USE OF STERILANTS OTHER THAN ETHYLENE OXIDE

In concept, CFC emissions could be reduced in this end use area by replacing ethylene oxide with some other sterilizing agent that did not require the use of a diluent. Eliminating ethylene oxide would thus mean eliminating the need for a CFC diluent. The subject of possible alternatives to ethylene oxide sterilization has recently been addressed in several studies responsive to the Environmental Protection Agency’s announcement that regulation of ethylene oxide was under consideration (Glaser, 1977; Phillips et al., 1978; and Cioffi et al., 1978).

These studies concluded that none of the potential substitutes for ethylene oxide sterilization constituted a feasible alternative that could maintain ethylene oxide’s present level of effectiveness. After examining radiation (primarily electron beam and gamma ray radiation from cobalt-60 sources) and various chemical agents, most notably formaldehyde gas, formaldehyde liquid (formalin), and glutaraldehyde (liquid), the consensus was that radiation might be a reasonable alternative to ethylene oxide sterilization for some fraction of the operations now carried out in industrial sterilizing firms. However, it was considered unsuitable for certain applications now employing ethylene oxide. In particular, a large variety of widely used polymeric materials are not generally suited to radiation sterilization. Cioffi et al. (1978) list acetal copolymers, polymethylmethacrylate, polypropylene, polytetrafluoroethylene, polyvinyl and polyvinylidene chloride, vinyl chloride/acetate copolymers, and butyl rubber. Electronic circuits are also incompatible with radiation sterilization. Because not all items containing these materials are significantly degraded by the radiation and because the product formulations are often proprietary, Cioffi et al. also pointed out that it was virtually impossible to catalog all radiation compatible products. Thus, the extent to which the substitution of radiation for CFC-ethylene oxide sterilization can reduce CFC emissions is unknown, although most likely only a small fraction of the industrially used CFC diluent is replaceable. The use of radiation for sterilization in hospitals is considered impractical for all but the largest facilities.

In the studies cited above, the problems associated with the replacement of ethylene oxide by formaldehyde or glutaraldehyde were considered severe enough to create unacceptable adverse impacts on the quality of health care in the United States. The liquid sterilants (glutaraldehyde and formalin) are not as reproducibly reliable as ethylene oxide because they do not always penetrate every crevice of a surface because of the high surface tension of the liquid. Furthermore, the chemicals do not penetrate packaging materials and thus repackaging is not possible. Likewise, pure formaldehyde gas does not penetrate these materials (e.g., glassine and plastics) and is so poor at killing spores and some exudate-protected viruses that it is often considered as a disinfectant and not a sterilant at all (Gardner, 1974).
Chapter 4

SOLVENT APPLICATIONS OF CHLOROFLUOROCARBONS

I. Introduction and Summary

The primary chlorofluorocarbon used in solvent applications is CFC-113. Its characteristics make it attractive for cleaning printed circuit boards and metals, in certain drying processes, and in miscellaneous solvent-related operations. In Rand's earlier work (Palmer et al., 1980), we estimated domestic sales of CFC-113 for solvent-related uses as 65.5 million pounds in 1976. DuPont (1981) has indicated that about 130 million pounds of CFC produced in the United States in 1979 went toward solvent applications. This figure may include some CFC-11, which is used to a limited extent as a solvent, but the amount is probably insignificant. CFC production differs from CFC domestic sales by the amount of CFC exported. In Rand's earlier work, exports were estimated at five percent of production. If we make this same assumption for 1979, then domestic CFC-113 solvent-related sales for that year amounted to about 123.5 million pounds. This represents an increase in CFC-113 domestic sales of 89 percent for the period 1976 to 1979.

We do not have an explanation for the startling increase in CFC-113 sales in the last few years. In our earlier work, we estimated domestic use at 90 million pounds. This estimate was based on projections supplied to us by the two CFC-113 producers—DuPont and Allied Corporation. We also developed two hypothetical projections of future CFC-113 sales based on alternative speculations about changes in the market. The actual sales increase between 1976 and 1979 was larger than the projected growth in the upper bound projection. The CFC-113 market is expanding rapidly and this emphasizes the importance of assessing the capability of methods for reducing CFC-113 emissions in this product area.

At least half the CFC-113 is sold in pure form. One CFC-113 producer estimated that 35 to 50 weight percent of sales is in mixed form. These mixtures can be blends or azeotropes (constant boiling blends) of CFC-113 and a second component. One producer estimated that sales of chemicals for use as second components in CFC-113 mixtures were about 7.5 million pounds in 1976. If we assume that 43 percent of the sales involved mixed CFC-113, the average mixture would be composed of 79 percent CFC-113 and 21 percent of a second constituent. If the estimate of pure and mixed CFC-113 still held in 1979, sales of pure and mixed CFC-113 would have amounted to 70.4 and 53.1 million pounds, respectively. Assuming that the mixtures retained the same average composition as in 1976, 67.2 million pounds of CFC-113 mixtures were sold in 1979.

In our chemical control options analysis, we have identified three control technologies that might be effective in reducing emissions. These include recovery and recycle of waste, carbon adsorption, and improved equipment and operating practices. Although improved operating practice could be classified as a work practice, we consider it, together with improved equipment, as a control technology. We have also identified several potential chemical substi-

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2In 1976, approximately five million pounds of CFC-11 were used in solvent applications.
3In the past, CFC-113 imports were negligible.
tution candidates in our assessment of chemical substitutes. We examine no options under the categories of work practices or final product substitutes.

In Table 4.1, we present the results of our analysis of the options for reducing emissions. As discussed in the Introduction to this report, we evaluate the options along two dimensions. The first is the potential of each individual option for reducing emissions, given in terms of CFC-11 equivalents; the second is the magnitude of dislocation to the industry if the option were adopted. Of the options listed in Table 4.1, three (carbon adsorption for pure CFC-113, improved equipment and operating practices, and external reclamation) also appear in Table 1.1 of the Introduction. All three options would result in at least a medium emissions reduction and would cause no more than a moderate dislocation.

**Table 4.1**

<table>
<thead>
<tr>
<th>Technical Option</th>
<th>Potential Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substitution</td>
<td>Very Large</td>
</tr>
<tr>
<td>Carbon adsorption</td>
<td></td>
</tr>
<tr>
<td>Mixed and pure CFC-113</td>
<td>Large</td>
</tr>
<tr>
<td>Pure CFC-113</td>
<td>Medium</td>
</tr>
<tr>
<td>Improved equipment and operating practices</td>
<td>Large</td>
</tr>
<tr>
<td>External reclamation of waste</td>
<td>Medium</td>
</tr>
</tbody>
</table>
II. Chemical Control Options Analysis

CONTROL TECHNOLOGY ASSESSMENT

Below, we discuss each of the control technologies that might be effective in reducing emissions. These include recovery and recycle of CFC-113 waste, carbon adsorption for the capture of CFC-113 vapors, and improved equipment and operating practices. Although improved operating practice is, in fact, a work practice, the manner in which the equipment is operated is intimately related to the characteristics of the equipment itself. We therefore discuss the two methods for reducing emissions in conjunction with one another.

Recovery and Reuse of Waste

The recovery and reuse of CFC-113 waste results in a reduced requirement for virgin solvent to accomplish the cleaning and drying. Potential emissions are therefore also reduced. According to Palmer et al. (1980), in 1976, about 84 percent of domestic solvent sales went toward cleaning and drying applications; the balance was used in dry cleaning, chemical processing, as a carrier medium, cutting fluid, and for other miscellaneous activities. Recovery of CFC-113 in these latter uses does not appear technically feasible but does hold some promise in cleaning and drying applications. One CFC-113 producer indicated that the fraction of CFC-113 devoted to each of the various end uses has not altered significantly since 1976. Therefore, we will assume that cleaning and drying applications accounted for 84 percent, or approximately 104 million pounds, of 1979 CFC-113 sales. Thus, recovery and recycle of waste might be used in the majority of CFC-113 applications.

The soils removed in the cleaning process accumulate in the boil sump of a two-sump vapor degreaser during cleaning operations. Eventually, this solvent becomes too contaminated for further use and it must be either reclaimed or discarded. Reclamation of CFC-113-based solvents for reuse is frequently accomplished in-house by the user. The two-sump vapor degreaser itself can be used to reclaim solvent. Most users, especially those with high product cleanliness standards, cannot use this purification technique indefinitely. The vapor degreaser serves only as a crude still that can delay, rather than prevent, the use of better purification methods or disposal.

For users with more exacting standards that require a more pure solvent, other reclamation methods can be used. One technique is single plate distillation, which can separate a volatile solvent or lower boiling point azeotrope from less volatile higher boiling contaminants. Another purification method is aqueous extraction, which can be used to obtain pure CFC-113 from some of its alcohol and acetone azeotropes. The second component of the azeotrope is soluble in water, whereas CFC-113 is not. Upon addition of water, the water/alcohol or water/acetone and the solvent phase separate. The water phase can be removed from the CFC-113 by gravity decantation in a water separator.

A technique for removing the maximum amount of solvent from sludge and keeping the sludge in liquid form is thin film evaporation. It usually employs steam heated to a temperature below the decomposition point of the material. Steam in contact with a thin film of sludge causes the solvent to vaporize while maintaining the disposable residue in liquid form.
Another process for removing high boiling sludge from solvent is steam stripping. It operates by codistilling the water/solvent phase and separating it from the sludge.

The most common method of in-house purification employed by users is distillation. Our earlier study, using data supplied by the CFC-113 producers, placed the 1976 cost of distillation units capable of processing 10 to 80 gallons per hour at between $2,000 and $3,000. One equipment manufacturer we have visited since quoted an $8,000 price for a refrigerated still sized for 20 gallons per hour. Another manufacturer estimated that the cost of stills with a throughput of between 30 and 600 gallons per hour ranges from $7,000 to $15,000. A 50 gallon per hour unit might cost $8,000. Much of the difference between the earlier and the more recent cost estimates is due to inflation; it might also be that the figures reported in 1976 were for less sophisticated equipment. The other cost to the user in using distillation is the equipment operating cost. Although we do not know these costs, we suspect they are less than the annual capital costs.

Consider a CFC-113 user with one vapor degreaser of medium or large size (60 to 375 gallons capacity). In our earlier study, we designed a simulation model for determining losses from the stock of vapor degreasers. The annual waste losses for users of medium and large vapor degreasers were estimated at 1,670 and 4,369 pounds, respectively. Industry sources indicate that distillation units achieve about a 95 percent efficiency. On this basis, a user with a medium sized degreaser might distill and reuse 1,587 pounds of CFC-113 annually; the figure for a user with a large vapor degreaser would be 4,151 pounds.

Distillation is cost effective if the solvent recovery credit exceeds the annual costs of using the equipment. The current price of CFC-113 to the user ranges between about 85¢ and $1.35 per pound. Very large users would purchase their CFC-113 in larger amounts at the lower price; smaller users would purchase their CFC-113 in smaller quantities at higher prices. Given that medium and large users could reuse between 1,587 and 4,151 pounds annually and the price range for CFC-113, the savings in CFC purchases through distillation could amount to between $1,349 and $5,604 per year. On the basis of the costs of distillation units given earlier, it would seem that many medium and large users would find distillation cost effective.3

Two factors further suggest that distillation is economically justified for a number of users. First, the distillation units described above are capable of processing perhaps 20 to 50 gallons per hour, or between 261 and 653 pounds of pure CFC-113 per hour. This translates into more than 2,000 pounds in an eight-hour day. Only extremely large users would need this capacity. Thus, medium and even most large users could purchase a distillation unit with much smaller capacity and, presumably, at a lower price. Second, many users who recycle would have more than one cleaning or drying operation in a plant. A single distillation unit could be used, therefore, to reclaim CFC-113 from multiple sources each day, providing for a higher processing rate and lower equipment price than might first be estimated for a set of independently operating distillation units.

It should be noted that many users do not use pure CFC-113; between 35 and 50 percent of the CFC-113 is sold in combined form. Some of the combinations are azeotropes (constant boiling mixtures) and some are blends (non-constant boiling mixtures). Widely used combinations include alcohol/CFC-113 and methylene chloride/CFC-113. In-house distillation units can be used with pure CFC-113 and CFC-113 azeotropes but should not be used for blends unless reformulation is performed before the mixture is reused. We do not know what fraction of the combined CFC-113 is azeotrope and what fraction is blend; however, it seems likely

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3Even assuming that operating costs are significant, this conclusion is probably still valid.
that no more than about half the combined material is blended CFC-113. Thus, in-house distillation might be used without the need to reformulate for 75 to 85 percent of the CFC-113 used for cleaning and drying.

Another important consideration that should be mentioned is purity. In practice, during cleaning operations, solvent is continuously withdrawn from the degreaser and routed to the still. One industry source estimates that a single-plate still is capable of increasing the purity of each unit volume of transferred solvent by one-half to one percent. This implies that the solvent may have to be cycled through the still at a high rate to maintain an acceptable level of purity in the degreaser.4 For users with a very high contamination rate, the still throughput must be correspondingly large. This requirement would increase the still and operating costs.

In the earlier work, we concluded that most medium and large users were already practicing in-house recovery, where possible. Even assuming high costs for distillation, we see no reason to alter this conclusion today. Indeed, several industry sources (the CFC-113 producers, reclaimers, and equipment manufacturers) report that many users do take advantage of in-house reclamation.

For users whose purity requirements do not make it economical to use in-house recovery, external reclamation is an option. In our earlier study, it was assumed that the amount of waste available for external recovery during cleaning and drying operations in 1976 was about 11 million pounds, or approximately 20 percent of the CFC-113 sold for cleaning and drying. The amount actually sent for external reclamation was estimated at three million pounds by industry sources. Of the remaining eight million pounds, half may have been buried and half promptly emitted through improper disposal practices. One CFC-113 producer indicated that the fraction of sales reclaimed today has not changed significantly since 1976. Assuming that this held true in 1979, about 21 million pounds were available for reclamation. Five million pounds were probably sent to reclaimers, and 16 million pounds were either buried or promptly emitted.

We visited two firms that routinely reclaim CFC-113 solvents. The first reclaimer has established a solvent-recovery program in which pure CFC-113 and CFC-113 blends are reclaimed to better than 99 percent purity. Users store waste CFC-113 in a bulk storage tank equivalent in size to several drums. The reclamation firm delivers these drums and retrieves them by truck when they are full. This reclaimer indicated that reclamation activity has increased recently and predicted an even larger increase in the future. He believes that one factor making reclamation increasingly more attractive to users is the disposal problem. Spent solvent CFC-113 is classified as hazardous waste. There is generally only one Class I dump site (one authorized to accept hazardous waste) that satisfies the Resource Conservation and Recovery Act. It serves a large area, and disposal costs can be as high as $65 per drum. There is a federal requirement (Fed. Reg., 1980) that the chlorinated solvent content of disposed of waste cannot exceed 20 percent; some localities require it to be less than 10 percent. Reclaimers are in a better position than users to deal with these disposal requirements. Through the distillation process, contaminants are concentrated in a small amount of sludge, which can be sent for disposal more economically.

The second reclaimer we visited can reclaim CFC-113 contaminated up to 50 percent. Common contaminants include oils, metal particles, water, inorganics, rosin flux, and other chlorinated solvents. The firm receives the waste CFC-113, filters it, and analyzes the con-

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4An acceptable level of purity is achieved when the product cleaned with the solvent satisfies a specific cleanliness standard.
tents using gas chromatography. The waste is then distilled and yields CFC-113 of 99.8 percent purity, which is equal to that of virgin. Generally, from 100 pounds of CFC-113 waste, 90 to 95 pounds of purified CFC-113 can be recovered, according to this reclaimer. The sludge is sent for disposal at a cost of $45 per drum.

Many CFC-113 mixtures are also purified by this reclaimer. In the case of CFC-113/ alcohol mixtures, the two components are separated with a water wash, then the CFC-113 is purified and blended with fresh alcohol. One azeotrope that presents a problem is CFC-113/methylene chloride. It is apparently extremely difficult to separate the components.\(^5\)

One reason that reclamation is not more widespread is that users question the purity of the reclaimed solvent. This fear is well-founded since some reclaimers do indeed use inadequate purification techniques. There are only a few reclamation firms (perhaps three to five) in the country that use sophisticated techniques for reclaiming CFC-113. Several other reclamation firms purify CFC-113 using vapor degreasers, and the purity of the reclaimed solvent is not adequate for many applications. Nevertheless, users with high purity standards could sell their spent CFC-113 for reclamation and it could be reused in another application where purity requirements are less stringent.

The costs of reclamation vary, depending on the arrangement the reclaimer has with the customer. Under a contract arrangement, the reclaimer picks up the contaminated solvent, reclaims it, and delivers the purified solvent back to the same customer. In this case, the charge for reclamation depends on the reprocessing costs and ranges from 30 to 60 percent of the price of virgin CFC-113. Another arrangement might be described as a one-time-only purchase. The reclaimer purchases contaminated solvent from a customer, reclaims it, and sells the purified CFC-113 to a different customer. In this case, because the reclaimer must pay for the contaminated solvent, the price he charges for reclaimed CFC-113 is about 80 percent of the virgin price. According to one reclaimer, most customers prefer the contract arrangement. Users are reluctant to sell contaminated solvent to a reclaimer on a one-time-only basis because they fear they are being cheated.\(^7\)

Because the price of reclaimed CFC-113 is well below that of virgin CFC-113, it is not obvious why many firms are reluctant to reclaim. One reclaimer is convinced that the reasons for this are that many firms are not aware that reclamation is an option, and they have no prior assurance of quality control. The comparatively low price of reclaimed CFC-113 may increase in the future. Disposal costs have risen significantly in recent years, and reclaimers may have to pass on these costs to customers in the future.

Increased external reclamation can reduce the requirement for virgin CFC-113. If we assume that the fraction of CFC-113 that ends up as waste has not changed since 1976, then 21 million pounds of CFC-113 waste were generated from cleaning and drying applications in 1979. If all of that had been sent for external reclamation, perhaps 19 million pounds of reclaimed CFC-113 would have been available for reuse.\(^8\) Probably all users, even those with stringent purity requirements, could use CFC-113 purified by a reputable reclamation firm.

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\(^5\) Alcohol is soluble in water whereas CFC-113 is not.
\(^6\) The boiling points of CFC-113 and methylene chloride are 118°F and 104°F, respectively.
\(^7\) This fear is based on a lack of knowledge about reclamation. The alternative to selling to a reclaimer is disposal, which is costly.
\(^8\) This calculation assumes that external reclamation has an overall 90 percent efficiency.
Carbon Adsorption

Carbon adsorption is one method for capturing solvent emissions from cleaning or drying equipment. This technique was first used in the early 1950s in dry cleaning machines. Since then, carbon adsorption has been employed, to some extent, in other solvent applications. In using such systems, the first step is to collect the solvent vapor-air mixture and pass it through an activated carbon bed. The second step is to desorb the solvent from the carbon bed, usually with steam. The final step is to separate the condensed solvent from the water for reuse.

The top of most vapor degreasers is surrounded by a series of lip vents, each between one and one-half and two inches in length. Solvent vapor and air are pulled into the lip vents, and the resulting stream can be channeled to a carbon adsorption unit. The solvent vapor capture rate depends on the velocity of air pulled in at the lip vents.

According to one carbon adsorption system manufacturer, there is an Occupational Safety and Health Administration (OSHA) requirement of 100 cubic feet per minute (cfm) of air per square foot of vapor degreaser surface area. Another equipment manufacturer indicates that the value recommended by EPA and OSHA is 65 cfm per square foot of vapor degreaser surface area. High exhaust velocities draw in more solvent vapor. In one sense, this is an advantage because fewer emissions occur. In another sense, high velocity can be a disadvantage, since it can draw solvent from the degreaser at a faster rate than it would be emitted naturally. However, even if the initial rate of emissions is increased by the high velocity of air, the carbon adsorption system will still capture the solvent, lowering total emissions. DuPont (1979) illustrated this effect. Diffusive losses from a vapor degreaser with a four square foot vapor-air interface are estimated at about two pounds of CFC-113 per hour. Exhausting air at 50 and 190 cfm increases the solvent loss to approximately three and eight pounds per hour, respectively. Carbon adsorption, together with exhaust air at 50 and 190 cfm, decreases the solvent loss to about 1.2 and 0.6 pounds per hour, respectively.

In the adsorption step, the solvent is commonly adsorbed using activated charcoal of 4 × 10 or 4 × 6. The desorption step is generally accomplished with steam. The steam, at atmospheric pressure, is passed through the carbon bed and displaces the solvent vapors. One industry source contends that it takes between five and 15 minutes to heat the entire bed. After this happens, there is a rush of solvent vapor from the bed, which is routed through a vapor line into a condenser. Other desorption methods are available. One user employs a system designed to regenerate the carbon, where the bed is placed under partial vacuum and is heated electrically.

The final step in the carbon adsorption process is the separation of the solvent from water if steam is used for desorption. This is generally accomplished with either mechanical or distillation separation techniques. Pure CFC-113 and water are immiscible, and a decanter will successfully separate them. The heavy CFC-113 will sink to the bottom and will separate from the water, which remains on top. Distillation is also practical for CFC-113. It may even be preferred in cases where contaminants must be removed before the solvent can be reused. The distillation unit operates on the basis of widely differing boiling points. For separating pure CFC-113, with a boiling point of 118°F, and water, with a boiling point of 212°F, distillation, together with a simple drying step for separating the small amount of water that codistills, is sometimes convenient.

Traditionally, 4 means 4 openings per inch and 6 means 6 openings per inch. A 4 × 6 means that granular material will pass through a number 4 screen but remain on a number 6 screen.
There are more sophisticated methods of employing carbon adsorption techniques. One method, used in Japan, is based on the principle of a moving carbon bed. The carbon flows downward over a series of staggered trays. Adsorption occurs when the moving carbon intersects the solvent/air inflow stream. After adsorption, the carbon continues to the bottom of the unit where it passes through a series of parallel tubes heated on the outside by steam. The heat transferred from the steam to the carbon drives off the solvent, regenerating the carbon for a return pass by airlift. The adsorption/desorption cycle is continuous. One clear advantage of the system is that no distillation is required. A disadvantage of the system is that the capital costs are about twice those of the traditional bed carbon adsorption unit.\(^\text{10}\)

Another alternative adsorption system design is the arrangement of canisters in series. Each canister has a thin shell of carbon bed just within the outside wall of the canisters. The bed depth in each canister is about four inches, so the thickness of the "total" bed consisting of three canisters is about one foot. Efficiencies of traditional deep beds are at least 85 percent, according to one manufacturer. The canister arrangement can provide a slightly higher efficiency, since the solvent/air mixture can be passed through more than one carbon bed (more than one canister), each of which is 85 percent efficient. One disadvantage of the canister arrangement is that it can be used only with inlet gas streams whose solvent concentrations are low (50 to 200 ppm).

There have been few sales of carbon adsorption systems for CFC-113 in the last several years, according to two system manufacturers. One reason is the high cost of such systems relative to vapor containment techniques. One CFC-113 producer recommends against the use of carbon adsorption and, instead, favors emission control devices (higher freeboard,\(^\text{11}\) covers, condensation), which reduce solvent emissions before the vapors are diluted with air. Indeed, many users prefer condensation, which is considerably cheaper than carbon adsorption. This method, sometimes called the "cold trap," is also discussed later in the section on better equipment. Briefly, condensation involves adding a second set of refrigerating coils above the standard first set.

We visited one user who employs a carbon adsorption system with a deep bed arrangement for pure CFC-113. The system consists of two tanks about four to five feet tall and four to five feet in diameter, which together hold about 1,000 pounds of carbon. The CFC-113 is desorbed with steam and a gravity separator is used to separate the CFC-113 and the water. This system is used with a large (~ 400 gallons) conveyorized degreaser with a continuously operating still. Air is drawn through the entrance and exit ports of the degreaser at a rate of 1,700 cfm; the CFC-113 concentration in the exhaust stream is 300 ppm. Adsorption and desorption occur at two-hour intervals. According to this user, operating costs of the system are small compared to capital costs.

Carbon adsorption systems are more complicated to use when the solvent is a mixture because they alter its composition. In a CFC-113/alcohol mixture, for example, which is commonly used for the defluxing of printed circuit boards, the alcohol is soluble in water whereas the CFC-113 is not. Thus, when steam is used for desorption, the alcohol is retained in the water. The CFC-113, a separate phase, can be collected, but before it can be reused, the correct proportion of alcohol must be added. Users of mixtures are therefore reluctant to employ carbon adsorption, not only because of the difficulties of accomplishing this reformulation but also because some mixtures are proprietary and user reformulation may conflict with patents.

\(^{10}\)We do not know why this method is used in Japan and not in the United States. To learn the reason would require analyses of the economics in both countries.

\(^{11}\)Freeboard ratio is defined as the ratio of the height of the equipment above the vapor line to the width.
One system manufacturer, however, believes that the reformulation process itself is not a serious problem. It could be assumed that all of the alcohol is removed with the water during adsorption, and the correct proportion of alcohol could simply be added to the pure CFC-113 without analysis. In contrast, one CFC-113 producer does not believe that the reformulation process is that simple. This producer claims that, since water extraction may not remove all the alcohol, the solvent from the adsorber must be analyzed to determine the level of any remaining alcohol. The results of this analysis will indicate the amount of alcohol that must be added to bring the mixture back to its original composition. The addition of alcohol must be performed carefully, with thorough mixing, because the alcohol, in concentrated form, is flammable and may present a danger to the workers. Another system manufacturer is also concerned about flammability and claims that while carbon adsorption can be used readily with pure CFC-113 and with CFC-113/methylene chloride blends, he would never recommend carbon adsorption for use with CFC-113/alcohol blends because the blend could easily become alcohol rich, and therefore flammable.\footnote{It is important to observe that, even though alcohol does have a low flash point, it is widely used industrially for a number of other purposes. In those applications, industry has developed special handling procedures, controls, and equipment, which allow the use of alcohol with minimum risk.}

Reformulation of solvents that contain a small percentage of extractable component is in fact difficult. Such a solvent is CFC-113 mixed with four percent ethyl alcohol and about one percent nitromethane stabilizer. The difficulty arises because simple techniques for monitoring composition, such as specific gravity, are inadequate to assure quality control. More expensive instrumental control devices would have to be used instead. For solvents where no component is present in a small percentage, for example CFC-113/35 percent isopropyl alcohol, reformulation problems are less severe, in our opinion, since simpler and less expensive procedures are available for monitoring solvent composition. In this case, a simple specific gravity measurement could be used after desorption to reveal the remaining alcohol content. Alcohol could then be added to the CFC-113 proportion to bring the mixture back to its original composition. Of course, caution would have to be exercised during reformulation because of the flammability of the alcohol.

Many users of mixtures, to avoid the question of reformulation, do not consider carbon adsorption a viable option. Of the few systems sold, almost all are used with pure CFC-113. While water soluble components can be added to the recovered solvent on the basis of a specific gravity measurement, the procedure has not been successful in practice because degreaser operators are often inexperienced, poorly paid, and as a consequence, unreliable. One system manufacturer told of an attempt to automate the maintenance of solvent composition for a mixture of methylene chloride and alcohol, used for removing photoresist. This particular solvent requires a stabilizer additive. No inexpensive, reliable method to monitor the stabilizer concentration could be identified. This same problem would arise in the case of some CFC-113/alcohol mixtures that require nitromethane as a stabilizer.

Costs of carbon adsorption systems depend upon many factors, including the construction materials. For CFC-113, baked phenolic and steel vessels and copper condensing coils can be used. For a very basic deep carbon adsorption system, low cost units range from $10 to $15 per cfm of air; more expensive units lie in the range of $30 to $40 per cfm of air. The cost of a canister system with two tanks, one for adsorption and one for desorption, is lower, at $7 or $8 per cfm of air. Distillation units, which are used with some systems to effect the water/solvent separation, are priced as low as $20,000 and can range well above $30,000. According
to one carbon adsorption system manufacturer, if a plant does not already have a steam source, installation can double the capital cost of the adsorption system. The desorption step, which requires steam, is energy-intensive and is probably the main contributor to the operating costs.

DuPont (1979) presented the costs of a carbon adsorption system in new and existing facilities; some of their cost data were taken from another study, OAQPS (1977). Data from both sources are summarized in Table 4.2. The costing basis used by both DuPont and OAQPS assumes 2,250 operating hours per year, 4¢ per kilowatt hour, an interest rate of ten percent, an equipment life of ten years, and a degreaser with a vapor-to-air interface of 1.67 square meters.

Table 4.2

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>DuPont</th>
<th>OAQPS</th>
<th>Modified OAQPS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model New Facilities</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installed capital ($)</td>
<td>7,400</td>
<td>7,400</td>
<td>7,400</td>
</tr>
<tr>
<td>Direct operating cost ($/yr)</td>
<td>451</td>
<td>451</td>
<td>451</td>
</tr>
<tr>
<td>Capital charges ($/yr)</td>
<td>1,268</td>
<td>1,268</td>
<td>1,268</td>
</tr>
<tr>
<td>Solvent cost (credit) ($/yr)</td>
<td>0</td>
<td>(1,419)</td>
<td>(4,501)</td>
</tr>
<tr>
<td>Net annualized cost (credit) ($/yr)</td>
<td>1,719</td>
<td>300</td>
<td>(2,782)</td>
</tr>
<tr>
<td>Controlled emissions (metric tons/yr)</td>
<td>3.3</td>
<td>3.3</td>
<td>3.3</td>
</tr>
<tr>
<td>Cost (credit) $ per kg controlled</td>
<td>0.521</td>
<td>0.091</td>
<td>(0.843)</td>
</tr>
<tr>
<td><strong>Model Existing Facilities</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installed capital ($)</td>
<td>10,300</td>
<td>10,300</td>
<td>10,300</td>
</tr>
<tr>
<td>Direct operating cost ($/yr)</td>
<td>451</td>
<td>451</td>
<td>451</td>
</tr>
<tr>
<td>Capital charges ($/yr)</td>
<td>1,765</td>
<td>1,765</td>
<td>1,765</td>
</tr>
<tr>
<td>Solvent cost (credit) ($/yr)</td>
<td>0</td>
<td>(1,419)</td>
<td>(4,501)</td>
</tr>
<tr>
<td>Net annualized cost (credit) ($/yr)</td>
<td>2,216</td>
<td>797</td>
<td>(2,185)</td>
</tr>
<tr>
<td>Controlled emissions (metric tons/yr)</td>
<td>3.3</td>
<td>3.3</td>
<td>3.3</td>
</tr>
<tr>
<td>Cost (credit) $ per kg controlled</td>
<td>0.67</td>
<td>0.242</td>
<td>(0.692)</td>
</tr>
</tbody>
</table>

\(^a\) In the DuPont study (1979), this value was in error, and we have revised it.

For discussion purposes, we examine the values of Table 4.2 for new facilities. The DuPont and OAQPS entries for "installed capital," "direct operating cost," and "capital charges" in Table 4.2 are identical. This reflects the fact that the two sources used the same carbon adsorption system cost data. Under the entry "solvent cost (credit)," DuPont takes no credit for reusable solvent, whereas OAQPS takes a credit of $1,419. OAQPS derived this value by assuming that 3.3 metric tons per year of trichloroethylene (a chlorinated solvent), at a price

\(^b\) The purpose of the OAQPS study was to provide information to pollution control agencies on the various techniques for reducing emissions from solvent metal cleaning (degreasing) operations. One such technique, carbon adsorption, is examined in detail.
of 43¢ per kilogram, could be captured by the carbon adsorption system and reused.\(^{14}\) DuPont’s data are for CFC-113, and it is assumed that the 3.3 metric tons per year controlled by the carbon adsorption system cannot be reused.

The DuPont and OAQPS entries for “net annualized cost (credit)” in Table 4.2 were calculated by adding (subtracting) the figure for “solvent cost (credit)” from the sum of the values for “direct operating cost” and “capital charges.” The entry for “cost (credit)” in Table 4.2 for each source was determined by dividing the value for the “net annualized cost (credit)” by the number of kilograms of solvent controlled (in both cases 3,300 kilograms or 3.3 metric tons). DuPont obtains a cost of about 52¢ per kilogram of solvent controlled, and OAQPS calculates a lower value, approximately 9¢ per pound. DuPont’s figure is much higher because credit for the controlled CFC-113 was not taken.

In the third column of Table 4.2, we have modified the OAQPS trichloroethylene data to apply to CFC-113. In the entry for “solvent cost (credit),” we have assumed that the 3.3 metric tons of CFC-113 controlled through carbon adsorption can be reused. Since the OAQPS and DuPont data were based on first quarter 1977 costs, to be conservative, we have used the 1976 bulk CFC-113 price of 62¢ per pound.\(^{15}\) Using these assumptions, a net annualized credit of $2,782 could be realized, resulting in a credit of about 84¢ per kilogram of CFC-113 controlled in new facilities. In existing facilities, carbon adsorption for CFC-113 also appears cost effective and would generate a net annual credit of $2,285 or a credit of about 69¢ per kilogram of solvent controlled.

OAQPS also made a cost analysis of carbon adsorption units for a smaller vapor degreaser with a vapor to air area of 0.8 m\(^2\) (≈9 ft\(^2\)) for new and existing facilities. Using the 1976 price of CFC-113, it appears that carbon adsorption is clearly cost effective for new facilities and only marginally cost effective for existing facilities. They also analyzed conveyored units. For both monorail and cross-rod conveyored degreasers, carbon adsorption is cost effective for both new and existing facilities, again assuming the 1976 price of CFC-113.

The OAQPS values modified for CFC-113 address the cost of using carbon adsorption to collect vapors from one vapor degreaser. Those with multiple vapor degreasers in a plant could exhaust vapors from all degreasers to the carbon adsorption unit for collection. In these cases, carbon adsorption would be more economical.

For users of CFC-113 mixtures, carbon adsorption would be more costly. In these cases, it might be necessary to hire an additional worker to monitor the reformulation operation. This worker might devote approximately one-third of his time to carbon adsorption and perhaps two-thirds of his time to other emissions reduction activities (in-house or external reclamation). Let us assume that the annual cost to a firm of monitoring the carbon adsorption operation totals $7,000 per year. In a new facility with a vapor degreaser of the type given in Table 4.2, the price of the mixture that would justify this additional cost is $1.20 per pound; in an existing facility, the mixture price must reach $1.27 per pound. We suspect that these prices exceed 1976 mixture prices, which implies that carbon adsorption is probably not cost effective for mixtures.

We want to emphasize that our conclusion in this analysis, that the costs of carbon adsorption are justified for some pure CFC-113 users, may not be accurate today. Indeed, we have based our analysis on the early 1977 cost estimates and assumptions of OAQPS. Energy costs, which affect operating costs, have increased significantly in the last few years. Our only current evidence that operating costs are far below capital costs comes from a user of pure CFC-113 with a very large conveyored degreaser.

\(^{14}\)3 metric tons/year \times (1,000 kilograms/metric ton) \times (43¢/kilogram) = $1,419/year
\(^{15}\)3,300 kilograms/year \times (2.2 pounds/kilogram) \times 62¢/pound = $4,501.
Because of the economics, carbon adsorption seems to offer only limited promise for reducing vapor emissions in today's market and regulatory environment. It may be cost effective for certain users who employ pure CFC-113. Users with large open top and conveyerized degreasers, or users with multiple degreasers, would find it especially attractive. In the electronics industry, the defluxing of printed circuit boards usually requires one of the CFC-113/ alcohol mixtures. There are serious complications in using carbon adsorption with mixtures, particularly those where a stabilizer is required.

Improvements in Equipment and Operating Practices

Most open top vapor degreasers are small, generally holding less than 100 gallons. According to one equipment manufacturer, approximately 80 percent of the degreasers hold less than 50 gallons; most units are in the 13 to 34 gallon size range. Another manufacturer estimated that the average degreaser used in the electronics industry has two sumps, is 18 to 20 inches wide, 30 inches to 36 inches long, and has a capacity of 25 to 30 gallons. Two types of conveyerized degreasers are available. The "in-line" is the oldest type and has a long rectangular appearance with a flat mesh conveyor belt running lengthwise. One manufacturer reported that the latest design operates with a much lower solvent charge than the older type. The "cross rod" conveyerized degreaser is in the form of a deep bin with a computerized hoist, which is commonly used to circumvent operator difficulty in high freeboard degreasers. The smallest unit of this type has a capacity of 90 gallons. One user we visited has a conveyerized ultrasonic machine that is 60 feet long and holds 400 gallons of solvent.

An equipment manufacturer indicated that a firm with poor equipment could reduce vapor losses by 30 to 50 percent by purchasing better equipment that is more conservative of solvent. Poorly designed equipment will lead to high vapor losses. For several years, knowledgeable industry sources have been aware of some equipment features that can reduce emissions. The first is that a well-designed machine should have a 75 percent freeboard ratio. A second conservation measure is to design the equipment with spray attachments located well below the vapor/air interface and positioned such that the spray will be directed downward. A third feature of a well-designed machine is refrigerated condensing coils; the coils prevent the escape of vapors by condensation. One additional feature that has been suggested for conserving solvent is the "cold trap," also known as a freeboard chiller. On CFC-113 vapor degreasers, this is a second set of cooling coils operating at a temperature between −30°F and 32°F. According to one equipment manufacturer, this system is most useful on small units that frequently stand idle. On large conveyerized units, it may actually act to increase emissions. An induced turbulence can result from the large difference in the ambient and coil temperatures, and the coils must periodically go through a defrost cycle to remove ice condensed from the atmosphere. Otherwise, this ice insulates the coils and reduces their efficiency.

According to one equipment manufacturer, users replace equipment either to reduce costs or to increase throughput. The lifetime of vapor degreasers is variable, subject to the conditions under which they have been operated. One equipment producer cited an example of a machine built in 1940 that was still operating and told us of another that corroded in two or three years.

One equipment manufacturer claimed that improved operating practices could reduce emissions even further than better equipment. Dragout losses, where solvent is dragged out
on the part, occur in an open top vapor degreaser when the operator removes the part from the vapor zone too quickly. In conveyorized equipment, the part can be automatically shaken or rotated to reduce this loss. Freeboard chillers can prevent diffusion losses and so can covers on the equipment when it is not in use—but only the operator actually covers the machine. Waste losses can also be minimized if the operator follows the correct procedure. When the contamination level becomes high, the solvent should be boiled down to concentrate the contaminants and the solvent saved for reuse. Current practice is simply to remove the contaminated solvent and fill the tank with fresh solvent. With conveyorized units that are all sold with stills, the oils are continuously removed without operators.

The extreme variation in equipment lifetime, characteristics, and operation, and the fact that users number in the thousands, make it difficult to accurately define current degreaser losses. It is therefore not possible to calculate the potential emissions reductions from replacing a current machine with one that is better designed and operated. In our opinion, a satisfactory way of approaching this problem is to determine, with the help of users and other knowledgeable industry sources, the characteristics of current equipment and operating practices and improved machines and operating practices. The loss from an average current unit and the average improved unit can be calculated, with the difference representing the leverage of improved equipment and operation in reducing emissions. In our earlier study, we designed a simulation model to calculate the losses from vapor degreasers of various types and sizes. The model, designed with help from industry, proved a useful tool for determining machine losses and describing equipment currently in use. We have no reason to suspect that losses from these degreasers have changed significantly since this work was performed. At that time, our estimate of the reduction in annual vapor losses from improved equipment and operation was 45 percent.

Pedco Environmental, Inc., in a 1979 study performed for EPA, measured actual losses from vapor degreasers using 1,1,1-trichloroethane (TE) and methylene chloride (MC). The effects of various conservation measures, including the use of covers, an increased freeboard height, and refrigerated freeboard chillers, were compared with base case losses. Use of covers on idle degreasers holding boiling and non-boiling MC and TE decreased losses from 0 to 61 percent. A freeboard ratio increase from 50 to 75 percent decreased losses to between seven and 25 percent for the two solvents; increasing the freeboard ratio to 100 reduced losses to between 47 and 53 percent in TE vapor losses. The effects of two refrigerated freeboard chillers were studied, one at 1°C to 2°C and the other between −23°C and 32°C. For TE, both chillers were effective in reducing vapor losses at a freeboard ratio of 50 percent, had no effect at a freeboard ratio of 75 percent, and increased losses at a freeboard ratio of 100 percent. With MC, the first refrigerated chiller increased emissions at 50 and 75 percent freeboard ratio; the second decreased solvent loss at 50 and 75 percent freeboard ratios by 16 and 30 to 35 percent, respectively.

The PEDCO data are not especially useful for our purposes for two reasons. First, the study was designed to examine vapor loss reductions for TE and MC rather than CFC-113. Second, from the study results, it is not easy to extend the data for cumulative conservation effects. That is, the reductions achievable through simultaneous use of covers, increased freeboard ratio, and refrigerated freeboard chillers are not obvious. The data do provide confirmation, however, that our estimate that vapor emissions can be reduced by about 45 percent with combined improved equipment and better operation is not unreasonable.

One equipment manufacturer estimated the current price of a conservative16 13 gallon

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16Conservative is meant to describe equipment that is designed to minimize solvent makeup and emission losses.
vapor degreaser at between $3,300 and $6,600, depending on whether or not the machine is ultrasonic. Another manufacturer estimated that the cost of an average unit (25 to 30 gallons) would be in the range of $5,500 to $6,000. Ultrasonic capability would increase the price about a third. These costs are somewhat lower than those estimated in the earlier work; at that time the cost of a nonultrasonic 16 gallon unit was estimated to be in the range of $3,000 to $4,500; the price of an ultrasonic unit was estimated at between $6,200 and $7,500. These earlier estimates applied to machines manufactured in 1976 and 1977 and were made by a CFC-113 producer rather than an equipment manufacturer. Nevertheless, both the earlier and current estimates illustrate that equipment prices vary significantly depending on size and the features of a particular machine.

In the earlier work, our simulation indicated that losses from a 15 gallon vapor degreaser could be reduced by 1,228 pounds each year with a more conservative machine. As mentioned earlier, although the bulk price of CFC-113 is presently about 85¢ per pound, many users pay up to $1.35 per pound for the CFC-113 they purchase. Applying this CFC-113 price range to the savings estimate of 1,228 pounds, a user might reduce his costs for CFC-113 purchases by between $1,044 and $1,658 annually through using more conservative equipment.

We do not know the difference in price for poor and conservative equipment. In the earlier study, we assumed that a less conservative machine might be priced 40 percent below a conservative machine. For the purchase of a more conservative machine to be economically justified, the savings in CFC-113 purchases must outweigh the annual cost differential between the less conservative and more conservative equipment. Given the range of conservative equipment prices (about $3,000 to $8,000) and the assumption that less conservative equipment is priced about 40 percent lower, we suspect that purchase of the better equipment is cost effective today for many users. This is especially true for users who purchase CFC-113 in small quantities at higher prices.

For larger machines, we expect a similar result. These machines would be much more costly, but savings from the purchase of a more conservative degreaser would also be much larger.

It should be noted that we have based our analysis on the costs of improved equipment and have not included the costs of improved operating practices. The CFC-113 savings achievable through purchasing better equipment contain an implicit assumption that the equipment will be properly operated. For example, we presume that a refrigerated freeboard chiller would be operated at an appropriate temperature and that covers would be used when possible. It seems reasonable to assume that a firm willing to invest in a rather expensive sophisticated piece of equipment would also be willing to expend some effort to assure its correct operation.

SUBSTITUTION OF ALTERNATIVE SOLVENTS

Introduction

Substitution of alternative solvents for CFC-113 is frequently mentioned as one method of reducing CFC emissions. Since the uses of CFC-113 in solvent applications are diverse,
each use must be examined separately to evaluate whether or not an appropriate substitute is available.

Table 4.3 shows the distribution of CFC-113 sales for 1976.

Table 4.3

DOMESTIC SALES OF CFC-113 FOR SOLVENT-RELATED USES, 1976
(In millions of pounds)

<table>
<thead>
<tr>
<th>Category</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleaning and drying (total)</td>
<td>55.2</td>
</tr>
<tr>
<td>Vapor phase cleaning:</td>
<td></td>
</tr>
<tr>
<td>· Defluxing</td>
<td>14.3</td>
</tr>
<tr>
<td>· Metal cleaning</td>
<td>3.6</td>
</tr>
<tr>
<td>· &quot;Critical cleaning&quot;</td>
<td>18.4</td>
</tr>
<tr>
<td>Liquid phase cleaning:</td>
<td></td>
</tr>
<tr>
<td>· Open cleaning</td>
<td>6.6</td>
</tr>
<tr>
<td>· Closed systems</td>
<td>4.2</td>
</tr>
<tr>
<td>Drying</td>
<td>3.7</td>
</tr>
<tr>
<td>Government</td>
<td>4.4</td>
</tr>
<tr>
<td>Dry cleaning (total)</td>
<td>2.2</td>
</tr>
<tr>
<td>Other (total)</td>
<td>8.1</td>
</tr>
<tr>
<td>Chemical processing:</td>
<td></td>
</tr>
<tr>
<td>· Reaction medium</td>
<td>1.2</td>
</tr>
<tr>
<td>· Intermediate</td>
<td>2.2</td>
</tr>
<tr>
<td>· Carrier medium</td>
<td>2.7</td>
</tr>
<tr>
<td>· Cutting fluid</td>
<td>1.6</td>
</tr>
<tr>
<td>· Miscellaneous</td>
<td>0.4</td>
</tr>
<tr>
<td>Grand total</td>
<td>65.5</td>
</tr>
</tbody>
</table>


The "dry cleaning" and "other" uses of CFC-113 represent applications where the particular properties of CFC-113 are excellent for accomplishing the stated purpose. These uses together accounted for only 16 percent of 1976 CFC-113 domestic sales, and substitution of an alternative chemical offers very little promise for reducing total solvent emissions. Liquid phase cleaning involves cleaning and maintenance of electronic and computer components as well as the cleaning of tubing and piping; it also represents only 16 percent of total CFC-113 solvent sales. CFC-113 displaces water in its drying applications, which account for six percent of CFC-113 sales. Substitution for CFC-113 in vapor phase cleaning applications offers the most leverage for reducing emissions. Although we do not know exactly what the government uses of CFC-113 include, we suspect that some is used for vapor phase cleaning. Vapor
phase cleaning together with government uses represent 62 percent of 1976 CFC-113 solvent sales. Because these two applications account for the majority of CFC-113 solvent use, we limit our investigation of potential alternatives to these two areas.

One CFC-113 producer indicated that the allocation of CFC-113 solvent sales has not changed significantly since 1976. Thus, we presume that vapor phase cleaning and government uses accounted for more than half the 1979 CFC-113 sales. Assuming that the 1976 allocation applies to the 1979 sales estimated at 123.5 million pounds, about 77 million pounds of CFC-113 went toward vapor phase cleaning and government activities in 1979.

Components that are cleaned in the vapor phase in defluxing, metal cleaning, and critical cleaning are described in some detail below. In general, for defluxing, CFC-113 is usually combined with alcohol to remove ionic contaminants and rosin flux. According to one CFC-113 manufacturer, plain boiling alcohol would be the best cleaner for this purpose, except that it apparently does not dissolve a white residue left after soldering.\(^{14}\) Technically, there are alternatives to CFC-113 in metal cleaning where oil, grease, and particulates are removed from metal parts or assemblies. Indeed, one CFC-113 producer rates methylene chloride as the closest substitute. In critical cleaning, CFC-113 is used to clean components containing plastics, elastomers, or sensitive metals that must meet very high cleanliness standards.

In addition to CFC-113 and its mixtures, a number of other solvents are used in the United States today. These include various alcohols and ketones, both of which are flammable; chemicals belonging to the chlorocarbon family, which are generally toxic; and water. In our analysis, we exclude the ketones and alcohols from consideration as potential CFC-113 substitutes primarily because their flammability presents a danger to workers. In the following subsections, we present certain properties of various solvents. We include the properties of two alcohols—ethanol and 2-propanol—simply because they were identified by one CFC-113 producer as having nearly the ideal properties for defluxing. We also include the properties of several chlorocarbons—methylene chloride, trichloroethylene, 1,1,1-trichloroethane, and perchloroethylene—all of which are widely used as solvents and can be considered as potential alternatives to CFC-113. Three other chlorocarbons—chloroform, carbon tetrachloride, and 1,1,2-trichloroethane—appear in our analysis only for completeness. We do not consider these solvents to be potential substitutes for CFC-113 because their threshold limit value (TLV)\(^{15}\) ratings of 10 ppm virtually prevent their use.

One additional solvent we examine in our analysis is deionized water. According to one firm that markets the water, the largest industrial consumers of treated water are those in the microcircuitry business, which suggests that it may already have made inroads into the CFC-113 market for defluxing. Water is significantly cheaper than other common solvents, ranging in cost from $2 to $50 per 1,000 gallons depending on its quality and the method used for purification. Currently, most water used for cleaning is simply exhausted into the sewer systems, but this practice might be prevented in the future through regulation. There has been some indication, in recent years, that water has been displacing other solvents in certain applications, and it is largely for this reason that we include it as a potential CFC-113 substitute.

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\(^{14}\) Pure alcohol is also flammable and requires special handling controls and equipment.

\(^{15}\) TLV is the maximum allowable time-weighted average concentration to which a human may be exposed over an eight-hour working day, 40-hour work week. Generally, the more toxic the chemical, the lower the TLV. CFC-113 has a TLV of 1,000, the highest value assigned.
Specification of Contaminants and Substrates

The primary use of solvents is to clean and dry various items of communication equipment (e.g., copier equipment, magnetic tape, telephone relays, printers, and television receivers), electronic components (e.g., printed circuits, microcircuitry, capacitors, resistors, connectors, and ferrite computer cores), glass products (e.g., optical lenses and fiber optics), instrumentation and metering devices (e.g., gyroscopes and tape heads), machinery (e.g., relays, motors, and bearings), metals (e.g., aluminum, brass, bronze, steel, copper, nickel, stainless steel, tin, and titanium machined and drawn parts), and medical equipment (e.g., catheters, hypodermic syringes, and scalpel blades). These items are made from a large variety of substrate classes (e.g., plastics, elastomers, metals, glasses, and semiconductor materials) and each class has many individual substrate members. The principal metals have been listed above. The plastics include ABS plastics, acetal resins, acrylic fiber and resins, cellulose acetate and nitrate, epoxy resins, nylon, phenolic resins, polycarbonate resins, polychlorotrifluoroethylene, polyethylene, polypropylene, polystyrene, PVC, and silicone resins. The elastomers include neoprene, butadiene/acrilonitrile, butadiene/styrene, isoprene/isobutylene, and polysulfidic types. Each of these substrates can be expected to interact with a given solvent in a different way. The glasses and semiconductor classes are less sensitive to the differential action of solvents.

The contaminants on these substrates are varied but principally consist of greases and oils (including fingerprints), salt, rosin flux, plating salts, waxes, water, dust, and machined substrate fragments. These may be grouped into the generic classes of polar, nonpolar, and particulate contaminants. The greases (not including their surfactants), oils, rosin, and waxes make up the nonpolar group and are generally composed of long chain hydrocarbons or molecules with long hydrocarbon side chains. Rosin flux residues, sodium chloride, and soldering and plating salts make up the polar group, whereas dust and machining fragments make up the particulate group.

CONSIDERATIONS IN SELECTING AN ALTERNATIVE SOLVENT

In selecting an alternative solvent for cleaning and drying a particular item, several technical factors must be taken into account simultaneously. These include selecting a solvent that will (a) remove all contaminants rapidly while not attacking the materials of construction (the substrate materials); (b) provide a rapid rate of evaporation of excess solvent (so that remaining solvent will not interfere with following manufacturing steps); (c) provide a minimal risk to workers (i.e., low flammability and toxicity); (d) require a low expenditure of energy; (e) be compatible with existing or slightly modified degreaser designs; and (f) be a minimal threat to the ozone layer.

The requirement that a solvent remove all contaminants while leaving the substrate unharmed is complicated. As we have noted, the contaminants consist of polar, nonpolar, and particulate residues whereas, in general, a solvent that removes one of these residue types is poor at removing the others. Hence a compromise must be achieved that balances the solubilities of the polar and nonpolar contaminants in the solvent and the ability of the solvent to wet and detach particulates from the substrate surface.

In actual practice, the selection of alternative solvents would be determined case by case. The wide variation in item composition, contaminants, available equipment, quality specifications, and cost constraints would not practically allow any other approach. The analysis
would require that a particular item with its associated substrate makeup and expected set of contaminants be chosen, along with a candidate solvent. The time required for the solvent to eliminate the most difficult-to-remove contaminant in available or slightly modified equipment would be determined as well as the time to evaporate residual solvent retained on the part. All candidate solvents that have contaminant elimination and evaporation times that exceed those accepted in current practice would be eliminated from consideration. The remaining solvents would be examined for compatibility with substrates during the degreasing time. Next, one would determine the operating costs of solvents that were substrate-compatible—this would include the estimation of energy consumption. Finally, the lower cost solvents remaining at this stage would be examined for flammability and toxicity; the high risk solvents would either be eliminated from further consideration or proper contaminant removal practices (and additional costs) would be introduced.

Such a complete analysis is beyond the scope of this effort. To address the problem, we have taken a simpler approach in which we follow the principal elements of the decision-tree analysis outlined above, but determine only the relative ranking of solvents with respect to evaporation rates and certain contaminant removal capabilities (details are given in the next subsection). Operating costs of the various solvents in degreasers are not estimated but instead the energy of vaporization of the solvent (a dominant factor in operating costs) is used to establish a ranking. Solvents appearing high in all the solvency rankings are considered potential substitutes—xicity, energy use, and special problems are then considered separately to lead to a final list of possible substitutes.

The Selection of Alternative Solvents

A selected list of cleaning solvents has been gathered in Table 4.4, along with the values of several parameters that bear on their contaminant removal capabilities. Solvents have been selected from the CFC, chlorocarbon, and aqueous groups. Most CFC mixtures and all nonflammable chlorocarbons have been included except tetrachloroethylene (TCE), which is highly toxic (TLV = 5 ppm). CFC-11 is excluded from consideration because its ozone depletion factor is greater than that of the CFC-113 it would replace. Two alcohols (ethanol and 2-propanol) have been included because they are components of some of the CFC-113 blends and azeotropes and because the electronics industry knows they are capable of removing resin flux.

The evaporation rate of each solvent relative to carbon tetrachloride is tabulated in the first column. The second column gives the boiling point of each solvent. This is important because the relative volatility of a solvent is expected to be given by the ordering of inverse boiling points. (This expectation can be verified by comparing the volatility orderings given by the evaporation rate and inverse boiling point values—only trichloroethylene differs by more than one position between the two orderings and this occurs only because of a clustering of similar boiling points.)

The next two columns give measures of the solvent's capacity for forming solutions with a nonpolar constituent and a polar constituent. We have limited our consideration here to a long chain hydrocarbon, n-hexadecane, and to water. Molecules of the general chain length of hexadecane are found in several oils and greases and thus this compound may be considered

\[\text{Longer times must be considered if there is a substantial likelihood of a part falling into the solvent and remaining there for a long period of time, as is possible with certain in-line convoyerized degreasers.}\]
Table 4.4

SELECTED PARAMETER VALUES OF VARIOUS SOLVENTS

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Evaporation Rate (a)</th>
<th>Boiling Point (b)</th>
<th>Miscibility (b)</th>
<th>Solubility (Wt. % of H₂O at 77°F) (c)</th>
<th>Wetting Index (\psi_{1000}) (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC-113</td>
<td>260</td>
<td>118</td>
<td>.64</td>
<td>.01</td>
<td>126</td>
</tr>
<tr>
<td>CFC-113/5.7% methanol (e,d)</td>
<td>--</td>
<td>103</td>
<td>(.14)</td>
<td>.27</td>
<td>121</td>
</tr>
<tr>
<td>CFC-113/3.2% ethanol (e,d)</td>
<td>--</td>
<td>112</td>
<td>(.08)</td>
<td>.28</td>
<td>120</td>
</tr>
<tr>
<td>CFC-113/methylene chloride (c)</td>
<td>--</td>
<td>97</td>
<td>(.55)</td>
<td>.09</td>
<td>116</td>
</tr>
<tr>
<td>CFC-113/35% ethanol</td>
<td>--</td>
<td>119</td>
<td>(2.66)</td>
<td>8.3</td>
<td>68</td>
</tr>
<tr>
<td>CFC-113/35% 2-propanol</td>
<td>--</td>
<td>120</td>
<td>(.24)</td>
<td>9.1</td>
<td>43</td>
</tr>
<tr>
<td>CFC-112/14.5% n-propanol (c)</td>
<td>--</td>
<td>196</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>1,1,1-trichloroethane</td>
<td>139</td>
<td>165</td>
<td>.16</td>
<td>--</td>
<td>65</td>
</tr>
<tr>
<td>1,1,2-trichloroethane</td>
<td>21</td>
<td>235</td>
<td>1.40</td>
<td>.05</td>
<td>36</td>
</tr>
<tr>
<td>Perchloroethylene</td>
<td>27</td>
<td>252</td>
<td>2.89</td>
<td>.01</td>
<td>57</td>
</tr>
<tr>
<td>Trichloroethylene</td>
<td>69</td>
<td>189</td>
<td>1.69</td>
<td>.02</td>
<td>87</td>
</tr>
<tr>
<td>Chloroform</td>
<td>118</td>
<td>142</td>
<td>1.21</td>
<td>.07</td>
<td>98</td>
</tr>
<tr>
<td>Methylene chloride</td>
<td>147</td>
<td>105</td>
<td>2.25</td>
<td>.15</td>
<td>108</td>
</tr>
<tr>
<td>Carbon tetrachloride</td>
<td>100</td>
<td>171</td>
<td>.36</td>
<td>.01</td>
<td>62</td>
</tr>
<tr>
<td>Ethanol</td>
<td>37(e)</td>
<td>173</td>
<td>22.1</td>
<td>=</td>
<td>30</td>
</tr>
<tr>
<td>2-propanol</td>
<td>34</td>
<td>180</td>
<td>12.2</td>
<td>=</td>
<td>15</td>
</tr>
<tr>
<td>Water</td>
<td>--</td>
<td>212</td>
<td>237</td>
<td>=</td>
<td>14</td>
</tr>
</tbody>
</table>

\(a\) Based on American Society for Testing and Materials D-1901-67 where possible; relative to CCl₄ \((=100)\); source is DuPont (1978b).

\(b\) \(\delta = \frac{\text{solvent} - \delta_{\text{n-C}_{16}H_{34}}}{2}\) where \(\delta\) is a solubility parameter at 298°K (Hildebrand and Scott, 1962). Numerical values of \(\delta\), were supplied by DuPont except 1,1,2-trichloroethane, which was calculated from latent heat of vaporization and molar volume \((\delta_{1,1,2\text{-tri}} = 9.1)\). For reference, \(\delta_{\text{n-C}_{16}H_{34}} = 8.0\).

\(c\) Azeotrope.

\(d\) Stabilized with nitromethane.

\(e\) Estimated; must be below the boiling point of either component for azeotrope formation (boiling point of CFC-112 = 199°F; boiling point of n-propanol = 207°F).

\(f\) 95 percent ethanol.
as representative of these contaminant classes. Water has been selected as the representative polar constituent partly because it has a large dipole and partly because actual solubility data were available for the solvents listed in Table 4.4.

The solubility values for water in the various solvents are given as the weight percent at 77°F. The values given in the n-hexadecane column are not solubilities but are measures of its tendency to form miscible solutions with the various solvents. These miscibility figures have been calculated from the solubility parameters (δ) defined by Hildebrand and Scott (1962), and are equal to the square of the difference in solubility parameter values between n-hexadecane and each of the solvents.21

In the theory of regular solutions, the highest temperature at which two immiscible liquid phases of the components exist (the upper consolute temperature) is proportional to this square of the difference in solubility parameters. Thus, the closer this square is to zero, the further the region of immiscibility will be from the operating temperature of the solvent (its boiling point) in a degreaser and the greater the tendency of the solvent to take up the contaminant fluid.22

The solubility parameters we have used have all been referred to 298°K and most were obtained from an extensive table from DuPont, or from Table A5.1 of Hildebrand and Scott. Exceptions are 1,1,2-trichloroethane and the CFC-113 azoetropes and blends, which were estimated from experimental heats of vaporization and average molar volumes.

The fifth column in Table 4.4 presents the wetability index. It is the solvent density (g/cc) divided by the product of the viscosity (in cp) and the surface tension (dynes/cm). The density is related to a solvent's ability to float off debris, while the viscosity and surface tension indicate the ease with which a solvent may penetrate blind spaces in a part. This parameter is especially useful in estimating whether a particulate contaminant can be wetted and removed from the surface of a substrate.

Table 4.5 presents the relative ranking of our selected solvents for the four criteria in Table 4.4. In the case of ranking a solvent's ability to dissolve polar substances, we have also placed numbers next to some of the solvents giving the amount of conductive salts (in μg NaCl equivalents/cm²) remaining on a printed circuit board after these solvents have been used to remove activated rosin flux residue.23 The important thing to notice is that, within experimental error, the amount of defluxing residue remaining on the surface falls off as a direct function of the solubility of water in the solvent. For the special application of defluxing, it is therefore apparent that any substitute solvent should have a high polar content.

In Table 4.6 we have attempted a crude overall ranking of a solvent's cleaning potential based on the contaminant removal criteria of Table 4.5. We have assumed that for a solvent to be superior, it must better satisfy the four criteria of rapid evaporation rate, good polar and nonpolar solubility, and good wetability. Hence the rank of the quality appearing last in the

---

21Use of these parameters and regular solution theory assumes that all (binary) solutions being considered mix without volume change, have no excess entropy of mixing, and that the energy of interaction of dissimilar molecules is given by the geometric mean of those for the two pairs of similar molecules. For the polar molecules (and even CFC-113) in Table 4.4, the latter assumption is not true and the use of solubility parameters is somewhat questionable. However, as long as one considers mixtures of polar and nonpolar substances and the specific directional forces are relatively small, solubility parameters may still be used empirically to estimate qualitative solubility relations. These parameters may be related to several thermodynamic variables, but the simplest is their identity with the square root of the ratio of the molar energy of vaporization to the molar volume of the fluid.

22In some liquid-liquid pairs, the upper consolute temperature may never actually be reached before gas-liquid phase changes are encountered. Nonetheless, the "virtual" consolute point implied by (δ₂ - δ₃)² remains a useful concept.

23The defluxing method employed is outlined in DuPont (1977).
### Table 4.5

**Relative Selected Properties of Various Solvents**

<table>
<thead>
<tr>
<th>Rank</th>
<th>Evaporation Rate</th>
<th>Nonpolar Solubility</th>
<th>Polar Solubility</th>
<th>Post Deflux Contamination</th>
<th>Wettability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>113/MeOH®</td>
<td>113/3.8% EtOH®</td>
<td>(Water $^h$)</td>
<td>113</td>
<td>113</td>
</tr>
<tr>
<td>2</td>
<td>113/MeOH®</td>
<td>113/MeOH®</td>
<td>(EtOH $^i$)</td>
<td>113/MeOH®</td>
<td>113/MeOH®</td>
</tr>
<tr>
<td>3</td>
<td>TCE</td>
<td>TCE</td>
<td>(IPA $^j$)</td>
<td>TCE</td>
<td>TCE</td>
</tr>
<tr>
<td>4</td>
<td>113/3.8% EtOH®</td>
<td>113/35% IPA</td>
<td>113/35% IPA</td>
<td>113/35% IPA</td>
<td>113/35% IPA</td>
</tr>
<tr>
<td>5</td>
<td>113/35% EtOH</td>
<td>113/35% IPA</td>
<td>113/35% IPA</td>
<td>113/35% IPA</td>
<td>113/35% IPA</td>
</tr>
<tr>
<td>6</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
</tr>
<tr>
<td>7</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
</tr>
<tr>
<td>8</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
</tr>
<tr>
<td>9</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
</tr>
<tr>
<td>10</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
</tr>
<tr>
<td>11</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
</tr>
<tr>
<td>12</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
</tr>
<tr>
<td>13</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
</tr>
<tr>
<td>14</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
</tr>
<tr>
<td>15</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
</tr>
<tr>
<td>16</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
<td>113/5% EtOH</td>
</tr>
</tbody>
</table>

$^a$ Abbreviations: methane chloride, MC; methanol, MeOH; ethanol, EtOH; n-propanol, nPA; 2-propanol, IPA; 1,1,1-trichloroethane, TCE; 1,1,2-trichloroethane, 1,2-TCE; trichloroethylene, TCE; perchloroethylene, PERC; chloroform, CHCl3; carbon tetrachloride, CCL4; CPC-113, 113; CPC-112, 112.

$^b$ Based on inverse boiling point; decreasing order.

$^c$ Based on solvent/hexadecane solubility parameters; decreasing order.

$^d$ Based on solubility of water in solvent; decreasing order.

$^e$ mg NaCl equivalent/cm² of printed circuit board (see the text).

$^f$ Based on wettability index; decreasing order.

$^g$ Azeotrope.

$^h$ Brackets group solvents with nearly identical solubilities of water; ordering within brackets is based on solubility parameters with $\delta_h = 23.4$.

$^i$ Flammable.
data of Table 4.5 has been used to achieve the ordering in Table 4.6. This procedure formalizes the assumption that a solvent is only as good as its worst property. For example, a solvent with a high evaporation rate but poor solubility characteristics is no better than a solvent that is poor in both qualities. This approach is incomplete in that it does not weight each cleaning criterion in proportion to its effect on cost, but it does provide some idea of the ability of one solvent to substitute for another.

The ordering in Table 4.6 suggests that the CFC-113 azoetropes are the best solvents for simultaneously dissolving both oil-chain length hydrocarbons and highly polar compounds. They are excellent at mixing with the hydrocarbon and quite good at mixing with the polar species. Chloroform and methylene chloride appear next on the list, since they both have intermediate rankings of both hydrocarbon miscibility and water solubility.

The next entries must be considered in groups, since minor changes in weighting the cleaning characteristics could lead to upward or downward shifts of two or more positions. The CFC-113/alcohol blends appear below chloroform and methylene chloride, principally because their wetting capabilities are slightly poorer and, in the case of CFC-113/EtOH, because it is also somewhat poorer at forming solutions with hydrocarbons. Trichloroethylene and 1,1,1-trichloroethane appear next, largely because of their poorer polar solubility characteristics. Of the remaining solvents, 1,1,2-trichloroethane and perchloroethylene appear low on the list primarily because of poor evaporation rates; the alcohols, CFC-113, and carbon tetrachloride rank lower because of limited miscibility; water has a low ranking because of unfavorable values of all parameters except polar solubility.

The best candidate solvents at this juncture, based on the ranking of Table 4.6, appear to be the CFC-113 azoetropes (with ethanol, methanol, and methylene chloride), methylene chloride, 1,1,1-trichloroethane, trichloroethylene, and for the cleaning of relatively polar residues or light oils, chloroform and the CFC-113 ethanol and 2-propanol blends.

The flammability and toxicity characteristics of the various solvents are shown in Table 4.7. Except ethanol and 2-propanol, none of these solvents are flammable, reflecting our original selection. However, several of the solvents have TLVs at or below 100 ppm, a level at which environmental control often becomes difficult. Included in this group are chloroform (at 10 ppm, and a suspected human carcinogen), trichloroethylene (at 100 ppm, but on the list for change to 50 ppm), and methylene chloride (at 100 ppm). Although a low TLV is not sufficient to rule out future use of a particular solvent, it will encourage users to employ less toxic alternative solvents (including methylene chloride blends) or force them to enhance their environmental control equipment.

If we now consider the best choice of candidate solvents derived from Table 4.7, it is apparent that few low-risk, relatively available solvents remain. Those that do remain include 1,1,1-trichloroethane, the 35 percent alcohol/CFC-113 blends, the widely used CFC-113 azoetropes, and (coupled with enhanced control) methylene chloride.

Shown in Table 4.8 are the energy requirements of the various solvents when used in vapor phase degreasers. The figures in the left-hand column give the energy required only to raise the solvent to its boiling point and then to vaporize it. The figures in the right-hand column were derived in DuPont (1977) and are the annual energy costs per gallon of machine capacity for a metal cleaning process. The values represent total energy consumption (the energy to boil the solvent, condense it, pump it, and make up for radiative heat losses). A comparison of the figures in the two columns shows that the energy to vaporize a solvent gives a good idea of its overall relative energy cost. The exception in the table is the relative positioning of trichloroethylene, but this results in part from the fact that the trichloroethylene-containing degreaser considered by DuPont was not insulated, even though this com-
Table 4.6

**RELATIVE CLEANING CAPABILITIES OF VARIOUS SOLVENTS**

Based on $\text{C}_{16}\text{H}_{34} - \text{H}_2\text{O}$

Solubility, Wetting, Evaporation

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>113/MeOH$^c$</td>
<td></td>
</tr>
<tr>
<td>113/3.8% EtOH$^c$</td>
<td></td>
</tr>
<tr>
<td>113/MC$^c$</td>
<td></td>
</tr>
<tr>
<td>CHCl$_3$</td>
<td></td>
</tr>
<tr>
<td>MC</td>
<td></td>
</tr>
<tr>
<td>(113/35% EtOH)</td>
<td></td>
</tr>
<tr>
<td>(113/35% IPA)</td>
<td></td>
</tr>
<tr>
<td>(TRI)</td>
<td></td>
</tr>
<tr>
<td>(TCE)</td>
<td></td>
</tr>
<tr>
<td>CCl$_4$</td>
<td></td>
</tr>
<tr>
<td>EtOH</td>
<td></td>
</tr>
<tr>
<td>IPA</td>
<td></td>
</tr>
<tr>
<td>2-TRI</td>
<td></td>
</tr>
<tr>
<td>113</td>
<td></td>
</tr>
<tr>
<td>PERC</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Abbreviations are the same as in Table 4.5.
$^b$Ordered according to the row in Table 4.5 above which all four solvent cleaning properties are satisfied.
$^c$Azeotropes.
Table 4.7

Flammability and Toxicity Characteristics of Various Solvents

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Flash Point (°F)</th>
<th>Toxicity (TLV in ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC-113</td>
<td>none</td>
<td>1,000</td>
</tr>
<tr>
<td>CFC-113/5.7% methanol(^a)</td>
<td>none</td>
<td>475(^b),(^c)</td>
</tr>
<tr>
<td>CFC-113/3.8% ethanol(^a)</td>
<td>none</td>
<td>750</td>
</tr>
<tr>
<td>CFC-113/methylene chloride</td>
<td>none(^d)</td>
<td>270</td>
</tr>
<tr>
<td>CFC-113/35% ethanol(^a)</td>
<td>none(^d)</td>
<td>1,000(^b)</td>
</tr>
<tr>
<td>CFC-113/35% 2-propanol</td>
<td>none(^d)</td>
<td>700</td>
</tr>
<tr>
<td>CFC-112/15.5% n-propanol</td>
<td>none(^d)</td>
<td>--</td>
</tr>
<tr>
<td>1,1,1-trichloroethane</td>
<td>none</td>
<td>350</td>
</tr>
<tr>
<td>1,1,2-trichloroethane</td>
<td>none</td>
<td>10</td>
</tr>
<tr>
<td>Perchloroethylene</td>
<td>none</td>
<td>100(^e)</td>
</tr>
<tr>
<td>Trichloroethylene</td>
<td>none</td>
<td>100(^e)</td>
</tr>
<tr>
<td>Chloroform</td>
<td>none</td>
<td>10</td>
</tr>
<tr>
<td>Methylene chloride</td>
<td>none</td>
<td>100</td>
</tr>
<tr>
<td>Carbon tetrachloride</td>
<td>none</td>
<td>10</td>
</tr>
<tr>
<td>Ethanol</td>
<td>57</td>
<td>1,000</td>
</tr>
<tr>
<td>2-propanol</td>
<td>56</td>
<td>400</td>
</tr>
<tr>
<td>Water</td>
<td>none</td>
<td>--</td>
</tr>
</tbody>
</table>

\(^a\) Stabilized with nitromethane.
\(^b\) Calculated by OSHA procedure for gaseous mixtures.
\(^c\) Nitromethane stabilizer leads to this value; if only CFC-113 and ethanol are considered, it is 1,000 ppm.
\(^d\) At stated concentration of alcohol. However, because these are blends, boil-down will concentrate the flammable component to the flash point.
\(^e\) Proposed for change to 50 ppm.

The table above lists the flammability and toxicity characteristics of various solvents. Each solvent has a flash point and a toxicity level, represented by the TLV in ppm. The table includes solvents like CFC-113, methanol, ethanol, and others.

Compound has a high boiling point and potentially high conductive and radiative losses. On the other hand, the other high boiler in this series, perchloroethylene, was considered to be contained in an insulated unit, and this difference in design configuration could lead to substantially different energy requirements.

Once again, the CFC-113 azeotropes and the CFC-113/propanol blend have the most favorable energy requirements. Next come carbon tetrachloride and 1,1,1-trichloroethene followed by chloroform, trichloroethylene, methylene chloride, CFC-113/ethanol, and perchloroethylene. Of the solvents with good contaminant removal properties as well as favorable flammable and toxicity qualities, their energy ranking appears to be: CFC-113/3.8 percent ethanol, CFC-113/5.7 percent methanol, CFC-113/35 percent 2-propanol, CFC-113/methylene chloride, 1,1,1-trichloroethane, methylene chloride and CFC-113/35 percent ethanol. Solvent-related CFC emissions could be substantially reduced by substituting those solvents containing less CFC-113 for those containing more. The energy cost for these substitutes can be determined from the figures in Table 4.8.
Table 4.8

ENERGY USAGE OF VARIOUS CLEANING SOLVENTS

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Energy to Vaporize Solvent (Btu/gal)</th>
<th>Annual Energy Cost per Gallon Capacity ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC-113</td>
<td>943</td>
<td>27.10</td>
</tr>
<tr>
<td>CFC-113/3.8% ethanol</td>
<td>1062</td>
<td>29.80</td>
</tr>
<tr>
<td>CFC-113/5.7% methanol</td>
<td>1157</td>
<td>32.80</td>
</tr>
<tr>
<td>CFC-113/35% 2-propanol</td>
<td>1298</td>
<td>--</td>
</tr>
<tr>
<td>CFC-113/methylene chloride</td>
<td>1301</td>
<td>35.10</td>
</tr>
<tr>
<td>1,1,1-trichloroethane</td>
<td>1383</td>
<td>42.10</td>
</tr>
<tr>
<td>Carbon tetrachloride</td>
<td>1385</td>
<td>--</td>
</tr>
<tr>
<td>Chloroform</td>
<td>1509</td>
<td>--</td>
</tr>
<tr>
<td>Trichloroethylene</td>
<td>1579</td>
<td>49.30</td>
</tr>
<tr>
<td>Methylene chloride</td>
<td>1654</td>
<td>44.40</td>
</tr>
<tr>
<td>CFC-113/35% ethanol</td>
<td>1655</td>
<td>--</td>
</tr>
<tr>
<td>Perchloroethylene</td>
<td>1723</td>
<td>47.70</td>
</tr>
<tr>
<td>1,1,2-trichloroethane</td>
<td>1832</td>
<td>--</td>
</tr>
<tr>
<td>2-propanol</td>
<td>2293</td>
<td>--</td>
</tr>
<tr>
<td>Ethanol</td>
<td>2754</td>
<td>--</td>
</tr>
<tr>
<td>Water</td>
<td>9484</td>
<td>--</td>
</tr>
<tr>
<td>CFC-112/14.5% n-propanol</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

*Energy required to raise solvent from 75°C to its boiling point and then vaporize it.

Based on a DuPont laboratory model of a metal cleaning process operating 40 hours a week, and with electricity priced at 4.3c/kWh in 1977 dollars.

Seven separate energy use factors (unspecified) were considered.

*dAzote trope.

Stabilized with nitromethane.

*Considered to be contained in an insulated tank.

Other Considerations

The four principal chlorocarbon solvents (methylene chloride, 1,1,1-trichloroethane, trichloroethylene, and perchloroethylene) all have their problems as electronic cleaning agents. Printed circuit board components containing aluminum, zinc, or magnesium react with most chlorocarbon solvents, although this can be restrained by the addition of stabilizers. However, in the case of 1,1,1-trichloroethane, for example, care must be taken to ensure that the water soluble stabilizer does not get extracted by any water that forms on the condensing coils if they are allowed to operate at a temperature below the dew point (-60°F). One degreaser manufacturer claims that flexible mylar-like materials, which are used to join rigid circuit boards, are incompatible with all present solvents except the CFC-113/alcohol mixtures. Epoxy (often joined to the mylar-like polymers) is attacked by methylene chloride and trichloroethylene on long exposure. Electrolytic capacitors (often cold-cleaned) are also incompatible with methylene chloride and trichloroethylene. Many elastomers are swollen by the chlorocarbons. Ceramic components are compatible with all the solvents.

Because substrate incompatibility is encountered with many printed circuit board components when the chlorocarbon cleaning is considered, the CFC-113/ethanol and 2-propanol
blends appear much better suited to this task. Even the modest ability of the ethanol blend to mix with long chain nonpolar contaminants (see Table 4.4, column 2) is not a serious problem here because one of the substances that must be removed, rosin, is composed primarily of abietic acid ($C_{27}H_{46}COOH$), which has at least one fragment with polar character. Furthermore, flux activators and residues are quite polar and could easily be handled by the CFC 113/ethanol blend. The ability of these solvents to remove activated resin flux residues has been demonstrated in DuPont (1974, 1977), and, in the case of CFC-113/ethanol, shown to yield ionic removal results equivalent to that obtained with the stabilized CFC-113/methanol azetrope and better than that obtained with the other azeotropes or 1,1,1-trichloroethane.

The difficulty with the use of alcohol-rich CFC-113 blends is the increased risk of flammability. Because the alcohol has the higher boiling point, it tends to be left behind in the degreaser or on the surface of a quickly withdrawn part as the more volatile CFC-113 escapes. In the case of the CFC-113/ethanol blend, control measures can be taken to reduce this risk. The degreaser design could be modified so that both the temperature of the boil sump and liquid level were monitored. The solvent vapor could be kept below the flammability range by automating the addition of makeup CFC-113 (actually added in the form of its alcohol azetrope). Of course, while this guards against ignition in the degreaser, it will not protect against a flammable condition arising on the surface of a part withdrawn from the degreaser before solvent evaporation is complete or on the floor following a spill. Only careful operating practices can minimize this risk.

**Water as an Alternative Solvent**

While we have addressed some of the difficulties in using pure water for (rosin) defluxing of printed circuit boards, we have not yet discussed two other options, one where water is combined with alkaline detergents to clear rosin-based fluxes and another where pure water is used to clean water soluble fluxes. The choice and proper use of such defluxants is crucial to the well-being of the electronics industry. In this subsection we present some of the details of those processes and discuss their technical limitations.

In the first option, warm water may be combined with inorganic detergents and amine detergents such as monoethanolamine to form a cleaning solution capable of emulsifying nonpolar soils and saponifying the organic acid (primarily abietic acid) components of rosin. The saponification reaction yields a soap that can be floated off in the aqueous phase. The soaps that are formed carry over to the next phase, the water rinse, and may cause foaming if antifoaming agents are not employed. The most recent cleaning systems remove the small amount of contaminated rinse water that remains on the surface with a hot air knife, a jet of high velocity air that blows off the fluid before the water has a chance to evaporate and concentrate the higher molecular weight impurities on the surface. Finally, the circuit board is heat dried.

Several difficulties are encountered in this process. First, reactive metals on the board (e.g., Al, Zn, Cu) are subject to corrosive attack by this defluxant and tin and lead ions may be precipitated as insoluble hydroxides (Kenyon, 1978; Van der Molen, 1977). Second, because rosin is a nonhomogeneous, natural substance subject to undesirable polymerization, not all of it can be saponified and flux residues may remain on the board after cleaning (according to DuPont, this may be as high as ten percent of the rosin present). Third, the residue left behind may lead to insulation failure, particularly for boards later used in high humidity environments. Fourth, it is difficult to rinse off all the alkaline soap (Kenyon,
1978). Furthermore, the detergents themselves are quite difficult to remove from printed circuit boards when the components, such as surface mounted chips or lead wires with insulating sleeves, provide entrapment sites into which the detergent solutions may flow but the pure rinse water will not, due to its much higher surface tension. In this case, the flux residue contaminants may be exchanged for detergent contaminants. Occasionally a CFC rinse has been used to remove the remaining surfactants but, from a CFC emission viewpoint, this would negate the reason for seeking a water solvent alternative.

In the second defluxant option, water soluble fluxes are used. They are then dissolved in tap, deionized, or acidified water, depending on the particular cleaning requirements (Kenyony, 1978; Keller, 1981). As the detergent removal of rosin flux, a good system should use a hot air knife to blow off the contaminated water remaining on the surface after defluxing; this is called flash drying. In aqueous cleaning where high resistance (10^10 – 10^12 ohms) is required on the finished circuit board (such as for some military and communication items), very low volume conductivity water of 6 to 8 megohms-cm is used (Keller, 1981). In most applications, the ultra-pure deionized water is recirculated and reprocessed to achieve the most economical use. Further efficiency is attained through the use of shut-off valves to prevent recirculation when the cleaning machine is not in use.

This option also encounters several difficulties. First, the components of some polyglycol based fluxes are quite hostile and may react with epoxy or polyimide printed circuit boards with a consequent degradation of up to three orders of magnitude of substrate resistance. According to Keller, however, milder fluxes are often available, such as a mildly activated water soluble organic flux. Second, high molecular weight polyglycol fluxes can soften board polymers or the buttercoat adhesives between polymer and copper laminate. Keller again points out that the use of lower molecular weight polyglycols such as glycerin may alleviate this difficulty. Third, it is difficult to remove entrapped rinse water from the circuit board, particularly at high component densities. For small or moderate densities, however, Keller states that flash drying helps considerably; this technique is probably the most critical factor for cost effective aqueous cleaning. Kenyon (1978) has pointed out that water soluble fluxes may require a highly acid wash (pH about 2) to avoid tin and lead hydroxide deposition, and hence any of this rinse water remaining on the surface may corrode solder fillets or attack the laminate surface. Fourth, Kenyon warns that insulation failure may occur at high relative humidities if any tin or lead oxides are left on the surface.

The difficulties presented for both the rosin saponification and aqueous soluble flux techniques indicate that they may not always be used in place of CFC solvent cleaning. Uncleanable boards, i.e., those with insulating sleeves or with components lying flat against the surface, are considered by Keller (1981) to be best cleaned with CFC solvents. However, recent experience has shown that "organic-acid-flux water cleaning has been very successful when used on products considered to be cleanable, i.e., free from entrapment sites."

Drawing on experience, especially at Motorola, Keller has also stated that for many of these applications, both the CFC and water based technologies "are acceptable and equally efficient as to cost and product reliability when the newer technology is properly used." Keller claims, for example, that relatively complex 6\times8 inch circuit boards being processed at the rate of 240 boards an hour can be cleaned to current military specification requirements by a closed loop CFC/rosin system for $0.061/board, by a closed loop heated deionized water/water soluble flux system for $0.063/board, or by a closed loop deionized water plus detergent/rosin system for $0.084/board. The new technologies that would be used with the water systems include flash drying and the use of new highly soluble fluxes and leveling and soldering fluids. With water soluble flux technology, it is also critical to reduce the level of ionic con-
tamination left on bare boards during earlier plating and etching steps. This is because the water soluble fluxes, unlike the rosin fluxes, do not encapsulate the impurities, allowing them to be removed during the later cleaning phase, nor do they, in the event of imperfect cleaning, provide a hydrophobic surface that prevents moisture adsorption and an environment for subsequent electromigration. On the other hand, the more costly rosin saponification technique will provide for these features.

Still other factors must be considered in a switch to water cleaning. Acceptance by the military is important. No close monitoring of the composition of certain polyglycol fluxes is presently performed, and hence new military specifications akin to MIL-F-14256\(^{24}\) for rosin fluxes may have to be developed. In addition, the current cleanliness test called for in MIL-P-28809\(^{25}\) is not applicable by itself to water cleaned assemblies because it measures only ionic contamination and not the nonionic contamination that is a problem with aqueous systems. While both Kenyon and Keller speak of insulation resistance and electromigration tests that may augment the present military specification, such tests are still under review.

Environmental problems posed by the disposal of aqueous cleaning wastes has also been noted by Kenyon as a possible barrier to implementation. Indeed, testing performed at the Alpha Metals Co., where rosin saponification and two versions of water soluble flux cleaning were investigated, has demonstrated that effluents discharged into the sewage system from a nonrecycling cleaning system will exceed the federal and many municipal standards for lead, pH, Biochemical Oxygen Demand, and Chemical Oxygen Demand. At increased water and energy expense, a closed system (employing ion exchange or precipitating agents) can eliminate this problem by converting the waste to a sludge. The cleaning cost per board figures quoted above from Keller included waste disposal costs for the CFC system ($100/drum of waste) but did not include these costs for the aqueous system. However, presuming that the monthly volume of aqueous process waste does not exceed that of the CFC process, the costs for the water systems would increase by no more than eight percent, or from $.063/board to $.068/board.

In summary, aqueous cleaning systems can be a viable alternative to CFC systems for low to moderate density printed circuit boards with very few entrapment sites. However, we must be careful to note Keller's point that the trend in the electronics industry is toward still more dense boards (component spacings of a few mils and > 80 solder joints/square inch by 1986). If this trend continues, an increasing number of circuit boards will be too dense to allow flash drying and the prospect must be considered that for purely technical reasons, water cleaning may lose ground to the CFC system.

\(^{24}\) A list of specifications on the composition of rosin introduced because it is a natural material.

\(^{25}\) See the maximum amount of ionic contaminants that can remain on printed circuit board in units of μg equivalents and NaCl eqn\(^{b}\).
Chapter 5

CHLOROFLUOROCARBON USE IN FLEXIBLE URETHANE FOAMS

I. Introduction and Summary

Flexible urethane foams are valued for their cushioning characteristics and are widely used in the manufacture of furniture, bedding, automobile seats, and other applications where cushioning is required. The cushioning ability of these foams is due to their cellular nature, and the holes or cells in the foam are formed by gaseous blowing agents. The primary blowing agent is the carbon dioxide that results from the reaction of two of the basic foam formulation ingredients; for softer foams, an auxiliary blowing agent is used. Two commonly used auxiliary blowing agents, CFC-11 and methylene chloride, are used in up to 14 percent of the raw materials, depending upon the product being made. These auxiliary blowing agents escape the foam promptly as a gaseous emission during the manufacturing process. Technical options to reduce the use of CFC blowing agents are the subject of this chapter.

Foams are made in molded form for such things as automobile seats, and as slabstock, a large, continuously formed bun that is later sawed into various sized pieces. This chapter analyzes both slabstock and molded foams.

In previous Rand studies, 1976 CFC-11 emissions from flexible foam manufacture were estimated at 33.6 million pounds\(^1\)—26 million pounds\(^2\) from slabstock and 7.6 million pounds from molded foams. Two technical options for reducing CFC emissions were identified. These were the replacement of CFC-11 by methylene chloride in slabstock manufacture and the recovery and recycle of emitted CFC-11 from both slabstock and molded foams. Neither product substitutes nor work practices were found to have realistic potential.

The present study found no additional technical options for reducing CFC emissions. In fact, at EPA direction, we concentrated mainly on the option of replacing CFC-11 with methylene chloride, because other EPA-funded research on the recovery and recycle option had not been completed. Our perceptions of the use of methylene chloride in slabstock are considerably sharper than they were in the earlier works. We found that almost every slabstock foamer uses both methylene chloride and CFC-11, concentrating the use of the CFC in the softer foams. We found, first, that these firms generally tend to optimize their use of the two blowing agents and, second, that a wide variety of factors impede further conversion to methylene chloride. These factors are usually peculiar to individual foamers and include equipment limitations, ventilation problems, customer requirements, inadequate storage areas, and the like. The costs of coping with these factors vary with each individual case.

Reducing slabstock emissions below the 26 million pounds estimated for 1976 generally entails replacing CFC-11 in the softer foam formulations. Again in generalization, one might expect a reduction in CFC use of about 13.5 million pounds if methylene chloride was used.

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\(^1\)Palmer et al. (1980), Table 3.A.4.
\(^2\)Moos and Quinn (1980), Table 7.
exclusively in all slabstock production from the firmest foams to 15 to 20 pound ILD\textsuperscript{3} foams, a reduction of 14.5 million pounds if it was extended to 11 to 15 pound ILD foams, and a reduction of 26 million pounds if it was used in all slabstock. However, as formers attempt to use methylene chloride in ever softer formulations, the manufacturing difficulties become greater. The fact that they do not use more methylene chloride at present is generally because of a variety of impediments, most of which require either investments or other dislocations that raise their manufacturing costs.

We found that a wide variety of factors presently bear on CFC use in the manufacture of molded foam. Molded foam automobile seats, which dominate the molded foam market, are made by both hot molding and the newer high resiliency (HR) foam process. HR foam requires substantially less CFC than hot molding, and some automobile manufacturers use no CFC, producing a firmer seat than those who do. Recent changes in automobile design have reduced the amount of foam in car seats, but concurrent reductions in the foam density by adding more CFC have kept CFC consumption steady.

Recovery and recycle of CFC from molding operations and from slabstock manufacture may be a viable option to reduce emissions, depending upon costs. If recovery and recycle proved economical for molded foams, perhaps 50 to 80 percent of the emissions could be eliminated. Using the 1976 estimates, this would be 3.8 to 6.1 million pounds.

Emissions from molded foam operations using the HR process could be completely eliminated if the automobile companies installed firmer seats in their cars. Outside suppliers to the auto industry who use hot molding, which requires an auxiliary blowing agent, would incur major expenses if they converted to HR foams. Without the conversion of the hot molders, emissions reductions possible by converting to firmer seats might be similar to those of recovery and recycle.

Since emissions from flexible urethane foam manufacture occur at the time of manufacture, any actions to reduce emissions would have an immediate effect.

\textsuperscript{3}ILD (indentation load deflection) is a measure of foam softness. The softest commercial foams have an ILD of about 9 and are used in sofa cushions and similar applications. The firmest foams have an ILD of 40 or higher and are used in carpet underlay, for example.
II. Flexible Urethane Slabstock

Seventy-five percent or more of the flexible urethane foam made in the United States is slabstock. Slabstock is made continuously and emerges from the foam machine as a large loaf or bun four to eight feet wide and about four feet high. Usually, it is sawed into lengths varying from a few feet to about 200 feet. This form of urethane foam is then cut and fabricated into various sizes and shapes and is used in furniture, bedding, and a variety of other cushioning applications. Slabstock can be made very firm, such as for carpet underlay, or very soft, such as for sofa backs. Firm foams may have an ILD of 30 or higher, and super-soft foams may be as low as 9.

The primary chemical reactions used to make foam include the reaction of water and toluene diisocyanate, which yields carbon dioxide. This gas forms the bubbles and cells that make the foam. Water blown foams cannot be made very soft, since one of the other products of the reaction is urea, which makes the foam stiff and boardy. To make softer foams (with an ILD of less than about 44), an auxiliary blowing agent is needed, such as CFC-11. When heated by the exothermic foam reaction, CFC-11 boils and forms bubbles to augment the carbon dioxide. The slabstock formed in this way has open cells, and the CFC-11 leaves the foam during the manufacturing process.

CHEMICAL CONTROL OPTIONS

Several options are technically feasible for reducing CFC use (or emissions, which are identical) in the manufacture of flexible slabstock. A control technology—the recovery and recycle of the CFC—will be discussed only briefly because EPA had sponsored other research on the subject, and it was specifically deemphasized in the research performed under this contract.

Because work practices do not affect CFC-11 use or emissions in slabstock manufacture, these will not be discussed.

Chemical substitutes, particularly methylene chloride, are already used by most slabstock foamers for at least a part of their production. We will treat this technical option in detail. Other potential chemical substitutes, such as CFCs that are not fully halogenated, are either presently unavailable, or very costly, and thus will not be discussed.

Product substitutes are also a possibility, but probably are not likely to be considered in view of the other options available. Urethane foam slabstock is such a versatile material, and provides such good cushioning, that it seems unlikely that the furniture and bedding industries would revert to the use of materials such as cotton batting, rubberized horsehair, and the like. Consequently, this subject will not be discussed.

CONTROL TECHNOLOGY ASSESSMENT

The earlier Rand studies for EPA made a preliminary assessment of recovering emitted CFC during the manufacturing process and recycling it, thereby reducing CFC use and emis-

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4EPA contract 68-03-3011 with the Radian Corporation, Austin, Texas.
sions. Assuming that it is technically feasible to collect the CFC by carbon adsorption, the economics of the process essentially depend upon the total amount of CFC that can be collected and recycled annually. This means that the process is more likely to be economically viable at large foam plants where CFC-11 is either the major or exclusive blowing agent used, and where a large fraction of the CFC is already captured in the existing exhaust system.

Since the earlier Rand studies, Radian has confirmed the technical feasibility of the method. In addition, in 1969, a recovery and recycle experiment was successfully run for about six months in General Tire and Rubber Company's slabstock plant. This experiment also validated the technical soundness of the process. As part of their contract with EPA, Radian is developing cost estimates for the equipment required for CFC recovery. These are not yet published, but they will define that level and cost of total CFC collection needed to make the process attractive. We expect that with the present price of CFC-11, and with the present high rates of interest (which make equipment capital charges high), CFC recovery and recycle may be beyond the consideration of all but a few slabstock formers. And, as we shall see, if these formers are already partially using other blowing agents, the process may not be attractive to any foamers.

ASSESSMENT OF METHYLENE CHLORIDE AS A CHEMICAL SUBSTITUTE

A discussion of potential substitutes for CFC-11 in slabstock manufacture is essentially a study of the use of methylene chloride. A large fraction of the slabstock presently manufactured uses methylene chloride, and therefore this analysis is mainly concerned with the economics of using methylene chloride and the factors that presently constrain its increased use.

The basic economics of using methylene chloride can be summarized succinctly. Methylene chloride costs roughly 60 percent as much as CFC-11, and about 85 percent as much is required in equivalent foam formulations. Consequently, auxiliary blowing agent costs can be reduced by almost half if methylene chloride is substituted for CFC-11. Some other raw material costs change when a switch is made to methylene chloride, however, and these changes counteract some of the savings. Both the amine concentration and the tin catalyst concentration are usually increased, but the net effect of this on raw material costs is small in comparison to the blowing agent change. Figure 5.1 has been constructed from data supplied by Dow Chemical. It illustrates the net savings in raw material costs that result from using pure methylene chloride for foams of varying softness and foam densities of 1.0 to 1.2 pounds per cubic foot. The graph is plotted in terms of the indentation load deflection (ILD) and clearly shows what would be expected; the softer the foam, the greater the cost difference because more auxiliary blowing agent is required. Thus, on the surface, it appears that methylene chloride is most cost effective in the softest foams. This same information has been plotted in Fig. 5.2 in terms of the percent difference in material costs. Since the savings are a function of the softness of the product, the potential benefit of using methylene chloride

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5 This is because the foam lines in most plants are roughly similar in size, and variations in production result from the amount of time that the foam line is run. Thus, the capital investment of the recycling equipment would likely be similar for all size plants.

6 The experiment was terminated because of unfavorable economics at the time.

7 This begs the question of recovery and recycle of more than one blowing agent, which has not been investigated.
Fig. 5.1—Net savings in raw material costs from using methylene chloride instead of CFC.

depends upon the product mix of each plant. Figure 5.3 illustrates one typical manufacturer’s foam product mix (determined from interview). Multiplying the product mix in Fig. 5.3 by the material savings in Fig. 5.2 results in an overall potential material cost savings of about 2.4 percent. For a large plant making 20 million pounds of slabstock per year, this implies a potential annual saving of about $336,000. The distribution of this potential saving is plotted against ILD in Fig. 5.4 and is also shown cumulatively in Fig. 5.5. It is clear that the bulk of the potential savings is due to the heavy production of foams of from 20 to 35 pound ILD. Foams above 35 pound ILD have too little CFC to matter much, and foams softer than 20 pound ILD account for only about 15 percent of production. Note, however, that since these very soft foams have higher potential material cost savings, they account for 30 percent of the potential savings, even though they account for only 15 percent of production.

\[\text{Calculated at an average material cost of 70c per pound of salable foam.}\]
The attractiveness of these cost savings is apparent to slabstock foamers and the manufacturers of methylene chloride, and we found that most slabstock foamers use some methylene chloride. In fact, virtually all foamers use both methylene chloride and CFC-11; very few use either one or the other exclusively. What is surprising, however, is the diverse ways in which methylene chloride is used.

Some foamers use pure methylene chloride for some grades of foam and pure CFC for others. Some foamers limit their use of pure methylene chloride to foams no softer than 30 pound ILD; others push its use to foams of 15 pound ILD or less. There are also foamers who use 50-50 mixtures of CFC-11 and methylene chloride in some of their production and pure
Fig. 5.3—Product mix of a typical slabstock plant

Fig. 5.4—Distribution of maximum annual savings possible by using methylene chloride instead of CFC-11 to manufacture slabstock foam in a typical plant
Fig. 5.5—Cumulative distribution of maximum annual savings possible by using methylene chloride instead of CFC-11 in slabstock foam manufacture.

CFC-11 for the remainder. Last, some foamers purchase proprietary blends of CFC-11 and methylene chloride,\textsuperscript{9} rather than rely upon their own blending.

At first glance, it seems that each foamer uses methylene chloride in a different way. But in general, one can say that methylene chloride tends to be used in the firmer foams (25 to 30 pound ILD and higher), and that while there is a keen appreciation of the sizable economic benefits of extending its use into the softer foams, there are usually very sound reasons why this is not done. Figure 5.5 shows that if a foamer elects not to use methylene chloride in

\textsuperscript{9}From HF, a trade name product marketed by DuPont, is such a blend.
foams softer than 20 pound ILD, he forgoes the opportunity to save 30 percent of the 2.4 percent possible material cost savings. For a plant producing 20 million pounds per year, this saving amounts to about $100,000 per year.

Before attempts are made to replace CFC-11 in flexible slabstock manufacture, a careful examination must be made of the reasons why each foamer limits his use to the applications that he does. The foam industry seems to be highly competitive, and foamers generally act to minimize their costs.

In the remainder of this subsection on the assessment of chemical substitutes, we will discuss the factors that influence slabstock foamers. As will be evident, the factors tend to be local in nature, having to do with a plant's equipment, personnel, raw materials, climate, physical layout, technical expertise, and customers. Many of these local factors are difficult or expensive to change; some are beyond the foamer's control. Faced with the costs of changing some of these factors to achieve the raw material savings available by using methylene chloride, many companies have decided that the costs cannot be justified. Not surprisingly, we find that if a plant has decided to use methylene chloride, it will usually use it in every application where it is economical to do so. These applications may differ from plant to plant, and the reasons for not using methylene chloride in some applications are surprisingly diverse. We will explore some of the factors in the following text.

**Technical Factors**

The lay person tends to think that a specific type of flexible urethane foam has a specific formulation. Indeed, most raw material suppliers and blowing agent suppliers have specific formulations for each grade of foam. Some foamers, particularly small foamers with a limited product line and relatively few customers, use these standard formulations. However, virtually every large foamer (and even many of the small foamers just mentioned) must develop variations on these basic formulas, and in many instances they must develop different ones for each of their plants. The reasons for this include differences in equipment, raw materials, altitude, climate, and the specific requirements of customers. The raw material and blowing agent suppliers work with the foamer to develop these "tweaked" formulas, but in difficult cases the task falls on the shoulders of the foamer's technical staff. When this happens, development of a successful formulation depends on the ability of the staff, the complexity of the problem, and the potential rewards.

When methylene chloride is used in place of CFC-11, the fine-tuning of formulations becomes more difficult because of the differences in three physical characteristics between the two blowing agents: Methylene chloride has a higher boiling point and a higher latent heat of vaporization and is a more powerful solvent than CFC-11. Because of the higher solvency, the foam mixture is not viscous enough to form stable cell walls when frothing begins, and the frothing itself is delayed because it takes longer for the temperature of the reacting foam components to reach the boiling point of the methylene chloride. The temperature versus time profile for methylene chloride blown foam shows delayed temperature peaks in comparison to CFC blown foam. In fact, while CFC blown foam usually reaches its peak temperature in the foam tunnel, methylene chloride blown foam often reaches its peak outside the tunnel. This has some important emission effects, which will be discussed below.

To cope with these differences, catalysts are used to adjust the reaction rates, and some of the other ingredients are specifically tailored to the particular application. For "bread and butter" foam formulations in the 15 to 35 pound ILD range, the problems involved are usu-
ally (but not always) small. The softer the foam formulation, the more auxiliary blowing agent is required, and the more difficult it becomes to satisfactorily solve the technical problems when using methylene chloride.

If a very soft foam methylene chloride formulation cannot be successfully developed, because of the characteristics of the plant, its location, its equipment, or its technical staff, the plant management may judge that the economic rewards are insufficient to continue pursuing the use of methylene chloride and may simply elect to use CFC-11 in those formulas. This can occur because the trial formulations are expensive, or because the annual sales of the particular foam are low. Only limited work can be done in the laboratory, and about $5,000 worth of foam must be poured on the foam line before a judgment can be made as to its quality. If the foam collapses, or if it fails to have open cells, it may be suitable only for landfill. The profit margins on the foam are low enough that only a few unsuccessful trials will offset any potential savings for an entire year on a foam that only has a limited market.

It is probably true that there is a technical solution to even the most challenging set of circumstances and that given sufficient time and money, even companies with unsophisticated technical staffs could develop formulations that would work. But as we will see when we discuss some of the other factors involved, even a successful formulation can fail for reasons that are outside the control of the technical staff. This is particularly true of super soft foams containing high levels of methylene chloride, which are very sensitive to minute changes in operating conditions.

**Operating Factors**

The operating crew of a foam line controls the flow of seven or more ingredients to a discharge nozzle through which pass hundreds of dollars worth of raw materials per minute. As these ingredients leave the nozzle, a series of chemical and physical reactions begins, each of which must proceed in concert with each other, and all of which must terminate at approximately the same moment. One source estimated that all reactions had to be complete within five seconds of one another.

Small changes in humidity, barometric pressure, and temperature, as well as batch-to-batch variations in raw materials, can affect the reactions, and the crew must observe the forming slabstock, deduce what is happening, and make minor adjustments in the flows of raw materials so that a high quality product is made. The gelling of the foam is critical. If it gels slightly too fast, the continued evolution of the blowing agent will cause splits in the foam. If it gels much too fast, the cells will not burst open, the blowing agent will be trapped in the cells, and when the bun cools, the cells, and the bun, will shrink into a "prune" which has no commercial value. If gelling is too slow, all of the blowing agent will leave the frothy liquid before the cells have structural strength, and the bun will collapse into an unsalable "pancake."

As the foam crew controls gelling, they must simultaneously make adjustments to control the topography of the bun surface. Allowed to rise without control, a slabstock bun would resemble a loaf of bread with a domed top. Such a top is undesirable, since the slabstock is later cut into rectangular pieces, and the first operation is to slice off the dome. Of course, the higher the dome, the more the scrap. The primary control on the shape of the top is the foam line design, many of which are patented. But the operating crew also has control over some aspects of the upper surface shape and the crew must work together to turn out as flat and uniform a bun as possible.
The ease with which the reactions are controlled depends upon the operators' skill and experience, as well as on the type of foam equipment and the particular formulation used. Methylene chloride blown formulations provide the most challenge; as the amount of methylene chloride increases, so does the operating difficulty. Thus, the most demanding formulations for the operators to control are those for the super soft foams—the foams for which there is a smaller market demand and which are produced less frequently. When a super soft foam is to be run, the operator not only intrinsically faces a greater challenge, but also faces a heightened probability of failure, since these grades are run infrequently. Operators can "feel" their way from run to run of regular foams as conditions change, but, since super soft foams may be run only once a week or so, there are jarring discontinuities, and it is difficult to rapidly make the necessary adjustments on these formulations, particularly when they incorporate methylene chloride. As a result, many foamers elect not to take a chance, and conservatively use CFC in these formulas, even though they may have a successful methylene chloride formulation worked out.

Equipment

The design of the foam machine can be a dominant factor in the ability to use methylene chloride. There is a wide variety of foam machines, and many "standard" machines are modified by their owners after installation. Many of the basic differences in machines are due to the method of obtaining a flat top on the bun. As previously mentioned, this is an important attribute of the foam machine, and widely different methods are used to achieve it. These methods are not germane to the discussion here except as they affect the ability to use methylene chloride. Many foamers mentioned the differences in compatibility of machines; some are extremely tolerant and others are almost completely intolerant. This difference is so pronounced that one foamer, after installing a new machine, had to abandon the use of methylene chloride and "go back to the drawing board" with his formulations. There is no way to quantify each type of machine regarding its tolerance. There are too many types, and the interplay between technical and operating factors is such that separating out the machine factors is too difficult. Thus, some machines present challenges severe enough to preclude using methylene chloride in any formulation, and others will tolerate its use in some formulations but not others.

Ventilation

Several blowing agent characteristics make ventilation a factor in the choice between CFC-11 and methylene chloride. The first of these is their relative TLV\textsuperscript{10} values. CFC-11 has a TLV of 1,000 parts per million (ppm), which is the highest value that is assigned to gaseous chemicals. In contrast, methylene chloride has a TLV of 200 ppm. Second, while CFC-11 is virtually odorless, methylene chloride has a distinctive odor and an odor threshold of about 300 ppm. Third, methylene chloride is emitted from the bun later than CFC-11.

The concentration of the toluene diisocyanate (TDI) reactant, which has a TLV of 0.02

\textsuperscript{10}TLV (Threshold Limit Value) is the maximum allowable time-weighted average concentration to which a human may be exposed over an eight-hour working day, 40-hour work week. Generally, the more toxic the chemical, the lower the TLV. The values quoted here were taken from a publication of the American Conference of Governmental and Industrial Hygienists (1980).
ppm, is controlled mainly by ventilation in the foam tunnel. This ventilation is usually sufficient to dilute a large fraction of the auxiliary blowing agent below its TLV before it is dispersed outside the plant. The process dilutes CFC-11 or methylene chloride equally well, even though their TLVs are different. A problem occurs, though, because not as much methylene chloride is emitted in the tunnel as CFC. Earlier we discussed how methylene chloride altered the foam reactions. Of particular reference to ventilation is the fact that methylene chloride blown foam has a delayed temperature rise. This contributes to a delayed emission of the blowing agent. One source has estimated that perhaps 30 to 40 percent of the CFC is emitted outside the tunnel, but that more than 50 percent of methylene chloride is emitted there. If the estimate is correct, almost twice as much methylene chloride as CFC is emitted outside the ventilation control of the foam tunnel. Not only could there be almost twice as much, but the TLV is one-fifth that of CFC; to compound things, the odor threshold of methylene chloride is low so ventilation must consistently dilute the emitted blowing agent.

Dealing with these differences is a chore regularly faced by many foamers. Those who handle it the easiest are located in warm climates where natural ventilation sometimes does the job, or where fans are installed in the warehouse or curing area walls to maintain an adequate flow of air through the area. There are, in fact, some foamers who store fresh slabstock buns outdoors; in these cases ventilation is no problem.

The problem is not so easily handled in cold climates. Exhausted air must be replaced with air from outside, and to insure workers’ comfort (and in some regions to comply with the law) this air must be heated. Foamers have dealt with this challenge adroitly. One multi-plant company alleged that in cold climates they use clever design techniques to control the TDI levels in the foam tunnels, with about one-third the flow of air used in warm climates. In addition, in cold climates the flow of air to the foam tunnel is often routed through the curing and warehouse areas, so that it clears them of any blowing agent. Nonetheless, the minimum air flow requirements for a plant using methylene chloride must almost always exceed those for a plant using CFC-11 and could be ten times as large.11 Where this air must be heated, that cost is considered when blowing agents are chosen. For this reason, some plants in cold climates limit their use of methylene chloride to the amount that can be adequately handled by their ventilation system. This usually means that foams as soft as 30 pound ILD can be made with pure methylene chloride (formula concentration of 10 phr),12 and that foams softer than this are formulated with methylene chloride/CFC-11 blends in which the methylene chloride is limited to 10 phr.

Ventilation is also important in reducing corrosion. Both CFC-11 and methylene chloride decompose thermally in catalytic gas space heaters and in internal combustion engines operating in the plant (such as fork lifts). The decomposition products are dangerous (CFC-11 produces HF and HCl, and methylene chloride produces phosgene and HCl) and not only cause corrosion, but can make working conditions intolerable or unsafe. There is no evidence that corrosion with methylene chloride is any worse than that with CFC-11; in fact some claim the opposite. Plants with catalytic heaters require control of the emitted blowing agent, and when methylene chloride is used, this usually means an increase in the ventilation of the curing area. Of course this can increase costs as well.

As an example of how ventilation can be a limiting factor in another way, consider a plant with a curing rack area almost always full of curing buns. If that area is reasonably

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11 Twice as much blowing agent released outside the foam tunnel, with a TLV one-fifth as great.
12 Pounds per hundred pounds of resin (phr) is a standard industry term. The weight percent of blowing agent can be approximated by dividing phr by 1.5.
well isolated from the rest of the plant, when methylene chloride is used, the delayed emission from it will require the steady flow of air through the curing area so that the TLV requirements are met. Also, the delayed heat rise encountered with methylene chloride will cause the buns in the curing racks to be hotter than they would be had CFC been used. We were told that the combination of the confined space, hotter buns, and fresh ventilation air can result in internal scorching of the buns. In practice, this problem is dealt with by limiting the use of methylene chloride to those formulations that use low concentrations of blowing agent, thereby lessening the need for fresh air.

Another way of dealing with this problem would be to increase the size of the curing area. But given a fixed plant size, the economics of doing so may simply militate against such a choice.

Plant Layout

Plant layout and ventilation are closely related topics, but plant layout is treated here as a separate subject only because some plants have an acute problem that can be attributed directly to the layout. Such problems could be remedied only with great difficulty. To illustrate the point, we will describe a single example.

Foam plants are sometimes installed in existing buildings. One foam plant was installed in a multi-story building, with the foam line on the uppermost floor and other operations and offices on the floors beneath. Both CFC-11 and methylene chloride are denser than air, and the vapors not mechanically exhausted from the building settled on the lower floors. Recall from the earlier discussion that more of the CFC-11 is probably released in the foam tunnel than methylene chloride. Thus, less of it is present to settle on the lower floors. Further, it has a high TLV (1,000) and is virtually odorless. Thus, when CFC-11 was used, no such difficulties were incurred. With methylene chloride, more of the gas is present, its TLV is only 200, and its odor is easily detected at 300 ppm. Unquestionably a ventilation system could be designed to cope with the problem in this plant, but the expense and difficulty may have easily outweighed the benefits in this particular instance.

Warehouse Volume

With a foam manufacturing cost that is less than one dollar a pound, and a foam density of about one pound per cubic foot, it follows directly that warehousing and inventory time must be minimized so as not to add to product costs. One of the secrets of success in the foam business is to keep the foam moving from the foam line to the customer. The same philosophy holds true for the sellers of some foam products, notably mattresses. These occupy a large volume for their value, and the mattress seller also acts to minimize his inventory. One foamer advised us that it was not unusual for slabstock poured in his plant on one day to be in a mattress and slept on 24 hours later.

While a foamer tries to minimize warehouse residence time, the problem becomes acute when his sales increase to the point where his warehousing area is borderline in capacity. Then, measures must be taken to keep the foam moving rapidly from line to the customer. Success in this endeavor requires that foam cure rapidly, particularly if it is transported in compressed form. Because of methylene chloride's characteristics, the foam manufactured with it cures more slowly than that made with CFC. Once again, this can be an important factor—one that plant management must consider when choosing a blowing agent.
Atypical Product Distribution

The economics of using methylene chloride instead of CFC-11 clearly depend on the average amount of blowing agent used, as demonstrated earlier. For foamers with a "typical" line of foam, the savings possible appear to be about 2.4 percent of materials costs. These savings must be balanced against other factors, such as the potential of an increase in scrap rate, or a compromise in quality.

Some foamers specialize in low blowing agent foams, such as carpet underlay. The average ILD of carpet underlay that uses CFC (much of it requires no auxiliary blowing agent) appears to be quite high, perhaps about 40. Thus, the potential savings in material costs are far below one percent. In such a situation, very small changes in the quality of the output can overwhelm the potential of blowing agent substitution, and a foamer with this type of product may be understandably reluctant to switch. The character of carpet underlay is another factor. It is about one-quarter of an inch thick, and therefore has a very large exposed surface area per unit of volume or weight. Blemishes caused by uneven cell size distribution will be much more obvious than if the foam was several inches thick, and in fact, a large cell could even appear as a hole in the product.

We were told that methylene chloride produces a wider distribution of cell sizes, and that in the few trials that have been made, the product yield fell below the point at which a net savings would have been realized. Perhaps additional research and development would solve this problem, but it illustrates a case where blowing agent use is low, and where, as a result, very small changes in product characteristics can counteract potential savings.

Quality Factors

From the very beginning of our research into the use of methylene chloride as a blowing agent in 1977, we were told about quality differences between foams blown with CFC-11 and foams blown with methylene chloride. These differences were usually described by "pro-CFC" foamers who usually implied that methylene chloride produced an inferior foam. In the pursuit of this subject, we continued to ask foamers with various blowing agent preferences, raw material suppliers, and blowing agent manufacturers about these supposed differences. We found a diversity of answers. But what finally emerged as relevant is that there is sufficient difference in the two products that a knowledgeable and sophisticated buyer with exacting requirements not only can tell the two foams apart but will have a preference. If such a buyer insists on a CFC blown foam, even if the foamer's entire production is already geared to use methylene chloride, he will take his business elsewhere if he cannot obtain what he wants. This kind of a buyer is not often encountered, but we found more than one instance where a foamer deviated from his usual practice to retain the business.

Other buyers may either not know the difference, or they may perceive it but be convinced that the differences are insufficient to affect the characteristics of the product they make. But the occasional customer who has either an important and demanding application, or who caters to a persnickety clientele, may still be a factor in the foamer's choice of blowing agent.

Economic Factors

In a sense, all the factors that are described in this subsection have economic aspects that bear on the choice of blowing agents. But some economic factors have not been explicitly dealt with to this point and will be discussed here.
Foamers wishing to use methylene chloride in addition to CFC-11 must make certain additional investments. Storage tanks are required, and pumping and metering equipment is necessary. Also, the gaskets and hoses that contact either the methylene chloride or any mixture containing it must be resistant to its solvent action. We do not know what the cost of this additional equipment might be, but the savings in material costs that are possible appear to dwarf the investment. Evidence of this seems implicit in the actions of all the foamers who have made the investment.

Many foamers talk about the increase in scrap rate that either occurs or is likely to occur when changing from the use of CFC-11 to methylene chloride. We were unable to uncover any systematic treatment of this subject, but we did encounter many opinions. Beginning with the uncontested premise that using methylene chloride is more difficult than using CFC-11, present users of CFC-11 alone argue that their scrap rate would increase if they were to switch blowing agents, and that the increase might wipe out any savings. We discount this, simply by observing that a large number of foamers have lowered their costs by using methylene chloride. Yet, we did not find any foamer who had kept systematic records to demonstrate any differences at all. In fact, discussion with some foamers revealed that they had given little thought to the possibility of an increased scrap rate. What might be inferred from this is that scrap rate differences are relatively minor, particularly in technically competent, well run plants.

This inference covers only those foams that are actually blown with methylene chloride. As we have seen, foamers tend to avoid its use in super soft formulations, because the chances are higher that a complete disaster will result. It is not hard to put this in context. If a foamer makes one super soft run per week (about average), two bad runs per year will wipe out his expected material savings. Not only that, but even if disaster does not result, even small defects in the quality of the bun may increase the scrap rate disproportionately. Regular grade foams have a multitude of uses, and, therefore, if a bun has small defects, such as "shoulder splits," these can be removed and the remaining foam can be cut into salable pieces. Foamers refer to the market for these odd sized pieces as the "widget" market. There is virtually no "widget" market for super soft foams. Consequently, if a bun has shoulder splits, the entire width of the bun must be cut out and scrapped. Foamers are very sensitive to this possibility, since minor defects are more prone to occur in super soft foams blown with methylene chloride. They may not have systematic data to review, but they may judge that the odds of losing the raw material advantage to scrap are too great.

A second topic concerning scrap is the "scrap is in the eye of the beholder" argument. This emerged in a conversation with a large foamer who used both blowing agents and made all of his soft foam with CFC-11. His stated reason for using CFC-11 was that the scrap rate would be unacceptable if he did not. When told about a small foamer who used only methylene chloride, even to blow super soft foams, the immediate reaction was that the small foamer was making a lot of scrap, but that he did not recognize it. (We take this to mean that the quality of the foam was not equivalent to CFC blown foam.) This same view was echoed by another foamer, who recalled that when he adopted the use of methylene chloride, for a time he experienced problems with some customers.

Perhaps an appropriate definition of scrap in this sense, and in these examples, is that the methylene chloride blown super soft foam is only "scrap" if it is unsalable because of the ready availability of a CFC-11 blown alternative. Competition in the foam industry is active, and foamers are very responsive to customer desires. Consequently, if a customer can "shop around," a foamer may change his perception of what is scrap and may choose a different blowing agent.
Foam machines are of many types and feature various means of achieving flat topped buns. Some foam machine designs are patented and the purchaser of the machine must pay a royalty that is based on the amount of foam produced. We are not privy to all of the various royalty agreements, but one such arrangement included initial royalties of about 2-1/2 percent of the material costs, decreasing steadily to about 1/3 percent and ending after ten years.

We already know that some foam machines are more amenable to the use of methylene chloride than others, and we also know that on average, a foamer can save about 2.4 percent of his raw materials cost by using it. If a foamer could choose between a machine that could easily use methylene chloride but which entailed royalties, and one that was royalty free but could not easily use it, his choice might depend upon his time horizon. Clearly, he would be better off in the long run to choose the machine with which he can use methylene chloride, but it is conceivable that he could be influenced by short-term economics. We saw no indication that this has been a factor in machine choices, but we rarely were able to talk to those responsible for selecting the equipment. We merely make the point that royalties could be an economic factor.

At the inception of this study, we were under the impression that there might be geographical pockets where foamers all used CFC-11 exclusively in a stable situation. We now believe that this is not so and that methylene chloride is used everywhere. This is as one would expect if the economics favor its use.

Psychological Factors

It would be an understatement to say that there is a lot of feeling in the industry about methylene chloride. Many industrial hygienists simply dislike the material. Many raw material suppliers also dislike it. On the other hand, some foamers insist on using it. Their reasons vary, but it is certain that individual prejudices affect the use of methylene chloride. We discuss here, without any ranking, the kinds of fear and apprehension that we have heard voiced.

The fear of future government regulation of methylene chloride is often mentioned. Foamers know that it is a chlorocarbon and that chlorocarbons have increasingly come under regulation. They have no sense of a comprehensive government policy on chlorocarbons, and fear that sooner or later methylene chloride will be regulated in a way harmful to their interests. These same individuals are aware of the extensive testing that has been conducted by Dow Chemical and Kodak, but they discount the favorable results, sometimes saying that they are self-serving, and at other times saying that they will be ignored in future regulations. Instead, they concentrate on the knowledge that methylene chloride originally had a TLV of 500, which was then lowered to 200, and that there is currently a recommendation to drop it to 100. Further, they know that state regulations or local air pollution regulations supersede federal regulations when they are more stringent. We were told that several states are considering regulations that would affect the use of methylene chloride.

The question of worker attitudes and potential labor problems is also mentioned. Some foamers are afraid that the odor of methylene chloride will worry workers, and that this will lead, at a minimum, to unrest and turnover, possibly to union problems. While the TLV of methylene chloride is 200 ppm, this is an eight-hour time weighted average that allows peak exposures of greater than 300 ppm, which is when the odor is perceptible. At certain locations, mainly the cutoff saw, it is difficult not to exceed the odor threshold. Some foamers also
question the long-term health effects of methylene chloride. They allege that even if the
government does not regulate the chemical, health effects may emerge that they do not want
to face. This is voiced mostly by non-users of methylene chloride and takes no account of the
foamers who already use this blowing agent without reported health problems.

Some foamers, again non-users of methylene chloride, fear that the quality of their prod-
ucts will suffer, not because of the less forgiving nature of methylene chloride, but because of
its vapors. They fear that they may cause a minor narcosis of the foam line operators that
might make them less attentive.

Companies Who Use Only CFC-11

Not many companies use only CFC-11, and a special effort was made to determine why
they exist at all. We found companies with foam lines absolutely incompatible with methy-
lene chloride; these companies are working on the problem. We found small companies whose
major business was foam fabrication and whose foam line activities served only their own
needs for raw materials. As a result their product lines were limited, and the CFC-based
formulations were both easy to use, in the face of limited technical resources, and more
economical than buying slabstock elsewhere. We found companies that had started small and
had grown in size. They had begun operations with CFC-11 and were still using it, but almost
without exception they were either actively planning to change to methylene chloride or were
considering it.

We also found several companies who believed that because of their peculiar product
lines, customers, and plant and equipment, CFC-11 was no less economical than methylene
chloride, although it was obvious in many of these instances that the decision to remain with
CFC-11 had been arrived at subjectively and in several cases was not subject to any further
review.

Companies that use only CFC-11 probably account for about ten percent of the total CFC
used by slabstock foamers, or about two to three million pounds per year.

Extending Methylene Chloride Use

Since relatively few slabstock foamers appear to use pure CFC-11, the potential for ex-
tending methylene chloride use exists mostly with those foamers who already use it. We have
already noted that most foamers are aware of the economic benefit of substituting methylene
chloride and see the incentive in using it more. We also have observed that if there is any
movement in the industry, it is generally to increase the use of methylene chloride.

Estimating the potential for decreasing CFC-11 use and emissions is fraught with prob-
lems because of uncertainty in the present amounts of CFC and methylene chloride used.
However, a relatively simple approach may yield reasonable estimates.

We surveyed the foamers we interviewed and obtained their estimates of their annual
use of blowing agents (in phr). The values received were converted to terms of pure CFC-11
by dividing the methylene chloride use by 0.85. We found that there was a wide variation,
ranging from a low of about 3.5 to a high of just over 9. The variation was due to the distribu-
tion of the products made, and in each case of either a very high or a very low number, the
foamer knew which characteristics of his product distribution caused it.

The average value of those reviewed was 7.64 phr of CFC-11. This is not a weighted
average, and the survey was not extensive, but it is a starting place for demonstration pur-
poses. In terms of weight of CFC-11 per pound of finished foam, 7.64 phr is about equivalent to 5.3 percent. In 1978, an estimated 781 million pounds of slabstock were made, implying that 41.4 million pounds of CFC-11 would have been used, if it was the only blowing agent. The actual amount of CFC-11 used was estimated to be 26 million pounds, meaning that about 15.4 million pounds of CFC-11 were replaced with methylene chloride. Since it takes 15 percent less methylene chloride, the actual amount of methylene chloride used was probably about 13.1 million pounds.

We now use the formulation data that were the basis for Figs. 5.1 and 5.2, together with the production distribution of Fig. 5.3 and the actual blowing agent use for that product mix, to develop the curve in Fig. 5.6. This curve represents the approximate use of CFC-11 for foams of typical production densities at various ILD values. Finally, using the product mix in Fig. 5.3, together with the curve of Fig. 5.6 and the 1978 total blowing agent consumption of

![Graph](image)

**Fig. 5.6**—Weight percent CFC-11 used in average production of slabstock foam (for formulations using only CFC-11)
41.4 million pounds of CFC-11 equivalent, we can construct a CFC-11 use distribution by ILD, as shown in Fig. 5.7. This is shown in cumulative form, and also shown is the 26 million pound level that was actually used in 1976.

Figure 5.7 shows that on average, the dividing line between foams made with either 100 percent methylene chloride or 100 percent CFC-11 appears to be at about 25 to 30 pound ILD.

From Figure 5.7, it follows that 1976 emissions could be reduced from 26 million pounds to 12.5 million pounds by extending methylene chloride to 20 pound ILD foam, to 11.5 million pounds by extending it to 15 pound ILD foam, and, of course, to zero if all slabstock was made with methylene chloride.

![Graph showing CFC-11 use distribution](image)

**Fig. 5.7—Synthesis of 1976 CFC-11 use in flexible urethane slabstock manufacture**

This discussion admittedly oversimplifies the subject. We already know that some foamers use no methylene chloride and that some use it even for super soft foams. But it serves to illustrate that the average foamer uses methylene chloride and, on average, uses it to make firmer foams. Even as foamers attempt to increase their use of methylene chloride, there is increasing resistance to the replacement of CFC-11, because of the factors discussed above.

**ASSESSMENT OF OTHER CHEMICAL SUBSTITUTES**

EPA specifically requested that we investigate the substitution of water for CFC-11 and the use of reduced atmospheric pressure as a means of reducing CFC use. Recall that the
fundamental blowing agent in slabstock is the carbon dioxide that results from the reaction of TDI and water. Carbon dioxide produced this way is much less expensive to use as an auxiliary blowing agent than either CFC-11 or methylene chloride. Therefore, one would expect that formers would capitalize on it to the maximum. That is exactly what is done, and the prospect for further increasing the use of water appears limited. As has been previously explained, the TDI-water reaction also produces urea, which stiffens the foam and makes it boardy. Consequently, it acts to defeat the cushioning characteristics that are the prime attribute of the foam. Present formulations use as much water blowing as possible while still retaining the desired cushioning characteristics.

It is an observed phenomenon that the amount of auxiliary blowing agent required decreases as the atmospheric pressure is reduced. Foam line operators experience this every day as the barometric pressure changes. It is most clearly evident in foam operations in high altitudes, such as Denver, Mexico City, and Bogota, Colombia. At these high altitudes, no auxiliary blowing agent is required in a number of formulations that would otherwise need them, and the quantity of auxiliary blowing agent is reduced in others. It is a simple step from this observation to the thought that providing reduced pressure on the foam line would reduce CFC use (or methylene chloride use). The idea is well known, there have been a number of corroborating laboratory tests, and there may even be patents. The transition from the philosophy to a production process is a much greater problem, for two reasons. The first is that the problems that exist at sea level for successfully operating a foam line to produce a high percentage of quality foam appear to be enormously magnified at low pressures, where the foam becomes hypersensitive to other operating variables. The second is that it is operationally very difficult to create a low pressure on the foam line. The line must be accessible to workers who monitor the foam and who operate the flat topping devices; to achieve this, it might be necessary to enclose the foam line in a pressure-tight building equipped with air locks for the workers to enter and exit. The building could not be small, since the finished foam occupies a large volume—20,000 to 100,000 square feet of building may be necessary. The construction of such a hermetically sealed building and its operation are sure to be substantially more expensive than the use of CFC-11 or other auxiliary blowing agents.

ASSESSMENT OF PRODUCT SUBSTITUTES

We previously mentioned that there was probably only a remote possibility that other cushioning materials, such as rubberized hair and cotton batting, would be considered as viable substitutes for urethane slabstock. In earlier work we determined that HR foams could be made in equivalent softness to regular urethane slabstock, and that they use less auxiliary blowing agent. While this is true, the HR foams are roughly double the density of urethane slabstock, and the raw materials are higher in cost. Consequently, the HR foams sell for over twice the price of regular slabstock. Because of this, their present use is restricted to mattress cores, carpet underlay, and other specialty areas where their particular characteristics are required and where the market can support the price.

There is no question that HR foams could be used in many of the places where slabstock is now used, but not without the consequences of the higher density and price. The higher density implies proportionately higher use of petrochemicals and thus implies heavier furniture and bedding products. These in turn will affect transportation energy requirements and marketability (a foam mattress that now weighs 50 pounds would weigh 100 pounds).
III. Molded Foams

Most molded foam is used in automobile seats, and a very large fraction of it is HR foam. For practical purposes, the study of CFC use in molded foam is largely a study of the practices of the automobile industry. Automobile seats differ by manufacturer according to the philosophy followed and the segment of the consumer market catered to. As an example, the seats of German cars are generally very firm, and the seats of French cars are generally very soft. Within the United States, Ford seats are generally firmer than those of GM. As mentioned, this is a conscious design criterion. In addition, all design criteria generally call for seat bottoms that are firmer than seat backs. Thus, softer foams are used in backs than in bottoms, and softer foams are used by GM than by Ford.

The automotive industry in the United States is also undergoing dynamic changes. Cars are being downsized, and weight is being reduced. This has affected seats in several ways. The front bench seat is virtually a thing of the past; modern cars seat five instead of six. The density of the foam in the seats has also been reduced by about ten percent, and in some instances wire springs have been molded into the foam so that less foam (and less weight) is present. Cross-cutting all these changes are automobile sales, which vary from year to year, and which have recently been low.

The net result of all of these changes is that CFC-11 use has remained about the same, and the forecast is that it should decrease in the future. At the present time, GM is using CFC-11 in both seat backs and seat bottoms, partially to reduce the density of the seat and partially to achieve the design softness. Ford is not using CFC-11 in the foams that they manufacture, but some of their outside suppliers (particularly those who use hot molding instead of HR foam) may be using CFC-11.

CHEMICAL CONTROL OPTIONS

As with slabstock foam, the option of recovering and recycling the CFC is an option for reducing CFC use and emissions. There are no applicable work practices in this product area. Chemical substitutes, which do exist in the form of methylene chloride for slabstock, cannot be used in molded foam. There are a number of reasons for this, but the most compelling one is that the product so made is unsatisfactory. Unacceptable surface blemishes are common, and the surface character is such that it will not easily slide into the seat covers.

Non-foam product substitutes are a possibility, but an unlikely one. Automobile seats were originally made of wire springs and cotton batting, rubberized hair, and similar materials. These substitutes are heavier, less versatile, and make poorer seats than foam. They are also more expensive. As a result, they are not under consideration by any of the automobile companies. At one point, the General Seating Division of Lear Siegler suggested in a news release that there might be a movement away from foam and toward wire springs, but this meant that wire springs could be imbedded in molded foam to reduce the amount of foam required.

One possible product substitute is a non-CFC blown foam seat that would be firmer and denser. This would require a design philosophy change by GM and would eliminate virtually all of the CFC used in HR foam molding. It would reduce, but not eliminate, the CFC used by
firms still using the hot molding process. Total CFC-11 reductions by using firmer seats might be in the range of four to six million pounds per year.

CONTROL TECHNOLOGY ASSESSMENT

Where CFC-11 is being used in molded foam, recovery and recycle of the CFC may be an option. This was discussed under the slabstock foam section, and its viability depends upon the economics. Very large molding plants are among the largest foam users of CFC and thus satisfy one of the criteria for economic success—that of a sizable amount of CFC available for recovery. But the configuration of the molded foam ventilation system, and the volumes of exhaust air used, may impose costs that lessen the attractiveness of the recovery option. This can only be evaluated after the Radian work is complete. If the option proves economically viable, it might have the potential of reducing CFC emissions by 50 to 80 percent, or 3.8 to 6.1 million pounds, based on 1976 use.
IV. Conclusions

Options to reduce emissions in slabstock foam manufacture essentially consist of further replacement of CFC-11 by methylene chloride. Making this mandatory will cause some slabstock foamers to incur costs that they now do not have. These costs could range from small increases in scrap rates, to replacement of foam line equipment, to relocation of an entire plant. Not all foamers would incur these costs. A reasonable number of slabstock plants presently use methylene chloride for the majority of their production, and these plants would probably have the fewest problems and lowest costs if methylene chloride use was expanded. But other foamers would encounter a variety of difficulties and added costs.

The dislocations involved, both for the entire industry and for customers, in replacing about 14 million pounds of CFC-11 with methylene chloride, are probably small to moderate.

If we set aside the possibility of recovery and recycle of the CFC-11, in plants that manufacture molded foam, the only apparent option is to use firmer seats in cars and eliminate much of the CFC use.
Chapter 6

REFRIGERATION USES OF CHLOROFLUOROCARBONS

I. Introduction and Summary

In this chapter, we analyze CFC use and emissions characteristics in two refrigeration product areas. Our examination includes the use of R-12 in home refrigerators and freezers and the use of R-12, R-22, and R-502 in retail food refrigeration systems. The CFC-11 used to make insulating foam in the refrigeration devices and the R-22 employed in supermarket air conditioning are addressed in Chapters 2 and 7, respectively.

Both home appliances and retail food refrigeration are examples of product areas where not all refrigerant emissions occur promptly; most of the CFC is retained in the product during its useful life. Emissions occur at manufacture, at servicing, through leakage, and at disposal. The 1976 emissions from home refrigerators and freezers were estimated in the earlier Rand study (Palmer et al., 1980) at about five million pounds, which represents only about two percent of total emissions. The 1976 losses (excluding R-22) from retail food refrigeration applications amounted to about 13 million pounds, or approximately five percent of total emissions. The two refrigeration product areas taken together therefore account for only about seven percent of total emissions.

In the earlier work, several methods for reducing emissions were identified. For home appliances, these included helium leak testing at manufacture, recovery at manufacture, recovery at servicing, recovery at disposal, use of only reciprocating compressors in new appliances, and substitution of R-22 for R-12. In the present study, we have examined the same general options. However, instead of limiting our investigation to the substitution of helium during leak testing, we also consider substituting R-22; instead of investigating only R-22 as the working fluid alternative, we also address some implications of using other substitutes.

The findings of our research in home appliances are summarized in Table 6.1. The emissions effects of the options listed are neither additive nor cumulative. Rather, they are based on the assumption that each option would be implemented separately. For example, we list both recovery at disposal and substitution for the working fluid. These two options are interdependent. If recovery at disposal were implemented first, the base of potential refrigerant savings through substitution would be lowered; similarly, if substitution were to occur first, the potential savings through recovery at disposal would be lower.

The options in Table 6.1 are ranked according to their ability to reduce emissions. Those on the left represent the immediate or short-term emissions reduction potential. Those on the right represent the long-term emissions reduction potential. This separation is necessary because not all of the emissions from home appliances are prompt, so that the full effect of certain options will not be achieved until the current stock of appliances has turned over. The

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1The use of the prefix "R," rather than "CFC," simply indicates that the chlorofluorocarbon functions as a refrigerant in these product areas.

2Total CFC emissions exclude R-22, which is thought to pose a small threat to the ozone layer.
Table 6.1

**Emissions Effects of Home Appliance Technical Options**

<table>
<thead>
<tr>
<th>Short Term</th>
<th>Long Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Option</td>
<td>Technical Option</td>
</tr>
<tr>
<td>Recovery at disposal</td>
<td>Recovery at disposal</td>
</tr>
<tr>
<td>Recovery at servicing</td>
<td>Recovery at servicing</td>
</tr>
<tr>
<td>Substitution for working fluid&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Recovery at servicing</td>
</tr>
<tr>
<td>Recovery at rework</td>
<td>Substitution of reciprocating compressors in new units</td>
</tr>
<tr>
<td>Substitution of reciprocating compressors in new units</td>
<td>Substitution at testing</td>
</tr>
</tbody>
</table>

<sup>a</sup>The short-term emissions effect is that occurring in the first year of implementation.

<sup>b</sup>The long-term emissions effect is that occurring approximately two decades after implementation, when the stock of current equipment has been disposed of.

<sup>c</sup>Assumes that the substitute would be R-22 or a fluorocarbon containing fluorine but no chlorine.

Two options that best illustrate this point are substitution for the working fluid and substitution of reciprocating compressors in new units. For example, the immediate emissions effects of substitution for the working fluid are very small, as shown in Table 6.1. In the first year of implementation, substitution would reduce emissions at manufacture and emissions that occur through leakage and at servicing of those appliances with the alternative refrigerant. The long-term emissions effects would be larger; substitution is ranked first on the right-hand side of Table 6.1. Once the stock has turned over, substitution would reduce emissions at manufacture, emissions that occur through leakage and servicing of all appliances, and emissions that occur upon disposal. A similar effect is observed for substitution of reciprocating compressors, which ranks fifth in the short-term list and fourth in the long-term list.

As discussed in Chapter 1, only those technical options that would have a very large, large, or medium effect on emissions were included in Table 1.1. The maximum emissions reduction that could be achieved through any of the home appliance technical options in Table 6.1 is small. Thus, none of the options is included in Table 1.1.
It should be noted that the ranking of options in Table 6.1 reflects only the ability of the option to reduce emissions. The ranking does not include an evaluation of the degree of dislocation. For example, recovery at disposal, although it leads the list in emissions reduction potential, would generate extremely high costs and dislocations. The ease or difficulty with which the other options might be adopted are discussed below.

The methods for reducing retail food refrigeration emissions identified in Rand's earlier work included using R-22 as a substitute during leak testing at manufacture, at installation, and as the working fluid; R-502 use in medium temperature systems; recovery at servicing; recovery at disposal; better installation; and preventive maintenance programs. International Research and Technology Corporation (IR&T), Rand's subcontractor in the earlier study, assumed that recovery of refrigerant at manufacture would be adopted over time; in the current work, we examine the recent progress. Although we also discuss use of R-22 as the substitute working fluid, we give it less attention than substitution of R-502, which is preferred by the industry.

In Table 6.2, the retail food refrigeration options are ranked according to their ability to reduce emissions. Again, the entries on the left are ranked according to their short-term or immediate emissions effect, those on the right are ranked on the basis of their long-term emissions effect.

As before, the rankings are based only on the ability to reduce emissions and do not reflect the ease or difficulty of implementing an option. For example, although recovery at disposal appears high on each list, in some cases the associated costs and dislocations are so high that it is doubtful that it would ever be practiced. Conversely, the use of R-502 in new units could result in relatively large emissions reductions with low costs and only moderate dislocations. The details of each control option are discussed in later sections.

The two options in Table 6.2 that differ greatly in their long-term and short-term emissions effects are the substitution options. They rank low on the short-term list and high on the long-term list. This reflects the fact that the full impacts of substitution occur only after the stock has turned over.

Our findings indicate that implementation of all but two of the control options in the retail food refrigeration product area would result in only small or very small emission reductions. One of these, use of R-22 as a substitute in new medium temperature units, would have a large associated dislocation. The other, substitution of R-502 for R-12 in all new units, could provide a moderate emissions reduction with a small to medium dislocation. This latter option is the only retail food refrigeration option that appears in Table 1.1.
Table 6.2

Emissions Effects of Retail Food Refrigeration Technical Options

<table>
<thead>
<tr>
<th>Short Term</th>
<th>Long Term</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technical Option</strong></td>
<td><strong>Technical Option</strong></td>
</tr>
<tr>
<td>Recovery at disposal</td>
<td>Use of R-22 as a substitute in new medium temperature units</td>
</tr>
<tr>
<td>Better equipment installation</td>
<td>Use of R-502 as a substitute in new units</td>
</tr>
<tr>
<td>Recovery at servicing</td>
<td>Recovery at disposal</td>
</tr>
<tr>
<td>Preventive maintenance program</td>
<td>Better equipment installation</td>
</tr>
<tr>
<td>Substitution at installation</td>
<td>Recovery at servicing</td>
</tr>
<tr>
<td>Substitution at manufacture</td>
<td>Preventive maintenance programs</td>
</tr>
<tr>
<td>Recovery at manufacture</td>
<td>Substitution at installation</td>
</tr>
<tr>
<td>Use of R-22 as a substitute in new medium temperature units</td>
<td>Substitution at manufacture</td>
</tr>
<tr>
<td>Use of R-502 as a substitute in new units</td>
<td>Recovery at manufacture</td>
</tr>
</tbody>
</table>

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a. The short-term emissions effect is that occurring in the first year of implementation.
b. The long-term emissions effect is that occurring approximately two decades after implementation, when the stock of current equipment has been disposed of.
c. Assumes that the substitute would be R-22 or a fluorocarbon containing fluorine but no chlorine.
II. Home Refrigerators and Freezers

INTRODUCTION

According to the 1972 Census of Manufactures, thirty-six firms manufacture home refrigerators or freezers. Six firms dominate the industry and together hold more than 90 percent of the market. There are numerous other small refrigerator and freezer manufacturers (EIS, 1980). Most of these firms hold less than one percent of the market and some produce very small under-the-counter models.

Table 6.3 lists each of the major refrigerator and freezer manufacturers, together with the number of plants and market share held by each.

Table 6.3

<table>
<thead>
<tr>
<th>Firm</th>
<th>Refrigerators</th>
<th>Freezers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of Plants</td>
<td>Market Share</td>
</tr>
<tr>
<td>General Electric</td>
<td>4</td>
<td>33</td>
</tr>
<tr>
<td>Whirlpool</td>
<td>3</td>
<td>26</td>
</tr>
<tr>
<td>White Industries</td>
<td>3</td>
<td>22</td>
</tr>
<tr>
<td>Revco</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Amana</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>Admiral</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Other(^b)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Total</td>
<td>12</td>
<td>100</td>
</tr>
</tbody>
</table>

SOURCES: EIS (1980), Appliance Manufacturer (1981), and industry sources.

\(^a\) Refrigerators and freezers are frequently manufactured in the same plant.

\(^b\) Includes Amana.

Table 6.4 shows the shipments, exports, imports, and domestic sales of refrigerators and freezers for 1980.

R-12 is the only refrigerant used in refrigerators and freezers today. In our chemical control options analysis for this product area, we have identified four areas of control technology that offer promise for reducing refrigerant emissions. These include: (1) the use of only reciprocating compressors in refrigerators and freezers; (2) recovery and reuse of the refrigerant at rework during manufacture; (3) recovery and reuse of the refrigerant at servicing; and (4) recovery and reuse of the refrigerant at disposal. Although each of these controls involves work practices as well as equipment, we classify them here as control technologies. For the assessment of chemical substitutes, we focus on two methods for limiting R-12 emissions. The first is use of an alternative test gas during manufacture, and the second is substitution for R-12 as the working refrigerant. We discuss no product substitutes for this product area.
Table 6.4

APPLIANCE SHIPMENTS AND DOMESTIC SALES, 1980
(Millions of units)

<table>
<thead>
<tr>
<th>Item</th>
<th>Refrigerators</th>
<th>Freezers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shipments</td>
<td>5.123</td>
<td>1.681</td>
</tr>
<tr>
<td>Exports</td>
<td>0.342</td>
<td>0.954</td>
</tr>
<tr>
<td>Imports</td>
<td>0.789</td>
<td>0.843</td>
</tr>
<tr>
<td>Domestic sales(^a)</td>
<td>5.570</td>
<td>1.670</td>
</tr>
</tbody>
</table>

SOURCES: Appliance Manufacturer (1981) and Bureau of the Census.
\(^a\)Total domestic sales equal shipments minus exports plus imports.

CONTROL TECHNOLOGY ASSESSMENT

Substitution of Reciprocating Compressors

In our earlier study (Palmer et al., 1980), Rand's subcontractor, IR&T, reported that about half of the refrigerators and freezers that were manufactured contained rotary compressors, and half contained reciprocating compressors. It was also reported that rotary compressors required a higher refrigerant charge, and that substituting reciprocating compressors could be an effective way of reducing refrigerant emissions. We have verified this through conversations with industry sources. The rotary compressor housing is at the discharge pressure, which permits lubrication of the relatively large contact area with a minimal oil pump pressure rise. Attempts to make inexpensive oil pumps so that the higher housing pressure would not be necessary have been unsuccessful. Whereas units with rotary compressors require a larger refrigerant charge, units with reciprocating compressors require a larger oil charge.

Only Whirlpool currently produces units with rotary compressors; the firm also manufactures its own compressors. According to the values of Table 6.3 and Table 6.4, of the refrigerators manufactured in 1980, 28 percent contained rotary compressors; of the freezers produced in 1980, 30 percent had rotary compressors.\(^4\)

For units with reciprocating compressors, one industry source estimates the size of the refrigerant charge in the average refrigerator at 5½ ounces and the size of the average refrigerant charge in the average freezer at 6½ to seven ounces. This same source estimates that the average refrigerator with a rotary compressor requires a charge of 13 to 13½ ounces; the average freezer with a rotary compressor requires 14 to 16 ounces. A second industry source reports that the refrigerant charge in units (refrigerators and freezers) with recip-

\(^4\)We assume that the 1979 market share allocation applies in 1980.
ocating compressors ranges between 5½ and 12 ounces, whereas for units with rotary compressors the charge varies from 16 to 20 ounces. From these data we estimate that the average charge of a refrigerator and a freezer with reciprocating compressors is 5½ ounces and seven ounces, respectively. For a refrigerator and a freezer with rotary compressors, we estimate average charges of 13 ounces and 17 ounces, respectively.

Given the market share figures in Table 6.3, these estimates lead to an industry-wide average charge for a refrigerator of about 7½ ounces and for a freezer of approximately ten ounces. These 1980 estimates differ from those reported in Rand's earlier work primarily because of recent changes in market share. The earlier estimates of a ten ounce average refrigerator charge and a 15 ounce average freezer charge were based on the assumption that half of the units manufactured contained rotary compressors and half contained reciprocating compressors.

Because of market share changes in recent years, the potential savings in R-12 use and emissions through exclusive conversion to reciprocating compressors have also changed. Before we analyze the effects of the conversion, we estimate the amount of R-12 used for initial charge and manufacturing in 1980.

The amount of R-12 used for initial charge can be calculated by multiplying the shipment figures in Table 6.4 by both the market share and the average charge of units with reciprocating or rotary compressors. On this basis, the R-12 initial charge for refrigerators amounted to about 2.4 million pounds and that for freezers totaled one million pounds. Consequently, the total amount of R-12 that went toward initial charge in 1980 was 3.4 million pounds. If all new home appliances during that year had been manufactured with reciprocating compressors, R-12 use for initial charge would have been approximately 2.5 million pounds. Therefore, the savings in refrigerant for initial charge if all appliances manufactured in 1980 had contained reciprocating compressors would have amounted to 0.9 million pounds.

Manufacturers also purchase R-12 for testing units at manufacture. Rand's subcontractor in the earlier work, IR&T, estimated total manufacturing losses at eight percent of initial charge in 1976. Three types of losses occur. The first two, emissions from leak testing and at rework, depend on initial charge and therefore also on compressor type. IR&T estimated the magnitude of these losses at 6.5 percent of initial charge. The third type of loss occurs at charging when the connection is broken; the magnitude of this loss does not depend on initial charge or, by extension, on the compressor type. IR&T assumed that emissions during charging amounted to 1.5 percent of initial charge. Although the losses at charging may total 1.5 percent of the initial charge at a particular time, the loss from charging is constant and does not change when the initial charge changes. Since two types of manufacturing emissions do vary with initial charge, however, emissions at manufacture from appliances with rotary compressors are larger than those for appliances with reciprocating compressors. Assuming that the 6.5 percent loss remains valid for 1980 and using the initial charge requirements given above, the conversion to reciprocating compressors exclusively would have saved the manufacturers 0.061 million pounds in losses during manufacture in 1980. Total savings in R-12 use for that year, including savings from initial charge and losses during manufacture, would amount to about one million pounds.

One industry source estimates the capital cost of building a new compressor plant at $100 million. Current capacity for producing reciprocating compressors is apparently not sufficient to supply the whole appliance industry. As well as a new facility, a new location, new tooling, and new design would be required. The original rotary compressor plant would have to continue operation for about 20 years after the last units containing rotary compressors were manufactured to provide replacement parts for units still in use. This industry source estimates the total cost of maintaining the servicing capability at $45 million.
A second industry source estimates the capital cost for constructing a new compressor plant at between $100 and $200 million, with a five-year delay before the plant could begin producing compressors. Moreover, there might be a high initial failure rate in the units with the new compressor type; this would affect warranty liability. This manufacturer also estimates that the costs to the manufacturer of warranty repairs might be as high as $1 million per day.

For purposes of analysis, we adopt conservative cost assumptions for the conversion to reciprocating compressors. We assume that the capital cost of building one new compressor would be $100 million, and that it would begin functioning in five years, in 1986. We neglect the cost to industry for dealing with the servicing problems. Assuming a fixed charge rate of 30 percent, the total annual cost to the producer would be $30 million.

Manufacturers' savings in R-12 purchases can be determined as before by taking the difference in R-12 used for manufacturing and initial charge for units with both compressor types and for units with only reciprocating compressors. In Rand's earlier work, the last year for which projections of domestic sales of refrigerators and freezers were provided was 1990. By 1990, the new compressor plant will have been operating for four years, and the R-12 savings in that year can be considered as representative of the period. Assuming that the manufacturers' shares do not change by 1990, converting would save them about 1.5 million pounds of R-12.

The costs of conversion would vastly exceed the potential refrigerant savings at present R-12 prices. Manufacturers purchase R-12 at the bulk price, presently about 75¢ per pound. Given the estimated 1990 reduction in R-12 purchases of 1.5 million pounds, the annual savings would total approximately $1.1 million. This is significantly less than the annual cost of conversion.

In the earlier work, IR&T estimated the capital cost of conversion at $20 million, which is far lower than the estimate we recently obtained from industry. If we again assume a fixed charge rate of 30 percent, and further assume that there are no costs associated with servicing, the annual conversion cost would amount to $6 million. Even this value is still well above the potential savings in R-12 purchases.

Although conversion would result in rather small R-12 annual use reductions (about one million pounds in 1990), emissions reductions would be greater. Once all operating units contained reciprocating compressors, total emissions from refrigerators and freezers could be reduced by 25 to 30 percent. Total 1990 emissions from this application were estimated in the earlier study at about 7.5 million pounds. If we assume that by then all units contain reciprocating compressors, savings in R-12 emissions for that year might total 1.9 to 2.3 million pounds. This reduction, although significant when compared with total home appliance emissions, is negligible when compared with total emissions from all CFC product areas.

Recovery and Reuse at Rework

Before evaluating the effectiveness of recovering the refrigerant at rework, we describe the individual steps of the appliance manufacturing process and develop estimates of the losses that occur during each step.

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*Whenever a firm puts a new design on the market, the expected failure rate is higher for some period of time until the design is perfected.*

*The fixed charge rate has traditionally included all costs associated with capital.*

*This, of course, would not be the case, since the unit lifetime is about 20 years. If the new compressor plant had been operational in 1986, many units containing rotary compressors would remain in 1990.*
In general, components are first charged with dry air and tested for gross leaks in a water bath. The second step varies, depending on the manufacturer. One manufacturer leak tests the condenser and the entire assembled unit with helium before final charging. Another manufacturer charges the assembled units with R-12 and tests for leaks with halide “sniffers.” All units, once assembled and charged, are put through an operating refrigeration cycle. Sometimes the units do not function properly, perhaps because of air in the system or a motor burnout. Malfunctions are detected with an infrared temperature sensor. Units that do not function properly are reworked and their R-12 charge is released to the atmosphere.

The Association of Home Appliance Manufacturers (AHAM) has summarized R-12 in-plant losses for refrigerators, freezers, dehumidifiers, and foam insulation for 1974 and 1977. AHAM reports that 5.168 million pounds of R-12 were used in refrigerators, freezers, and dehumidifiers in 1977. An additional 1.119 million pounds (22 percent of the initial charge) were lost during manufacture. Since there is no reason to expect that manufacturing and emissions characteristics of dehumidifiers differ significantly from those of refrigerators and freezers (as the earlier Rand study showed), the percentage loss at manufacturing is probably also reasonable for refrigerators and freezers alone.

A representative of AHAM indicated that about half the R-12 losses were reported by two small firms. The large manufacturers, who probably have better quality control, may have lower manufacturing losses, perhaps ten percent of the initial charge. Although the AHAM data are useful for estimating total losses by manufacturers, they do not pinpoint the sources of loss. Their figures include R-12 lost from a number of sources such as leaks in refrigerant storage facilities and transmission lines, and development work in the laboratory.

In Rand’s earlier work, IR&T estimated 1976 manufacturing losses at 1.5 percent of initial charge at component testing, 1.5 percent of initial charge at charging, and 5.0 percent of initial charge at rework. One manufacturer indicated that the IR&T estimates of losses at component testing and charging were approximately correct, but that rework losses were more likely in the range of two to three percent of initial charge. A second manufacturer indicated that the rework loss might be as low as one percent of delivered refrigerant.

In our earlier work, we felt that IR&T’s estimates of the rework losses were too high. We were led to this conclusion because manufacturers had not adopted recovery even though it appeared cost effective at that time. If we assume that rework losses are actually two percent of initial charge, and that 3.4 million pounds of R-12 went toward initial charge, 1980 rework losses totaled about 70,000 pounds.

According to Table 6.3, there are 12 refrigerator plants, some of which also manufacture freezers. One method of apportioning rework losses is to assume that each plant accounts for one-twelfth of the total losses. On this basis, the annual plant loss would amount to about 6,000 pounds. A few of the large manufacturers have at least one very large plant at which the rework losses could be as high as 12,000 pounds annually. The current bulk price of R-12, the price paid by manufacturers, is about 75¢ per pound. If all of the refrigerant lost during rework in one plant could be recovered, the manufacturers could save between $4,500 and $9,000 dollars each year in refrigerant purchases.

One manufacturer estimates the capital cost of a recovery unit at $100,000 per plant. This same manufacturer could not provide an estimate of the operating costs. If we assume a fixed charge rate of 30 percent, and assume that annual operating costs are negligible in comparison, the yearly cost of recovery would be $30,000. This cost significantly exceeds the potential savings in R-12 purchases. Indeed, under these assumptions, it would be necessary to recover 40,000 pounds of R-12 from one plant for the option to be economically justified. It is extremely unlikely that rework losses in any plant are this high.
If rework losses are actually five percent of initial charge as claimed by IR&T, the refrigerant that could potentially be recovered annually would amount to about 170,000 pounds. If this loss is apportioned as before, each plant might recover between approximately 14,000 pounds and 28,000 pounds each year. The savings in refrigerant purchases, assuming a 100 percent recovery efficiency, would range between $10,500 and $21,000 annually. If the recovery costs reported by industry are accurate, even under the assumption that rework losses are very high, the savings in refrigerant purchases do not outweigh the costs.

It should be noted that if the malfunction requiring rework of an appliance were a motor burnout, the refrigerant would be contaminated. Then it could not be reused unless it were first analyzed and purified. Contaminants that might be present in the refrigerant include water, air, CO₂, organic acids, metal particles, varnish, HCl, and HF. Manufacturers, when considering recovery, are extremely concerned with identifying a reliable method for purification.

We are aware of two devices, both of which were designed for other purposes, that could conceivably be used for recovery at rework. The first was originally manufactured by DuPont but is now produced by the Serv-I-Quip Company. The unit is designed for recovery and reuse of refrigerant used for leak testing. At leak testing, the contaminants present are air, oil, and moisture. Because the unit is not capable of removing some of the other contaminants present in a motor burnout, it is not especially applicable for recovery at rework.

A second manufacturer, Draf Industries, Inc., manufactures a recovery unit called the Draf Tool Device for use in automotive service facilities. The device contains a coalescing filter and molecular sieve. The estimated amount recovered is 97 to 99 percent, depending on ambient temperature and time of reclamation. The manufacturers claim an average reclamation time of 15 to 30 minutes, which is apparently the time required to reclaim the R-12 contained in one mobile air conditioner. This implies that it would take between five and ten minutes to reclaim one pound of R-12.

One refrigeration/freezer manufacturer has apparently tested the Draf Tool Device for recovery of refrigerant from a refrigerator. Although the device is capable of neutralizing acid, the acid present in the refrigerant overwhelmed the system. This manufacturer, understandably, did not think the device promising. A representative of Draf Industries, Inc., has recently indicated that this test was performed in 1979 on an early unit design; he is certain that the new design would be capable of removing acids generated during a burnout.

Another method of recovery would involve collecting the contaminated refrigerant in the plant and shipping it to a reclaimer for purification. We have identified one reclamation firm, Omega Chemical, that has extensive experience in purifying R-12 and other refrigerants. Reclamation of R-12 is accomplished with distillation, and the R-12 received by Omega generally contains about five percent contaminants. The reclamation procedure reportedly can purify 95 pounds of refrigerant from 100 pounds of contaminated material; the purity is equivalent to that of virgin refrigerant (99.8 percent). Costs of the reclaimed refrigerant are well below the price of virgin refrigerant (30 to 60 percent), but there is an extra charge for non-local transportation. Omega Chemical is located in Whittier, California, and refrigerator/freezer plants are primarily in the Midwest. It is possible, therefore, that transportation costs could increase the price of reclaimed R-12 above that of virgin R-12.

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7 We make the same assumptions as before to obtain this range of losses.
Recovery at Servicing

One manufacturer claims that 95 percent of service calls involve a malfunction in a timer, fan, heater, or thermostat; only five percent of service calls involve a malfunction in the hermetically sealed refrigeration system. Another manufacturer indicates that only eight to ten percent of service calls result in venting of the R-12 charge. A representative of a servicing organization reports that service of the hermetic system is required for only two to three percent of service calls.

In the earlier work, IR&T estimated R-12 servicing losses at 1.5 percent of the stock of R-12 in refrigerators and freezers; this amounted to approximately 1.3 million pounds in 1976. One manufacturer indicated that this loss might actually be as low as one percent of stocks. The AHAM data show 330,000 pounds as the quantity of R-12 used and lost during service of refrigerators, freezers, and dehumidifiers in 1977. Assuming that servicing losses from dehumidifiers were negligible, the AHAM figure represents about 0.3 percent of 1976 stocks.

Since we do not know what actual losses are, we will use the data of the earlier work for purposes of analysis. The servicing losses in 1976 were estimated at about 1.3 million pounds and the servicing losses in 1990 were projected to be approximately 1.6 million pounds. Assuming a uniform growth rate for the period 1976 through 1990, 1980 servicing losses would amount to about 1.4 million pounds.

The Draf Tool Device, or other appropriate equipment, might be used for recovery of R-12 during servicing. Draf Industries claims that its device can reclaim about three pounds of refrigerant in 15 to 30 minutes. In the case of refrigerators and freezers, the largest unit might contain 20 ounces of R-12 which, according to the Draf data, could be reclaimed in about ten minutes. One refrigerator/freezer manufacturer tested the Draf Device and maintains that it actually would take the service person approximately 30 minutes to perform the recovery process.

Two manufacturers provided estimates of labor costs ranging from $25 to $50 per hour. A representative of a servicing organization indicated that his firm charges $36 for the first half hour and $9 for each 15 minute period thereafter. If we assume that 20 ounces of refrigerant can be reclaimed in ten minutes, at a labor cost of $25 per hour, the labor cost of recovery would be about $4. With less conservative assumptions, the cost would be even higher.

The current bulk price of R-12 is 75c per pound. The price is higher for refrigerant purchased in cylinders. Contractors who service retail food refrigeration units, for example, pay about $2.25 per pound for R-12. Although we do not know the refrigerant price paid by refrigerator/freezer servicing organizations, we suspect it is in this same range. The savings in refrigerant purchases for recovery of 20 ounces of R-12 priced at $2.25 per pound would total $2.61. Since most refrigerators and freezers contain less than 20 ounces, this is the maximum potential savings. It appears that the savings in refrigerant purchases do not outweigh the labor cost of recovery.

It is worth noting that only one manufacturer includes a service valve on refrigeration units. This further complicates recovery at servicing and also at disposal (see the following subsection). Service people would need several pieces of equipment to gain access to the hermetically sealed system. The Draf Tool Device, for example, was intended for use with automotive air conditioning units, which do contain service valves.

Although servicing emissions are a rather significant fraction of total home appliance emissions, it is very unlikely that recovery at servicing will be practiced in the near future.
Indeed, for most refrigerators and freezers, recovery is not technically feasible, since few units are manufactured with service valves. Both manufacturers with whom we talked stated that even if a recovery device were available and the process were cost effective, the service people would probably not use the recovery equipment.

Recovery at Disposal

In Rand's earlier work, emissions of R-12 at disposal were estimated at about 3.2 million pounds in 1976 and were projected to be approximately 5.2 million pounds by 1990. Assuming a uniform growth rate for the period, 1980 disposal emissions would be 3.7 million pounds. Recovery at disposal has the potential of reducing total home appliance emissions by about two-thirds.

According to one manufacturer, scrapped refrigerators and freezers are crushed and used as landfill. This is verified by a representative of a servicing organization, which receives 20 or 30 inoperative units per week. A salvager first removes the compressor and other metal parts (copper, aluminum, and iron) before the box is dumped. The servicing organization takes used units in trade and will also fix a malfunctioning unit for second-hand sale if the cost of the required parts does not exceed $20. A representative of the servicing organization indicated that only nonfunctional units are taken to dump sites, and, of those taken, perhaps only 35 percent have a full R-12 charge.

Recovery at disposal could perhaps be accomplished using equipment like the Drafi Tool Device. Purification, either within a portable device or by an external reclaimer, would be necessary. The recovered refrigerant might be sold to the refrigerator-freezer manufacturers in place of virgin R-12 for charging new appliances.

Since refrigerators and freezers are not generally disposed of until they no longer function, we can assume that none of the units that reach the dump site are operative. One manufacturer indicated that only about 60 percent of the refrigerant in an appliance that is not operating can be recovered if the oil is not also collected. Moreover, some of the units that reach the disposal site will contain no refrigerant. With a labor cost comparable to that during recovery at servicing, this technique is not cost effective at current refrigerant prices.

The high cost, however, is probably not the most significant deterrent to recovery at disposal. One important consideration is logistics, which could be complicated by legal restrictions. Could a state or federal law require appliance owners to deliver their used appliances to dealers or dump sites? Alternatively, could dump sites hire individuals to pick up the disposed of appliances? Either way, the already high cost would be increased even further, and in addition, enforcement of the process would be difficult. Thus, even though home appliance emissions could be reduced significantly through recovery at disposal, it does not appear promising.

ASSESSMENT OF CHEMICAL SUBSTITUTES

Substitution at Testing During Manufacture

In the earlier subsection on "recovery at rework," the process for manufacturing refrigerators and freezers was described. When the units are charged, the traditional method of
detecting leaks is the halide "sniffer." As mentioned above, an alternative method of leak detection using helium is used by one large manufacturer. It is no coincidence that this firm also markets a helium leak detection device. IR&T indicated in Rand's earlier work that other manufacturers were converting to the helium system. In our conversations with industry sources, we found no evidence of this.

One industry source estimated the capital cost of the helium detection system at between $100,000 and $300,000. Annual operating costs, including labor and maintenance, are reported to range from $100,000 to $500,000. The equipment consists of a mass spectrometer and a vacuum chamber. The helium that is actually used is diluted with air to between two and 15 percent by weight. The cost of the helium is currently $7.75 per hundred cubic feet and is essentially negligible compared to the operating costs.

One savings to the manufacturer adopting the helium system would be from reduced purchase of refrigerant. As indicated earlier, the R-12 lost through halide "sniffer" leak detection amounts to about 1.5 percent of the annual initial charge. Because rotary compressors require a higher refrigerant charge than reciprocating compressors, a larger amount of refrigerant is lost through leak testing units with rotary compressors.

To derive a conservative estimate of the costs of substitution, we will examine the possible R-12 savings for the one manufacturer of units with rotary compressors. This firm, Whirlpool, holds 26 percent of the refrigerator market and 30 percent of the freezer market. The initial charge for refrigerators with rotary compressors in 1980 was 1,082 million pounds; for freezers, it was 0.536 million pounds. Leak testing losses amount to about 1.5 percent of initial charge. The R-12 savings in 1980 at all three Whirlpool plants might total about 24,000 pounds through adoption of the helium system. At the current R-12 bulk price of 75¢ per pound, the savings in refrigerant purchases would therefore total $18,000. One of Whirlpool's plants is significantly larger than the other two, and so that our costs remain conservative, we will assume that the R-12 savings apply to only one plant.

All of the other manufacturers produce units with reciprocating compressors and the leak testing emissions are therefore less than Whirlpool's. This implies that, for the other manufacturers, potential savings in refrigerant purchases would be much less than $18,000 annually. The potential savings in refrigerant purchases, even for Whirlpool, are far less than the costs of the helium system supplied by industry. If we neglect the capital costs, the annual operating cost of the system is between $100,000 and $500,000.

Because one manufacturer who employs reciprocating compressors clearly does find helium leak detection cost effective presently, this simple analysis does not account for all relevant factors. The dominant cost of the helium system is the annual operating cost, estimated to be a minimum of $100,000. Adoption of the helium system would save the manufacturer the cost of operating the halide "sniffers," which are currently used by most manufacturers. The "sniffers" are comparatively simple, hardy pieces of equipment, and it is hard to imagine that their maintenance costs are significant. However, even if the costs of operating and maintaining the "sniffers" were half that of the helium system, conversion to helium would still not be economical.

One factor that may lower the costs of the helium system is the one manufacturer using it is greater use volume. At this firm's largest manufacturing facility, home air conditioners are produced as well as refrigerators. Helium leak detection is also used for testing air conditioners. Thus, if the same system were used for air conditioners as well as refrigerators, in addition to the foregone R-12 purchases, the manufacturer would receive the benefit of foregone R-22 purchases. The current bulk price of R-22 is in the range of $1.15 per pound, higher than the price of R-12, and the savings realized might be sufficient to make the helium system economically attractive.
Another factor, which may have the most important influence on leak detection system economics, is warranty repairs. Virtually all manufacturers sell units with a five-year warranty. There is an increasing trend, in the home appliance industry, to reduce problems with units in the field covered by warranty. The helium system, an extremely sensitive method, is much better able to detect minute leaks than the halide "sniffers." We do not know the costs to manufacturers for warranty repairs resulting from leakage and servicing, but industry sources report they might be as high as $2 million per day. Because one manufacturer uses the helium system, the savings from fewer warranty service calls at least for that manufacturer may be sufficient to justify the higher operating costs.

The manufacturer using the helium system probably finds it economical for a combination of reasons. First, the firm itself markets the system, which may reduce the capital cost. Second, the firm has one large plant where both refrigerators and air conditioners are manufactured. This implies that R-12 losses may be high and that the system could also be used for leak testing air conditioners. Third, the avoided warranty costs may be sufficiently high to justify use of the more sensitive helium system.

Another method of reducing R-12 leak testing emissions involves substituting R-22, or indeed any halogenated chemical thought to be less hazardous, for R-12. The halide "sniffers," already used widely by the industry, could still effectively detect leaks of the halogen. This substitution would be cost effective if the price of R-12 exceeded that of the alternative test gas. The current bulk price of R-12 is about 75¢ per pound; the R-22 bulk price is approximately $1.15 per pound. Substitution of R-22 as the test gas would therefore be economically justified at an R-12 price increase of about 40¢ per pound.

There is one problem regarding the use of an alternative to R-12 that should be mentioned, since it might cause a substitution to be much more costly. During our visits to refrigerator/freezer manufacturing plants, we toured the production operation. Units are moved through the plant on an automated assembly line. Each unit is charged and leaks are detected after charging with the halide "sniffers." Leaking units are removed from the line and examined for the source of the leak. Units passing the leak test are sent on to have the cabinet put on. Substitution of an alternative test gas would require modification of this automated procedure. Units would need to be charged with the substituted gas, tested for leaks, evacuated, and recharged with R-12, the working fluid, before being sealed. This change in procedure would increase the cost of substituting an alternative test gas.

End Use Substitution

Refrigerants used before the advent of R-12 included methyl chloride, ammonia, and sulfur dioxide. Methyl chloride is moderately flammable and explosive between certain concentration limits in air. It is also incompatible with aluminum. Ammonia rapidly corrodes copper or zinc alloys (brass, bronze) and is explosive in air. Sulfur dioxide is an irritating acid vapor, and it must be kept dry during use, since it forms acid in the presence of air that contains moisture. The use of any of these refrigerants in home appliances could be considered dangerous by EPA unless the hermetically sealed unit could be removed from the home to a remote location (perhaps the roof). This segregation would result in enormous cost to the consumer. For this reason and because of their hazardous nature, these refrigerants will not be considered further as viable substitutes for R-12.

On our visits to two CFC manufacturers, we learned of a promising substitute for R-12.
FC-134a contains no chlorine, and therefore does not pose a threat to the ozone layer. The chemical can be substituted for R-12 in existing refrigeration equipment with no redesign. However, it does require a different oil than that used with R-12, but one CFC manufacturer felt that an alternative oil could be readily found. A more serious problem with the substitution of FC-134a is that, to date, no manufacturing process for the FC exists. The most optimistic estimate for the FC's availability is six or seven years.

Another R-12 substitute suggested by one CFC manufacturer is R-500, an azeotrope containing 73.8 percent R-12 and 26.2 percent R-152a by weight. The latter refrigerant (R-152a) contains no chlorine and therefore would not contribute to ozone depletion. However, since R-500 contains such a large percentage of R-12, substitution of the azeotrope for R-12 could reduce R-12 emissions eventually by a maximum of about 26 percent. In addition, the azeotrope is a direct R-12 substitute only with changes in the expansion device that is used currently. One home appliance manufacturer also indicated that the use of R-500 in place of R-12 would raise energy requirements by one percent.

A CFC producer mentioned a mixture of about 40 percent R-22 and 60 percent R-142b as a potential R-12 substitute. The mixture has apparently been tested in a home refrigerator as well as a mobile air conditioner. In the mobile air conditioner, the R-22 portion of the mixture was found to permeate the hose material selectively. This was not a problem in the refrigerator where the unit is hermetic. However, in a leaking refrigerator or freezer, the R-22 could leak faster than the R-142b. The remaining mixture, containing primarily R-142b, would probably be vented before servicing. Since R-142b is flammable, there might be safety problems in its use.

Another mixture, about 40 percent R-22 and 60 percent R-114, was also mentioned as a potential R-12 alternative. Testing of this mixture is far from complete. Once again, there is not much to be gained with respect to ozone depletion potential by substitution of this mixture, since R-114 is fully halogenated.

R-22 has frequently been suggested as an alternative to R-12, particularly because of its much lower ozone depletion factor. The appliance industry is also very familiar with the characteristics of R-22, since it has been used for many years in air conditioning applications. One appliance manufacturer estimated the cost of converting to R-22 in new refrigerators and freezers at between $100 and $200 million dollars per plant, and suggested that the conversion would take five to ten years. Resized compressors would be necessary in all units, and modifications to capillaries and heat transfer components would also be required. There would be an additional unspecified warranty cost because of the risk of marketing a new system. Although manufacturers would avoid R-12 purchases, they would have to purchase R-22, which is currently more expensive than R-12. Costs to the industry of substituting R-22 for R-12 in new appliances are very high. Even though R-12 emissions from home appliances would ultimately be eliminated, manufacturers would not be likely to adopt the substitute unless the price of R-12 exceeded that of R-22 by several dollars a pound. Retrofit costs would be even more prohibitive, since compressors and perhaps other components as well, would require replacement in units in use.

The manufacturers we visited pointed out two other disadvantages of the substitution. They were concerned that the threat of future R-22 regulation would prevent the CFC manufacturers from augmenting current R-22 capacity, perhaps restricting its availability. The

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8It is therefore designated as a fluorocarbon (FC).
9An azeotrope is a constant boiling blend.
10The ozone depletion factor of R-12 is 0.79, whereas that assigned to R-22 is 0.05.
trend toward energy efficiency also militates against a conversion to R-22. One manufacturer pointed out that operating energy requirements would increase by about six percent. This is based on the results obtained in operating a few R-22 experimental models. A second manufacturer thought energy requirements would be increased by two to four percent.

R-502, an azeotrope\textsuperscript{11} used in the retail food refrigeration industry, is another potential alternative to R-12 in home appliances. One manufacturer claimed that R-502 substitution would pose problems and costs similar to R-22 substitution. There would also be an increase in energy requirements. Industry sources pointed out that home appliance manufacturers have no familiarity with R-502, which might act to increase the time for conversion and the warranty costs, once the conversion was begun.

\textsuperscript{11}R-502 is 51.2 percent R-115 (fully halogenated) and 48.8 percent R-22 by weight.
III. Retail Food Refrigeration

INTRODUCTION

Three refrigerants, R-12, R-22, and R-502, are used in retail food refrigeration systems today. R-12, R-502, and to a small extent R-22 are used in the medium temperature range, whereas R-502 is used almost exclusively in the low temperature range. Medium temperatures are maintained for dairy and meat cases as well as walk-in coolers; low temperatures are required for ice cream and frozen food.

In this study, we have gathered no new data on refrigerant use and emissions in retail food refrigeration applications, since industry statistics for total system shipments are unavailable. Indeed, the technique for estimating use and emissions in Rand’s earlier study (Palmer et al., 1980) seems to be an excellent approach. Four categories of retail food store were defined according to annual sales: Over $2 million; $1 million to $2 million; $500 thousand to $1 million; under $500 thousand. IR&T, Rand’s subcontractor in the previous study, estimated the number of each store type in 1976 and projected the number for 1990 using certain assumptions regarding new construction, remodels, and permanent closings. The number of stores in each category, together with an estimate of the amount of each refrigerant used and emitted per store, was the basis for determining refrigerant use and emissions. Since we have collected no new data on refrigerant use, we will use the earlier estimates of use, emissions, and stocks in our analysis.

There are five primary retail food refrigeration system manufacturers. They include: Hussman Refrigerator Co., Hill Refrigeration Co., Tyler Refrigeration Corp., Friedrich Air Conditioning and Refrigeration Co., and Warren-Sherer Co. The first three firms dominate the market. In addition to these large manufacturers, there are a number of smaller manufacturers who are members of the Commercial Refrigeration Manufacturers Association (CRMA). These manufacturers generally make walk-in coolers and display cases but purchase items like compressors, tanks, control components, and condenser surfaces. The firms offer a standard line, consisting of many variations, to satisfy demand for a wide range of size and type of unit. In certain cases, they will also assemble special systems with specific requirements. One industry source estimates that about 40 percent of the walk-in cooler and glass door refrigeration manufacturers are not members of CRMA and are considered small businesses.

Several techniques for reducing emissions from retail food applications were identified for our chemical control options analysis. Three control technologies include recovery and recycle of refrigerant at manufacture, at servicing, and at disposal. For the work practices assessment, we consider better equipment installation and preventive maintenance. In our assessment of chemical substitutes, we examine substitution at three different stages: at leak testing during manufacture, at system installation, and during the useful life of the system. In this product area, no product substitutes have been identified.
CONTROL TECHNOLOGY ASSESSMENT

Recovery and Reuse at Manufacture

We visited two of the three largest manufacturers to obtain information on recovery of refrigerant used for leak testing during manufacture of the retail food systems. Both manufacturers use a mixture of R-12 and air or nitrogen for leak testing units. The mixture usually contains about ten percent of refrigerant. R-22 and R-502 are not used for this purpose, apparently because of their higher cost.12

In Rand's earlier work, 1976 R-12 emissions during manufacture were estimated at about 400,000 pounds and R-22 emissions were estimated at about 100,000 pounds. These manufacturing emissions represent a very small fraction of total retail food refrigeration emissions. One system manufacturer indicated that emissions are even lower today, and that it is unlikely that R-22 is still used for testing. Apparently this refrigerant was used in the past at manufacture as a holding charge for shipment of small self-contained systems.

IR&T, Rand's subcontractor in the earlier work, predicted a large decline in manufacturing emissions by 1990 as a result of widespread adoption of reclamation systems. Indeed, one industry source has recently installed such a system. This manufacturer claimed that recovery was cost effective for his firm currently and he indicated that a second large manufacturer would also implement recovery in the near future. A third manufacturer stated that his firm had no plans for reclamation, since it is not yet justified economically. Thus, one manufacturer has adopted recovery, and another plans to do so, verifying IR&T's prediction that the movement toward reclamation would occur naturally.

Although we have collected no new data on manufacturing emissions, we suspect that they have not changed significantly. For purposes of analysis, we assume that the level of 1976 R-12 manufacturing emissions holds today. The firm that has implemented recovery is one of the three largest manufacturers; these three firms together hold 80 percent of the market. If we assume that manufacturing emissions are proportional to market share and that they can be apportioned equally among the three largest firms, each firm accounts for about 107,000 pounds of the R-12 lost during manufacture. At a recovery efficiency of 85 percent, a large manufacturer might recover approximately 91,000 pounds annually. At the current R-12 bulk price of about 75¢ per pound, the savings in refrigerant purchases could amount to $68,250 per year.

The manufacturer that has implemented recovery reports that the capital cost of the reclamation system is about $150,000. The operating costs are unknown as yet, since the process was adopted so recently. Even if we neglect operating costs, it is unlikely that the annual cost for recovery would exceed about $68,000, the savings in refrigerant purchases. For example, assuming a fixed charge rate of 30 percent, the annual cost to the manufacturer would amount to $45,000, well below the savings. Even if we assume that operating costs amount to half the yearly capital cost, the savings in virgin refrigerant purchases would still outweigh the costs of recovery. On the basis of our assumptions, recovery and reuse appear economically attractive for the three largest manufacturers.

Two other large manufacturers account for about 15 percent of the market. As before, we assume that manufacturing emissions can be apportioned according to market share. This

12Current bulk prices for R-12 and R-22 are about 75¢ and $1.15 per pound, respectively. The price of R-502, an azeotrope consisting of 48.8 percent R-22 and 51.2 percent R-11b (fully halogenated), is in the range of $2 per pound.
implies that each manufacturer might recover 30,000 pounds of R-12 and reuse 25,500 pounds if recovery efficiency is 85 percent. At the current R-12 bulk price, this amounts to a savings in refrigerant purchases of $19,125. If we make the same assumptions about capital and annual equipment costs as before, these costs outweigh the savings. We suspect, however, that equipment for recovery of a smaller amount of refrigerant (30,000 pounds, in this case) would be smaller and less costly. If this were true, recovery might be economical.

Smaller users, according to our assumptions, together account for about 20,000 pounds of the R-12 manufacturing emissions. It is unlikely that recovery would be cost effective for these firms if the cost of the capital equipment were $150,000. Again, we suspect that equipment for recovering the small amounts of R-12 used by all but the three largest manufacturers would be much less costly. Thus it is quite possible that a less costly unit might prove adequate to purify refrigerant used for leak testing in the smaller manufacturing plants.

Recovery and Reuse at Servicing

According to industry sources, virtually all retail food systems are sold with receiver tanks. Small units generally have receiver tanks capable of holding the entire system charge. Receiver tanks in larger systems cannot always hold the total charge. One manufacturer indicated that a 1,000 pound unit, for example, might have a receiver tank with a capacity of 200 to 300 pounds. A second manufacturer estimated that the average receiver tank capacity might be 80 percent of the system charge; representatives of a large retail food chain agreed with this estimate. One system installer claimed that even in large systems, receiver tanks can hold 80 to 90 percent of the charge. These comments are consistent with one another. Small units up to five horsepower can hold a full charge in the receiver tank. If the unit is between five and 30 horsepower, the receiver tank is capable of holding perhaps 80 percent of the charge. In very large systems (~1,000 pounds of refrigerant) where there are multiple compressors connected in parallel, receiver tanks might hold only 200 to 300 pounds.

Retail food stores usually arrange for servicing in one of three ways. The retailer may have an in-house maintenance staff, the food store may contract for continuing service, or it may have servicing performed on a one-time-only basis. One manufacturer indicated that a good installation contractor will attempt to sell a package including installation and periodic servicing to the retailer. Representatives of one large food chain indicated that the firm accepts bids from local contractors for system installation. The lowest bid is accepted, the system is installed, and the retailer purchases a one-year servicing warranty from the contractor. After the first year, the individual stores generally use local contractors to provide servicing when it is required.

Every store is apparently unique and the number of annual service calls can vary widely. Representatives of a large food chain estimated that a store requires 50 service calls each year on average. One system servicing contractor indicated that systems require little servicing until they are seven years old; when systems are 10 to 15 years old, the servicing requirement increases significantly.

Malfunctions of the hermetic system apparently occur only rarely. One contractor claimed that such malfunctions represent only about one percent of all service problems. Most service calls occur because of poor "housekeeping" (shorts in the wiring or clogged drains). According to retail food store representatives, complete systems are generally not vented during a service call. Rather, the section of the system where the malfunction has occurred is isolated using valves. Thus, even when the refrigerant in this section is vented, it
accounts for only a very small fraction of the total system charge. For example, if the compressor fails, the rest of the system is valved off, by closing the inlet and outlet valves, the compressor is replaced, and only the refrigerant in the compressor itself (perhaps only ounces) is emitted. According to one manufacturer, compressor burnouts are rare today because of better motor protection.

Frequently, when a malfunction occurs within the hermetic system, the refrigerant in the compressor and sometimes also the refrigerant circulating in the system may be contaminated with moisture and acids. In this case, the service person isolates the malfunction from the rest of the system, repairs the system, and circulates the total system refrigerant charge through a suction line filter-drier, which is made of activated charcoal. These filter-driers are changed periodically until no contaminants remain.

According to industry sources, the only time refrigerant is vented is during a sudden failure (pipe or line failure) or when the service person is careless. In these cases, recovery is not possible, since the refrigerant is immediately emitted.

Industry sources indicate that in systems of five horsepower and larger, it is cost effective to save the refrigerant; for smaller systems, it is not. According to one refrigerant distributor, current costs to the retailer for R-12, R-22, and R-502 are $2.25, $3.00, and $4.25 per pound, respectively. Given these prices, at an average hourly labor cost of $35, it is economical to save between eight and 16 pounds of refrigerant, even if the process for recovering the refrigerant requires a full hour. Only in very small systems might recovery not prove cost effective.

Our original perception of recovery at servicing has been altered significantly as we have obtained further information from industry. The total system charge is apparently vented only when catastrophic failure occurs, and it is not obvious how one might recover the refrigerant in this event. During more typical malfunctions, in most cases, the service people routinely isolate a failed part from the rest of the system and very little refrigerant is emitted. When the refrigerant is contaminated, a suction filter-drier is frequently used for purifying the refrigerant. This perception of servicing practices is reasonable given the high cost of refrigerant today. It therefore appears that recovery at servicing is currently practiced routinely in instances where it is appropriate.

Recovery at Disposal

When retail food refrigeration systems are replaced, it is frequently for cosmetic reasons such as appearance, convenience, or space, or for greater energy efficiency, rather than because of a malfunction. When a retailer remodels, he will most probably choose the same refrigerant, according to the system manufacturers. The refrigerant contained within the unit is sometimes vented during disposal. System manufacturers, however, indicate that if the unit is still operational, the refrigerant is generally saved. A unit that is still functioning can be sold on the second-hand market.10

In Rand’s earlier work, IR&T may have overestimated disposal emissions. The procedure was to sum the number of closings, shiftouts, and remodels in a particular year, and multiply this sum by the average amount of refrigerant within the store type. For the two largest store categories, IR&T estimated that 85 percent of the refrigerant was lost; for the two small store categories, IR&T assumed a 100 percent loss rate. Through our contacts with industry, we

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10According to one system manufacturer, there is a robust second-hand market. Smaller chains and Mom and Pop stores reduce costs by purchasing units second-hand.
have become aware that the practice of saving the refrigerant may be more prevalent than was apparent previously. One system installer was especially eager to save R-502. Indeed, it seems obvious, with increasing refrigerant prices in recent years, that the refrigerant would be saved if possible. In most cases where the unit is functional (and therefore a candidate for the second-hand market), it seems reasonable to assume the refrigerant will be saved. IR&T's estimate of 100 percent emission of the refrigerant in the two small store categories is probably not unreasonable. The 85 percent emissions in the two large store size categories may have been too high.

When the unit is being replaced, if the compressor is still functional, the refrigerant could be pumped directly into the receiver tank. As discussed in the last subsection, industry sources estimate that receiver tanks generally hold 80 to 90 percent of the system charge. The unit could be sold on the second-hand market and the refrigerant already in the receiver tank might be used to constitute a high fraction of the initial charge in the new system. Another method might be used when the compressor is still operating. The contractor could bring empty cylinders, pump the refrigerant from the old unit to the cylinders, and pump the refrigerant from the cylinders to the new unit when it is installed. If the system is a simple one with a close-coupled condenser, the contractor might salvage the whole condensing unit with the refrigerant in it. The refrigerant could then be sold second-hand either alone or in conjunction with the unit.

When a unit is being replaced because of a system failure, the refrigerant may be emitted immediately, and its capture is probably not feasible. When there is a system failure and the refrigerant is not emitted, recovery might be possible. If the failure is in the hermetic system, the refrigerant is likely to be contaminated and it would be necessary to purify it before it could be reused. Repair is urgent to prevent food spoilage. For recovery and purification, additional equipment, and perhaps long delays, would be required.

We discuss the costs of recovery at disposal for two cases. The first case is when the unit is still functional and can be sold on the second-hand market. In this event, the refrigerant might be pumped into the receiver tank and sold with the unit or it might be pumped into cylinders for separate sale. One manufacturer estimated that it would take a few hours to pump 98 percent of the refrigerant from a system holding 1,500 pounds. A second manufacturer estimated that system pumpdown would require ten minutes to an hour, depending on system size. According to these two manufacturers, service costs range from $10 to $35 per hour. A system contractor estimated that one or two hours might be required for pumpdown. He indicated that this estimate would hold even when an entire system is involved, since pumpdown of several modular units could be accomplished simultaneously. The connections for pumpdown can be made in less than ten minutes and the service person is free to perform other tasks until pumpdown is complete. A contractor's estimate of labor costs was $25 per hour. A foodstore representative placed the cost for installation or servicing labor at between $42.50 and $49.50 per hour.

One contractor noted that system replacement must be completed in three to five hours, before the food can spoil. In a large grocery store, the potential loss in meat sales might total $7,000, whereas that for other refrigerated foods could amount to $5,000. Most contracts absolve contractors from responsibility for food spoilage; they frequently do pay the spoilage cost, however, to maintain an ongoing relationship with the store.

For our analysis of the cost effectiveness of recovery at disposal, we will choose high costs of recovery and low refrigerant savings. This will result in an upper bound to recovery costs. It might require two hours for pumpdown (the highest estimate we received), at a labor cost of $49.50 per hour (also the highest estimate). The total cost of the process would therefore be
$99. We will assume that 200 to 300 pounds of refrigerant can be recovered (the lowest percent of the system charge that is held by a receiver tank). The refrigerant prices paid by retailers range between $2.25 per pound (for R-12) and $4.25 per pound (for R-502). The savings in refrigerant purchases through recovery would amount to between $450 and $1,275, depending on the refrigerant in the system. The savings, under our assumptions, clearly outweigh the recovery costs. It should be noted that if the pumpdown process actually requires two hours and if the new system cannot be installed and running within one hour, food spoilage could occur. In this case, spoilage costs might amount to $12,000 and the savings in recovered refrigerant would not be high enough to make the procedure worthwhile.

The second case of recovery we examine occurs when the system malfunctions. When the unit is being replaced because there has been a motor burnout, recovery is not straightforward because the refrigerant may be contaminated. If the compressor is not operating, refrigerant cannot be pumped either into the receiver tank or into cylinders, and a suction filter-drier cannot be used for purification.

Omega Chemical of Whittier, California, has successfully reclaimed R-12, R-22, and R-502 to virgin purity with distillation techniques. In a case where the compressor has malfunctioned, the servicing people might use a substitute compressor to accomplish the pumpdown. The refrigerant could be sent to the reclaimer for purification and reuse. Industry sources indicate, however, that it is not likely that service people would be willing to take the time required for pumpdown. In another scheme, the reclaimer could go to the store with a working compressor, pump the refrigerant into cylinders, and take it back to the reclamation firm for purification. The reclaimer's participation in any recovery process would be highly dependent on the support of the system contractors. The pumpdown would have to be accomplished while the system was still connected, and the new system could not be installed until it was complete. In addition, the reclaimer would have to be notified, and unless the food store were in the immediate vicinity of the reclamation firm, even more time would pass before installation could be performed. This increases the possibility of food spoilage. Given that Omega Chemical is the only firm in the country that reclaims refrigerant, large-scale recovery during service of a failed unit does not appear promising for the near future.

During disposal, if the system is still operational, recovery appears attractive. This conclusion agrees with comments from industry sources that recovery is practiced whenever possible because of the high price of refrigerant. When the unit is not functional, recovery of the refrigerant does not presently seem feasible because of the possibility of contamination.

ASSESSMENT OF WORK PRACTICES

Better Equipment Installation

Installation of retail refrigeration systems is performed either by a branch of the system manufacturers or by an independent contractor. As described by one contractor, the installation procedure begins with the underground system testing. A nitrogen charge is put into the system and the pressure is monitored for two or three days to test for leaks. Then components above ground—the display cases and compressor—are connected.

One manufacturer suggests that there be a triple evacuation to eliminate moisture and noncondensibles from the system. Then the vacuum should be broken, preferably using nitrogen with a small refrigerant tracer. The system should then be evacuated and charged. Rep-
representatives of a food chain indicated that the underground piping is laid and pressurized during construction of the building. The fixtures and piping are installed and the system is evacuated three times; this evacuation process requires about two weeks.

The system is partially charged with refrigerant or a refrigerant/nitrogen mixture (perhaps 50 pounds) and the pressure is monitored overnight. Halide leak detectors can be used to isolate leaks. If there is a leak, some refrigerant will be lost; if there is no leak and pure refrigerant was used for testing, the balance of the charge is simply added. If the refrigerant/nitrogen mixture was used, it is vented and the system is charged with pure refrigerant.

Installing all the refrigeration units in a large grocery store might take several weeks. Representatives of a food chain claim that installation of the refrigeration equipment (above ground) takes at least 30 days. Two system manufacturers estimated that installation of one unit might take one to two days, if the installation were performed properly.

Proper installation generally involves careful fitting of connections and making sure there is provision for system access. Generally the system bugs are worked out of the system in 30 days and fine tuning is done within the first 60 days. This contractor felt that if the installation were performed improperly, the additional service calls that would be required would occur in the 90 day warranty period given by essentially all contractors. Because those service calls are the responsibility of the contractor, there is an incentive to install systems properly.

Representatives of a large food chain indicated that store managers frequently pressure contractors to install systems quickly. A delayed store opening can be extremely expensive. Food sales losses in an average large food store might amount to $100,000 per week, according to retailers. Other factors include the cost of warehousing the food, salaries for hired personnel, and losses of customer loyalty. One industry source claims that the contractor must be supervised by the store to ensure that the installation is performed properly. Thus, the store itself may have to pay the salary of a qualified person who would oversee the contractor. A representative of one food chain estimates that all costs associated with a delayed opening might range from $2,000 to $3,000 per day.

System manufacturers indicate that labor costs for installation range from $10 to $35 per hour; a contractor placed labor costs at $23 per hour. A retailer claims that the cost ranges between $42.50 and $49.50 per hour.

For purposes of analysis, we will make several assumptions. First, we assume that a better installation requires one additional day of a contractors time at a labor cost of $35 per hour, for a total cost of $280. Second, we will assume that the costs of the delayed store opening could amount to $2,500 per day. Total costs for a better installation would be $2,780. At a fixed charge rate of 30 percent, this amounts to an annual cost of $834. Our third assumption is that the system has a ten-year lifetime and that better installation will reduce service calls and therefore prevent leakage over the system life.

This option is cost effective when the annual savings from service calls and refrigerant purchases total $834. Neglecting refrigerant purchases, this would occur if about three service calls per year could be prevented within the ten-year lifetime, assuming the cost of each service call is $280. The cost of service calls will increase over time; indeed, one source

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14 Representatives of a large food chain indicate that units last about ten years on the average.

15 In 1976, annual leakage and servicing emissions of R-12, R-502, and R-22 for a large supermarket amounted to 75, 80, and 15 pounds, respectively. At prices paid by retailers—$2.25 per pound for R-12, $4.25 per pound for R-502, and $3.00 per pound for R-22—the cost of replacing the lost refrigerant is about $470 per year. Even if better installation could completely eliminate leakage and servicing emissions, the total annual savings in refrigerant purchases would be only $470. The actual savings would probably be much less.
indicated that labor costs would double by 1990. In later years, fewer than three service calls prevented annually might make the option economical.

One retailer claims that an average chain food store requires approximately 50 service calls each year. According to our analysis, better installation is justified if service calls are reduced by six percent in this average store. For stores with significantly fewer total annual service calls, a larger percentage of the service calls must be prevented; for stores with many more annual service calls, the percentage would be much smaller.

Most retailers would probably find better installation economical. The assumptions in our analysis lead to a conservative estimate of the potential savings. For example, we did not evaluate the savings in refrigerant purchases from reduced leakage and servicing losses. Our estimates of the costs of the option were also conservative. For example, it may actually require two additional days to ensure a better installation. In this case, prevention of six annual service calls would be required to make the option economical. This still represents a rather small fraction of total annual service calls for the average store.

Preventive Maintenance Programs

According to two system manufacturers and one contractor, a few retail food stores have preventive maintenance programs, but most do not. Representatives of a large food chain indicated that, although they have a policy to encourage preventive maintenance, they are wary of its implications. Some of the stores in this chain apparently have a biannual preventive maintenance program. After the first year, each store in this food chain arranges for system servicing with local contractors. If the local contractor is not qualified, a preventive maintenance program could be extremely expensive.

Preventive maintenance might be performed quarterly or biannually, with each system check requiring about one day of a contractor's time. The costs of such a program were estimated by one contractor at $50 per month for a small store, and in the range of $600 to $1,500 per month for a large supermarket. If we assume a cost of $1,000 per month for a supermarket, the annual cost of the program would be $12,000.

The benefits of such a program are a reduction in annual service calls and lower leakage and servicing losses. Annual leakage and servicing losses for a 1,500 pound system might amount to 150 pounds. We have no estimates on the amount of refrigerant that might be saved through a preventive maintenance program, but it probably would not exceed 25 percent of leakage and servicing emissions, or about 37.5 pounds annually. The cost of the saved refrigerant would amount to no more than a few hundred dollars per year even if it were R-502, the most expensive of the refrigerants. A larger savings could be achieved through reducing the required service calls. As mentioned above, one retailer estimated that an average chain store requires 50 service calls each year. Neglecting the cost of refrigerant that could be saved, a reduction in annual service calls, totaling $12,000, is necessary to economically justify the program. Assuming a labor cost of $35 per hour and one day per service call, about 40 service calls each year would have to be prevented to make preventive maintenance attractive. This represents more than 80 percent of the total annual service calls in an average store; it seems extremely unlikely that preventive maintenance could reduce service calls to this extent.

\(^{16}\)R&T estimated that in large grocery stores, leakage and servicing losses represent approximately ten percent of stocks each year.
For an average chain store, preventive maintenance may not be cost effective currently. For stores that require a significantly higher number of service calls than the average, a program of this type might be economical at present. Food chain representatives stated that they encourage preventive maintenance, but only if the contractor is qualified; this seems a very sensible approach. If a preventive maintenance program is offered by a qualified contractor, it could perhaps eliminate a very high fraction of the annual service calls. However, if the contractor were not qualified, a program of this type might even increase annual service calls and perhaps refrigerant emissions as well.

ASSESSMENT OF CHEMICAL SUBSTITUTES

Manufacturing Substitution

System manufacturers indicate that they use mixtures of R-12 and air or nitrogen for leak testing at manufacture. As mentioned earlier, IR&T's estimates of manufacturing emissions for 1976 were 400,000 pounds of R-12 and 100,000 pounds of R-22.

It is not clear why R-22 was ever used for testing at manufacture. The price differential of R-12 and R-22 of about 40c per pound is significant. The 1976 prices of R-12 and R-22 were 41c and 70c, respectively. Since then, the price of R-12 has increased more rapidly than the price of R-22. Nevertheless, it is not clear why a manufacturer would ever have chosen R-22 over R-12. One industry source reports that R-22 was once used as a holding charge in small self-contained units; the IR&T data on manufacturing losses may have included the R-22 used for this purpose.

The ozone depletion factors of R-12 and R-22 are 0.79 and 0.05, respectively; in terms of potential ozone depletions, there would be a distinct advantage in using R-22 for leak testing in place of R-12. Assuming IR&T's 1976 R-12 emissions estimates to be accurate for 1980, R-12 emissions during leak testing totaled about 400,000 pounds. Substitution of R-22 for R-12 would reduce R-12 emissions by this amount and increase R-22 emissions correspondingly. Substitution of R-22 for leak testing is not cost effective at current refrigerant prices. Present bulk prices of R-12 and R-22 are about 75c and $1.15 per pound, respectively. This substitution possibility would become attractive to the manufacturers only if the price of R-12 exceeded that of R-22.

It should be noted that we are examining two methods for reducing emissions during testing at manufacture, substitution for R-12 as the test gas, and recovery and reuse of R-12. Substitution of R-22 for testing is not cost effective at current refrigerant prices. At least one large manufacturer has recently implemented recovery. Substitution of R-22 for R-12 would reduce the effective ozone depletion factor of the test gas to 0.05. Recovery of R-12 at an efficiency of 93 or 94 percent would achieve the same effective ozone depletion factor.\(^{17}\) Recovery combined with R-22 substitution would reduce the effective ozone depletion factor even further.

The helium leak detection system used by one of the home appliance manufacturers is also a potential substitute for R-12 use with "sniffers." We will assume, as we did in the

\(^{17}\)Effective ozone depletion factor = R-12 ozone depletion factor \times (1 - efficiency) = 0.79 (1 - 0.37) = 0.05.
discussion on “recovery at manufacture,” that manufacturing emissions can be apportioned to each firm on the basis of market share. This implies that each of the three largest manufacturers uses about 107,000 pounds of R-12 for testing annually. The system manufacturers purchase R-12 in bulk at a current cost of about 75c per pound. Savings in R-12 purchases to a large manufacturer by helium substitution would amount to about $80,000 annually. This savings is well below the helium system operating costs, which have been estimated in the range of $100,000 to $500,000 per year. When the capital cost of the system and the opportunity cost of the capital are considered, the helium detection system is even less economically attractive. Indeed, manufacturers would probably substitute R-22 rather than helium simply on the basis of cost.

Substitution During Installation Testing

Retail food refrigeration systems are commonly transported to the store without a refrigerant charge. One of the system manufacturers and a representative of a large food chain indicated that installers should use nitrogen with a refrigerant tracer for leak testing. The higher pressures attainable with nitrogen are necessary to detect some leaks. The contractor we visited, however, claimed that the firm’s installers commonly use pure refrigerant for leak testing.

The gas used for installation testing, whether it is pure or mixed with nitrogen, is frequently the same refrigerant with which the system is ultimately charged. The system manufacturers we talked with agreed that the convenience to the service person of carrying only one refrigerant cylinder and avoiding one additional evacuation was influential in the choice of test gas. This is borne out by the fact that R-502, which is more costly than R-12 or R-22, is apparently used for testing routinely. If, for example, a contractor is installing a system in a store where R-502 is to be used for both low and medium temperature, the contractor would probably not bring an additional R-12 or R-22 cylinder and would use R-502 for testing. Because the choice of test gas is intimately related to the system charge use patterns, it is important to gain an understanding of current trends in refrigerant use in food stores.

The estimated emissions from installation leak testing are a very small portion of total emissions from retail food refrigeration systems (approximately three percent in 1976). Our earlier study estimated that the R-12, R-502, and R-22 emitted in 1976 during installation amounted to only about 390,000, 150,000, and 60,000 pounds, respectively. R-12 use represents 55 percent of total testing emissions; R-502 represents 25 percent; R-22 represents only ten percent. It is of interest to note that the use of R-12, R-502, and R-22 for initial charge in the same year was estimated at 3.90, 7.07, and 0.60 million pounds, respectively. R-502 accounted for 61 percent of total initial charge, whereas R-12 and R-22 represented 34 and five percent, respectively. R-12, the least expensive of the three refrigerants, was used for testing 65 percent of the time, and for charging only 34 percent of the time. R-502, the most expensive of the three refrigerants, was used in testing only 25 percent of the time, and for charging 61 percent of the time. This implies that the lower price of R-12 makes it attractive for testing units that will not contain R-12 as the working fluid. The higher price of R-502, in contrast, discourages its use in testing units in which it will be employed as the working fluid. A similar effect is observed for R-22, which is more costly than R-12, but less costly than R-502. It therefore appears that refrigerant price does play some role in the choice of refrigerant for installation testing, but convenience apparently also plays a role. If price were the only consideration, R-502 and R-22, with their higher prices, would not be used for testing at all.
In our earlier work, installation emissions were estimated at five percent of the initial charge. For a 1,500 pound system, this implies a loss of 75 pounds of refrigerant. Let us assume that the system requires R-12 as the working fluid and consider the substitution of R-22 or R-502 for testing during the installation. The 1,500 pound R-12 charge would be transported to the food store in several lower weight cylinders. If R-22 or R-502 were to be used for leak testing, one additional cylinder containing the appropriate refrigerant would be required. The labor cost for the installer to carry in one extra cylinder should be small. The presence of the second refrigerant, however, presents the possibility of an error occurring when the system is being charged. Contamination of the R-12 with R-22 or R-502 would render the entire system charge of 1,500 pounds useless.\textsuperscript{19} The potential cost to an installer for a mistake of this type is prohibitive. The implied cost of the potential contamination of 1,500 pounds of R-12 could be sufficient to discourage the use of an alternative refrigerant in testing.

One system manufacturer reports that in a display case requiring ten pounds of R-12, only nine pounds of R-22 or R-502 are necessary. In a given system, the R-22 and R-502 requirements amount to somewhat more than 90 percent of the R-12 requirement. In the case discussed above, perhaps only about 67.5 pounds of R-22 or R-502 would be needed for testing to substitute for 75 pounds of R-12. This difference, however, is not enough to make substitution cost effective at current refrigerant prices.

Any gas with the appropriate pressure characteristics can be used for leak testing at installation, because it is vented before charging. Electronic halide detectors are routinely used to isolate leaks. If leak testing is to be performed with the same equipment, at least a part of the test gas must be a halogenated chemical. One system manufacturer and a representative of a large food chain agree that installers should always use nitrogen with a refrigerant tracer. Indeed, it is obvious that this gas combination can be used at installation testing, since the manufacturers routinely employ it for factory testing.

One retailer reports that the refrigerant in the test mixture amounts to about two or three pounds. When the pure refrigerant is used at installation, if the system does not leak, the balance of the charge is simply added and no refrigerant is emitted. If the system does leak, perhaps 75 pounds of refrigerant are emitted. If the nitrogen/refrigerant mixture is used, the system must be vented before charging, and about three pounds of refrigerant are emitted. We do not know if emissions are higher when pure refrigerant rather than the mixture is used, since we do not have data on leak test failures. If failures occur in more than four percent of the systems tested, it is economical to use the mixture.\textsuperscript{19} If failures occur less frequently, then the pure refrigerant would be preferred as the test gas.

**End Use Substitution**

R-502 is used almost exclusively in low temperature systems today. R-12, R-22, and R-502 are all used, to varying degrees, in medium temperature systems. The ozone depletion factors of R-12, R-502, and R-22 are 0.79, 0.13, and 0.05, respectively. Because the ozone

\textsuperscript{19} R-12 and R-22 form an azeotrope, and separation of the two refrigerants cannot be accomplished easily, if at all.

\textsuperscript{19} We assume that out of 100 systems tested, four will fail. Using pure refrigerant, which is emitted only during a failure, 300 pounds will be lost. Using the mixture, which is vented before charging, in all tests, 300 pounds will also be emitted. If the failure rate is higher than four percent, emissions using pure refrigerant will be significantly higher.
depletion factors of R-502 and R-22 are significantly lower than that of R-12, the substitution of either refrigerant for R-12 in medium temperature systems would lessen potential damage to the ozone layer. A reduction in the possible threat could also be obtained by substituting R-22 for R-502 in low temperature systems.

One manufacturer reports a trend toward R-502 use in new medium temperature systems. Another manufacturer reports a resurgence in the use of R-22 at medium temperature. One motivation for the trend toward increased R-502 use in medium temperature systems is the convenience of using the same refrigerant at both temperature ranges. Another more important motivation, according to one manufacturer, is that the R-502 compressor at medium temperature in a system of a given size is smaller and less costly than the R-12 compressor. A compressor manufacturer reports that the largest difference in cost between a compressor for R-502 and a compressor for R-12 is about $150. Since, in the medium temperature range the same compressor can be used for R-22 and R-502, compressor cost may also be the factor influencing the resurgence of R-22 use. Because energy use among the three refrigerants is approximately the same, conservation apparently does not play a part in substitution. Pound-for-pound substitutability may also have an influence on the choice of refrigerant. As mentioned earlier, one manufacturer claims that only about 90 percent of the weight of refrigerant used in an R-12 system is required in a system using R-502 or R-22. This acts to decrease the current price differential between R-12 on the one hand, and R-502 or R-22 on the other hand. On the basis of refrigerant cost alone, R-22 would be preferred over R-502 as a substitute for R-12 in new medium temperature units.

One technical factor, emphasized by the manufacturers we contacted strongly discourages the use of R-22 at medium temperature. In general, the problem with R-22 use can be summed up by the statement "R-22 is a less forgiving refrigerant than R-12 or R-502." Systems using R-22 operate at higher discharge temperatures; this makes R-22 more susceptible to chemical breakdown than other refrigerants. In addition, R-22 does not carry oil well. When these problems compound one another, the R-22 systems tend to run at a higher temperature, and the life of the compressor can be shortened as a result. One major component supplier is opposed to R-22 use at medium temperature. In fact, when this firm sells an R-22 system, the guarantee specifically states that the purchaser should be aware of the problems of R-22. One system manufacturer claimed that if substitution for R-12 at medium temperature were required, he would prefer to see users adopt R-502 rather than R-22 as the alternative. A retailer predicted that the industry would never adopt R-22 widely because of its negative characteristics.

According to representatives of a large food chain, the average store today contains ten to 12 compressors and one or two of these are replaced each year. Systems for an entire store might hold 2,000 to 3,000 pounds of refrigerant. In 1976, leakage and servicing emissions were estimated at ten percent of stocks annually for large chain stores. For purposes of analysis, we will assume an average store has 11 compressors, replaces two each year and has a refrigerant requirement of 2,500 pounds. Over ten years (the system lifetime estimated by retailers), refrigerant use in a 2,500 pound system would total 50,000 pounds including the initial charge.

As mentioned earlier, the cost of a compressor for an R-12 system might be as much as $150 greater than for an R-22 or R-502 system. The difference in initial investment for 11 R-12 compressors would amount to $1,650; replacement of 20 of these compressors over the unit life would total $3,000. Thus, in the ten-year lifetime, R-12 compressor costs are higher than those for R-22 or R-502 by $4,650. Refrigerant prices are about $2.25 per pound for R-12, $3 per pound for R-22, and $4.25 per pound for R-502. The cost to the retailer of using 5,000
pounds of R-12 over the system life is $11,250. The total cost of using R-12 is therefore $15,900. If the refrigerant were R-22 or R-502 instead, only 90 percent, or 4,500 pounds of refrigerant, would be required. The total cost of using R-22 would amount to $13,500, whereas that of R-502 would total $19,125.

According to our assumptions, it may be economical to use R-22 in new medium temperature systems rather than R-12; it does not appear attractive to use R-502. Since some retailers are converting to R-502, our estimates of the number of required compressor replacements and the system lifetime may have been conservative. For example, if four compressor replacements were required annually, and the system lifetime were 15 years, both R-502 and R-22 would be preferred over R-12. Thus, retailers who frequently replace compressors or have systems with longer than average lifetimes may find it cost effective to convert to R-502 when replacing a system.

It should be noted that in this simple analysis, R-22 appears to be a more attractive refrigerant than either R-12 and R-502. We have not included the costs that result from the technical problems of systems using R-22. Since these systems run at higher temperatures, more frequent compressor replacement would be necessary; perhaps other components would fail earlier as well. More frequent component replacement could lead to longer downtimes increasing the possibility of food spoilage. When these additional costs are considered, the total costs of an R-22 system would be much higher and may even exceed those of R-502 systems.

An analysis of this type is certainly not complete, but it is useful in clarifying why R-502, in spite of its high cost, is used at all in medium temperature applications. It illustrates that R-502 is an attractive refrigerant to some retailers because compressor costs for this refrigerant are lower than those for R-12. Moreover, less R-502 is necessary to charge a retail food unit than R-12. Since conversion is occurring, the costs of R-502 systems must be close to the costs of R-12 systems, and the retailer has the advantage of using a single refrigerant for both low and medium temperature applications.

Retrofit of existing R-12 medium temperature systems for use with R-22 or R-502 would be extremely expensive. Systems are assembled for use with a particular refrigerant. We know that retrofit would require a change in compressor. One manufacturer has indicated that other components, including expansion valves, pipes, and controls would require changes for retrofit as well.

In low temperature systems where R-502 is used almost exclusively, a substitution candidate for all new systems is R-22. One factor that discourages the use of R-22 is its "unforgiving" nature. This is much more serious at low temperature than at medium temperature because of the high compression ratio. Indeed for R-22 use at low temperature, the system must contain a two stage compressor with intercooling. This complexity of equipment, according to one system assembler, is an acute disadvantage. Compressor costs would be at least double those of a single stage system and servicing costs would probably be much higher. In addition, the R-22 two stage compressor requires more energy than the R-502 single stage compressor. Moreover, not much potential benefit to the ozone layer could be attained by this substitution, since the ozone depletion factor of R-22 (0.05) is not significantly lower than that of R-502 (0.13). On balance, substitution of R-22 for R-502 in all new low temperature systems appears especially unattractive. Retrofit of existing low temperature R-502 systems for use with R-22 would be prohibitively expensive at best, and technically impossible at worst.

Use of alternatives other than those refrigerants that are currently used by retailers is not particularly promising. The retail food industry has at least established a working
familiarity with R-22 at medium temperature and R-502 at both low and medium temperatures. Other CFC substitutes could be used, but at much higher costs or significant delays. Alternatives to R-12 are being examined by the CFC producers, but none appears to offer a distinct advantage. One of these is FC-134a for which there is no manufacturing process. Another possibility is R-500, an azetropes composed of 73.8 percent R-12 and 26.2 percent R-152a by weight. R-152a contains no chlorine, so the effective ozone depletion factor of the azetropes would be 0.58, well above that of either R-502 (0.13) or R-22 (0.05). A mixture of 40 percent R-22 and 60 percent R-142b is another candidate, limited by the fact that R-142b is flammable. Testing of another mixture, 40 percent R-22 and 60 percent R-114, is not yet complete; in any case, the effective ozone depletion factor of this mixture, 0.31, is higher than that of either R-502 or R-22.
Chapter 7

AIR CONDITIONING USES OF CHLOROFLUOROCARBONS

I. Introduction and Summary

Air conditioning systems using chlorofluorocarbons as refrigerants constitute one of the major categories of CFC use and emissions. These systems range from small mobile units to the large chillers used to cool commercial and industrial buildings. Such units can be classified into three categories: mobile air conditioners, chillers, and room and unitary air conditioners. Because of their unique characteristics, we will discuss each of these categories in separate sections.

The importance of these categories, as a whole, can be seen from the previous Rand study (Palmer et al., 1980). In that study, 1976 data showed that these categories accounted for the use and emission of about one-third of all chlorofluorocarbons (CFCs). It is important to note, however, that the contribution from each of these three groups differs widely, because of their characteristics, the numbers of units in each group built and sold each year, and the specific refrigerants used for these systems. For example, although mobile air conditioners use R-12, and room and unitary air conditioners generally use R-22, chillers may use R-11, R-12, R-22, R-113, R-114, and R-500.¹ Therefore, individual problems and recommendations will be discussed for each.

We summarize these differences below:

- Mobile air conditioners are representative of small, lightweight systems, mass produced in great quantities, with generally short lifetimes due to disposal of the vehicle rather than to replacement of the air conditioning unit. These systems use R-12 as their working fluid and are usually optimized to produce the maximum cooling with low weight and energy consumption.

- Chillers represent the opposite extreme in size, being confined to fixed installations in moderate to large buildings. They are often produced individually by combining separate components into a single final configuration for installation in a specific building. Though produced in much smaller quantities than mobile air conditioners (less than one percent as many), each contains many times the amount of refrigerant of a mobile unit. These units have generally long lifetimes in service, and individual designs are often produced for twenty or more years with little change. Because of the wide capacity range of such systems (almost 10,000 to 1), a number of different refrigerants and configurations are used, each posing its own problems in emissions control and reduction.

- The category of unitary and room air conditioners contains almost all the remaining types of air conditioning units. These range from small room air conditioners for home use to larger central air systems for use in homes and small businesses. Al-

¹As noted in Chapter 1, the designation "R" used for a refrigerant is equivalent to the designation "CFC," which is used for the identical chemical in non-refrigeration applications.
though there are vast numbers of units in this category, compared to units in other categories, the relative effects of their CFC emissions are small, because of their use of R-22 with its low (0.05) ozone depletion factor.

In general, this chapter differs in three ways from the work done in the previous Rand study. First, room and unitary air conditioners have now been included. It was previously felt that, because R-22 is used almost exclusively in this category, emissions would have negligible impact. However, for the present study, it seemed desirable to estimate the actual emissions potential from this category, and to assess whether any control options would have noticeable effect.

Second, although similar emissions reduction options were considered in the present study, new information and more recent data are available that affect some of the emissions estimates and reduction potentials.

Finally, we have attempted to qualitatively order some of the emissions reduction options, both in terms of ultimate reduction potential, and technical and economic feasibility. Table 7.1 summarizes the results for each of the three categories.

Based on ultimate emissions reduction potential only, this table presents rankings, from highest to lowest, of the reduction in emissions possible by utilizing each of these options by itself. (Note, however, that the impact of some options would be reduced or eliminated if other options were implemented as well.) The right-hand column gives a rough estimate of the actual emissions reduction effect. Since each refrigerant used has a different ozone depletion factor (and thus may have a greater or lesser impact on a per pound basis), we have related all refrigerants used to an amount of R-11 with an equivalent ozone depletion effect, using EPA estimates of ozone depletion factors. The R-11 equivalent emissions reduction potential, in millions of pounds per year, for each category used in the right column, is as follows:

<table>
<thead>
<tr>
<th>Category</th>
<th>Emissions Reduction Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very small</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Small</td>
<td>1-5</td>
</tr>
<tr>
<td>Medium</td>
<td>6-10</td>
</tr>
<tr>
<td>Large</td>
<td>11-20</td>
</tr>
<tr>
<td>Very large</td>
<td>&gt;20</td>
</tr>
</tbody>
</table>

In addition, the center column indicates our estimate of the cost and technical difficulties (called dislocations) that implementing each specific option would entail. It is likely that any option with more than a moderate dislocation would not be feasible in the near future.

We point out several items of importance with regard to this table. First, for mobile air conditioners, conversion to R-134a is not possible at this time, because of the lack of a process for producing commercial quantities. However, if and when R-134a becomes available in sufficient quantity, this refrigerant is preferred over R-22 by much of industry. Second, the effect of using a mobile air conditioning system such as the ROVAC Corporation’s system has not been factored in, pending independent testing of this system. Third, there is a wide variance in dislocation among these categories. For example, the wide range in sizes of servicing organizations would place a larger burden on many smaller companies (and individuals), especially for options requiring installation of new equipment. This is also true for manufacturers of room and unitary air conditioners. Thus, installation of helium leak detection systems, used by at least one very large manufacturer, would be prohibitively expensive for

\*These factors are 1.0 for R-11, 0.79 for R-12, 0.05 for R-22, 0.49 for R-113, and 0.58 for R-500.
### Table 7.1

**RANKING OF ULTIMATE EMISSIONS REDUCTION POTENTIAL**

<table>
<thead>
<tr>
<th>Option</th>
<th>Mobile Air Conditioning</th>
<th>Centrifugal and Reciprocating Chillers</th>
<th>Room and Unitary Air Conditioners</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Size of Dislocation</td>
<td>Emissions Reduction Effect</td>
<td></td>
</tr>
<tr>
<td>Conversion</td>
<td></td>
<td></td>
<td>Conversion to R-22</td>
</tr>
<tr>
<td>To R-134a (not yet possible)</td>
<td>Moderate-Large</td>
<td>Very Large</td>
<td>Recovery at servicing</td>
</tr>
<tr>
<td>To R-22</td>
<td>Large</td>
<td>Very Large</td>
<td>Design changes to reduce leakage</td>
</tr>
<tr>
<td>Reduction in initial charge:</td>
<td></td>
<td></td>
<td>Initial charge reduction</td>
</tr>
<tr>
<td>Reduction above current trends</td>
<td></td>
<td></td>
<td>Recovery at disposal</td>
</tr>
<tr>
<td>Current trends</td>
<td></td>
<td></td>
<td>Substitution in test and rework</td>
</tr>
<tr>
<td>Recovery at servicing</td>
<td></td>
<td></td>
<td>Improved recovery at manufacturing</td>
</tr>
<tr>
<td>Improved servicing techniques</td>
<td></td>
<td></td>
<td>Recovery at servicing</td>
</tr>
<tr>
<td>Reduction in leakage&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
<td></td>
<td>Design changes to reduce leakage</td>
</tr>
<tr>
<td>Recovery at disposal</td>
<td></td>
<td></td>
<td>Conversion to He for leak testing</td>
</tr>
<tr>
<td>Improvements in mfg and testing</td>
<td></td>
<td></td>
<td>Recovery at rework</td>
</tr>
<tr>
<td>Current trends</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Reduction above current trends</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Because of rapidly increasing stocks of mobile air conditioners over time, this option could ultimately rank above recovery at servicing.

<sup>b</sup>Mainly improvements in purge systems.

<sup>c</sup>Substitution of nonhalogenated refrigerant would rank first. However, no real effort has been made in the past to identify a suitable replacement, and this option is not deemed feasible.
some smaller manufacturers. Finally, the room and unitary air conditioning category as a whole makes an essentially negligible contribution to total emissions, because of the 0.05 ozone depletion equivalence factor of R-22. Thus, even the highest rated option for this category would rank at or below the bottom of the rankings in the other two categories.
II. Mobile Air Conditioners

INTRODUCTION

Mobile air conditioners (MACs), including units for domestic and foreign automobiles, vans, and light trucks, are expected to produce approximately one-fourth of all CFC emissions from nonaerosol uses over the next decade. Even though economic pressures in the past year have lowered auto sales and have reduced even further the installation of MAC units, and manufacturers have typically reduced refrigerant charges in recent years, it is still expected that mobile air conditioners will play a major part in CFC emissions during the next decade.

To obtain a rough idea of the potential size of emissions from this category, even in light of current trends, we refer back to the 1976 data used in the previous Rand study (Palmer et al., 1980), plus more recent figures for 1980 (Automotive News, 1981). Given manufacturers' installations of about 5.2 million units in all domestically produced autos in 1980 (down from 6.2 million in 1976), and an average initial CFC charge per unit of approximately three pounds (compared with 3.4 pounds in 1976), this still represents an annual installation of MAC units accounting for 20 million pounds of refrigerant capacity in 1980 for all autos, light trucks, and aftermarket sales (sales and installation after vehicle purchase). And, although automobile sales and air conditioner installations are not expected to return to previous levels for some time, total installed mobile air conditioner capacity will still continue to rise, because of the relatively small number of MAC units installed in pre-1970 autos. Thus, even with depressed auto sales, more autos with factory-installed MACs will be sold than will be disposed of in the foreseeable future.

To help in the discussion of the repercussions of various alternatives that we will be discussing in this section, we present, in Table 7.2, 1980 figures for air conditioner installations by manufacturer. As can be seen, the market is dominated by three manufacturers, who account for over 96 percent of the total automobile installations (not counting light truck and aftermarket sales). There are few product areas in which so few manufacturers have such dominant positions. This has some significance in our findings, since options that may be

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Total Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Motors</td>
<td>3,532,273</td>
</tr>
<tr>
<td>Ford Motor Company</td>
<td>964,613</td>
</tr>
<tr>
<td>Chrysler Corporation</td>
<td>489,092</td>
</tr>
<tr>
<td>American Motors</td>
<td>103,848</td>
</tr>
<tr>
<td>Volkswagen (U.S. plant)</td>
<td>91,539</td>
</tr>
</tbody>
</table>

feasible for these top three producers may have severe economic, or other, impacts on the smaller manufacturers.

Within the category of mobile air conditioners, approximately 89 percent of the estimated emissions in the year 1976 fell within four categories: manufacturing/installation emissions (which are expected to play a smaller role in the future), leakage from units during operation, emissions during repair servicing, and emissions during disposal. The remaining 11 percent included recharge servicing and accidents. In the following discussion we will concentrate on the first four categories.

CONTROL TECHNOLOGY ASSESSMENT

Some of the more important control technology options, as identified by International Research and Technology Corporation (IR&T) (the research subcontractor who provided data for the previous Rand study), include transporting MAC units without their initial charge, using alternative gases for leak testing, and pretesting before leak testing. In addition, in some CFC applications, recovery and recycle during manufacture constitute key means of controlling CFC emissions. This is not as important in the mobile air conditioning industry, since only 11 percent of 1976 MAC emissions, and as little as four percent by 1990, might be attributed to the manufacturing and installation stages.

Our present study indicates not only that certain options can produce significant emissions reductions, but also that some of these options are already being implemented, at least by some manufacturers. For example, compressors built at the GM Delco Dayton facility are shipped with oil, but without CFC charge, to the final GM assembly plants located throughout the country. Furthermore, use of CFCs for leak testing is being phased out and being replaced by air and helium for all applications except long-term durability testing, where the actual working fluid must be used. At least one result is that helium testing, using a mass spectrometer, allows easy detection of much smaller leaks than previously possible, and thus provides an incentive in the form of improved testing performance. Using helium can also help reduce emissions from in-service leakage. Because of the much smaller leak sizes that might eventually have to be tolerated as a result of other emissions reduction efforts, the superior sensitivity of helium leak testing systems may make them almost a necessity.

Emissions can be greatly reduced by using helium leak detection systems during the manufacturing/installation stage. For example, leak testing with R-12 has been estimated to use approximately 0.8 pound of refrigerant per unit, out of a total of about 1.1 pounds emitted per unit during manufacturing and installation from all sources. Thus, this one stage contributes about 70 percent of the manufacturing emissions. During and since the time of the previous Rand study, there has been a continuing trend toward use of such helium systems, including almost total conversion by GM Delco, the dominant manufacturer of domestic MAC units, and conversion to helium by Ford for testing their new, smaller compressors. Therefore, in estimating emissions reduction potential from manufacturing- and installation-related sources, we will consider two categories: (1) current trends, including those changes already being implemented since 1976, and associated improvements possible with minimal additional cost, and (2) other emissions reduction options with larger economic and other disruptive effects. If, in category 1, we include not only a switch to helium leak detection systems but also improvements in charging systems and procedures, a total reduction in use and emissions of R-12 of up to 5.8 million pounds per year might be possible. (This estimate
is based on 1976 manufacturing numbers of 8.24 million units, with an average charge of 3.44 pounds.) Other options, with somewhat larger costs and disruptions, include a switch by all manufacturers to helium leak testing, implementation of more complex charging procedures, and installation of recovery equipment. These steps could save up to 1.4 million pounds of R-12 per year at 1976 levels.

We must point out, however, that helium leak detection systems are not only expensive in terms of initial capital costs, but are also costly to maintain and operate. Thus, it may be feasible for the largest two or three manufacturers to implement such systems, but smaller manufacturers may find it too costly to do so. Nevertheless, as already pointed out, even if only the largest manufacturers implemented these systems, 90 percent of the total potential reduction in leak testing emissions from all U.S. manufacturers could still be achieved.

A second major area for possible emissions reduction is in-service leakage. Among the major possibilities for redesign to reduce leakage are use of shorter hoses and less permeable hose materials, including bonded rubber/nylon materials or metal. In the previous Rand work it was noted that not enough data exist on the actual extent of hose leakage or on the cost of such improvements. GM/Delco noted that the effectiveness of this option is related to the choice of refrigerant used, since some hose materials are much more permeable to some specific refrigerants. Ford Motor Company has noted that the leakage reduction could be "significant," but that it might take five years to make such changes in hose materials. Using the previous Rand results and industry estimates, we believe that such changes might reduce in-service leakage by about 35 percent (but probably not more). Using the previous study's 1976 data, this would correspond to a reduction of about eight million pounds of R-12 per year with moderate expense and effort. Additional emissions reduction options would include improvements in all gaskets, seals, couplings, and the like.

The third major emissions reduction option is redesign to reduce the initial charge. This would affect emissions at all stages of the MAC lifetime. Again, manufacturers are already working in this area, generally for other reasons, such as energy conservation. Some significant gains have already been made by new systems with smaller compressors. In 1976, the industry-average charge was 3.4 pounds per unit; several current units require less than three pounds and several estimates of a feasible fleet-average of 2.75 pounds or less have been made. For example, Ford Motor Company projects a fleet-average of 2.73 pounds for its 1986 autos and light trucks. From a 1976 average of 3.4 pounds per unit, such a trend could eliminate up to 15 million pounds per year of R-12 emissions from all MAC sources, assuming that no other options were implemented. That is, manufacturing, leakage, servicing, and disposal emissions would each be reduced by a different amount, once a large fraction of in-service MAC units had lower-charge design. Additional estimates of an ultimate possible reduction to as little as two pounds per unit might be realized, but at a much higher cost and level of effort, including retooling of current designs. Industry sources indicate that such a level of effort could take seven years to implement; it might, however, save up to 17 million additional pounds per year, at the cost of lower reserve margins for leakage and more frequent recharging. Thus, to realize this reduction, associated improvements in servicing would be necessary, to prevent excessive increases in total servicing losses from the more frequent servicing that might be required. We consider that these difficulties make this option less feasible than most others.

Two other potentially significant control technology options are improvements in MAC servicing and recovery at salvage yards. However, since both these options also require changes in work practices, we will discuss them in the next subsection.
ASSESSMENT OF WORK PRACTICES

There are several areas in which work practices can affect R-12 emissions in mobile air conditioners. We have already discussed the role of testing units during manufacture for an adequate vacuum before leak testing, and using gases or mixtures of gases other than pure R-12 in the leak testing itself. Two other areas of work practices are potentially significant.

First, repair servicing is expected to produce approximately 35 percent of all MAC emissions by the year 1990 and will constitute the largest single contributor to MAC emissions from now through 1990. Therefore, improvements in servicing procedures appear to be an important concern. However, since there are thousands of MAC service facilities in the United States, each dealing with a tiny fraction of the total units serviced, most potential improvements in work practices would be difficult to implement. The basic problem is the practice of venting old refrigerant to the atmosphere, an often recommended procedure to minimize buildup of water and acid in air conditioning units. (Note, however, that even though manufacturers have often recommended venting in the past, manufacturers such as Ford no longer recommend venting for newer orifice tube systems. Also, service facilities appear to vent less frequently when only recharging is required.) Two solutions would be to minimize this practice by venting only when necessary, or to use recovery equipment in each shop. The magnitude of this problem suggests determining first the cost of recovering such CFC, and the cost of virgin CFC at which such a process would be economically feasible.

For example, a reclaiming device such as the Draf Industries system might initially cost from $700 to $2,000. In ten minutes it can recover about 90 percent of the refrigerant. For an average charge of 3.3 pounds, 70 percent of which is assumed to remain in a typical unit being serviced, about two pounds of refrigerant might be recovered. At a labor cost of $30 per hour, this results in a cost of about $2.50 per pound of refrigerant recovered. This is clearly not economical at the present. However, if the serviceman could spend less time connecting and operating the system, the cost savings could approach refrigerant costs in the near future.

We also need to consider the effect of the capital cost of the system. With approximately 200,000 servicing outlets in the United States performing an estimated 18.5 million servicings in 1980, the average shop serviced slightly fewer than 100 units per year (for many of these, air conditioning repair is only a side business to a larger automotive service center). If a low cost ($700) unit were available for the average shop, using, say, a 30 percent cost of capital, the capital cost contribution of about $1.12 per pound of refrigerant reclaimed and recycled would be well below that of the labor cost. Of course, the total cost would still be well above near-term projections for refrigerant costs, but if refrigerant costs rise significantly, such a reclaimation system could prove economical for some of the larger servicing outlets, where the relative size of the capital cost would be even lower.

We now examine the emissions reduction potential of this option. Using 1976 data, and assuming 85 percent recovery of vented CFC, a total reduction in use and emissions of about 12 million pounds of R-12 per year might be effected. However, this would require the cooperation of a wide range of service organizations and is expected to be one of the most difficult options to implement. In fact, few, if any, of the thousands of smaller service stations and garages that service automobile air conditioners might ever find it cost effective to attempt recovery.

Several MAC manufacturers (such as Ford and GM) have expressed interest in a CFC recovery/reclaim scheme. Such a scheme might be used at service centers, according to manufacturers, as a potentially more feasible and, perhaps, more cost effective means of reducing
CFC emissions than retcooling or CFC substitution in MACs themselves. Systems such as the
Drafl Industries reclaimer (being investigated by Ford and others, with technical assistance
by DuPont), and a similar version being developed by GM, are already being tested for practi-
cality, quality of reprocessed CFC, ability of MACs to successfully use reprocessed CFC with-
out excessive wear, and for development of optimal work practices for efficient recycling of
CFCs. However, not all results have been encouraging, and improvements in available sys-
tems will almost certainly be required. In summation, we consider that the costs, technical
problems, and difficulties in assuring the use of such systems make this option generally less
feasible as a future option.

Other service-related improvements exist that are somewhat easier to implement, but
still have moderately large emissions reduction potential. Improvements in leak testing, re-
charging, purging, and so on, might reduce R-12 use and emissions by as much as one half, or
about nine million pounds per year. This breaks down to about one million pounds for re-
charge servicing, and about eight million pounds for repair servicing. Again, however, proce-
dures and some equipment would have to be changed at many facilities to achieve this
reduction.

Recovery of refrigerant at the time of disposal of the unit (at a salvage yard, for exam-
ple) might have an impact equal to that of recovery at servicing. Although this stage is
expected to account for only about 58 percent as much emissions as repair servicing by 1990,
the far fewer number of salvage yards (about 800) makes recovery a possibility. Using 1976
data, a total recovery of about seven million pounds of R-12 per year (assuming 85 percent
recovery efficiency) might be realized, rising to 20 million pounds per year by 1990 as in-
creasing numbers of older autos with MAC units are disposed of. A production line using,
perhaps, multiple reclaiming units could keep the labor costs lower than those for servicing
operations, and the initial cost of the unit would be spread out over many times more oper-
ations per year. These reduced costs would have to be balanced against a possibly more
difficult procedure. Most of the vehicles would not be drivable, and the reclaimer unit might
have to be physically moved some distance in an outside environment. Many of the units
would have little refrigerant left. However, a rise in CFC cost might make either recovery of
R-12 or use of an alternative refrigerant more feasible. Most likely, it would promote recovery
in lieu of the expensive retcooling that might be required before substitute refrigerants could
be used. Nevertheless, we still consider this a costly and difficult option to implement.

ASSESSMENT OF CHEMICAL SUBSTITUTES

Since we have already discussed substitutes for R-12 in manufacturing use, we will con-
sider here only substitutes for the refrigerant itself. Only the use of entirely different systems
can bring about a total emissions reduction as significant as that possible by replacing the
refrigerant. However, little work was done previously to assess the feasibility of substitutes
for R-12, other than to indicate the high cost of the retcooling that would be required and to
mention a few of the alternatives. Because of the current interest in chemical substitutes,
especially R-22, Rand study members visited Delco Air Conditioning Division of General
Motors, and DuPont and Allied Corporation, and, in addition, contacted Ford Motor Com-
pany, to assess those chemical substitutes seen as most promising by the industries involved.
It is clear that tradeoffs will be involved in the use of any replacement refrigerant; redesign-
ring part, or all, of the MAC system may also be required. Potential problems, such as leakage
through hoses, have already been mentioned. Others will be briefly listed here.
The most promising alternatives to R-12 for mobile air conditioners at the present time appear to be R-22 (a partially halogenated CFC), R-134a (which contains no chlorine), and mixtures of R-22 with R-142b, R-114, or R-124. Of the three mixtures, R-22 plus R-142b is the most advanced in terms of development and testing. Although, in the long run, any of these alternatives might be used to replace R-12 in mobile air conditioners, each has special problems that could delay its introduction or impose severe economic penalties. We discuss the potential difficulties of the three most promising alternatives below.

R-22

Although R-22 is at present only slightly more expensive, it is partially halogenated, and thus poses some of the same potential problems as R-12, but to a smaller degree. Therefore, some potential users are concerned that, should the availability of R-12 be restricted in the future, R-22 might be similarly restricted, or at least more difficult to obtain. The key problem, however, is that use of R-22 as a refrigerant requires 50 percent higher pressures and would entail essentially complete redesign and retooling. In addition, R-22 requires a synthetic lubricant with high lubricity, has high permeability, retains water that could be dumped into the evaporator, and, at the high temperatures in such R-22 systems, dissolves and replaces out copper at high pressure points (such as bearings). Furthermore, the reduced coefficient of performance for R-22 versus R-12 systems will introduce an estimated six percent loss of efficiency, thus increasing energy costs or reducing performance. Finally, R-22 is suspected of being a mutagen, posing further potential problems with future use.

R-134a

This refrigerant is the most closely compatible with current MAC systems and could be used in current compressors with only minimal redesign and retooling (as a result of increased compressor discharge pressures). However, there is no current manufacturing process for this refrigerant. Current estimates are that it might be available in the mid to late 1980s. A further problem is that after a manufacturing process is found, it will still take about four years to conduct animal inhalation tests, requiring about 60 tons of R-134a. However, at least one firm (Imperial Chemical Industries) holds the somewhat more optimistic view that commercial quantities may be available in the near future. If this problem is overcome, R-134a would offer the advantages of being nonchlorinated, being compatible with current compressors, and having low hose permeation. However, some redesign would be required, since it has a ten percent loss of efficiency at high load and is insoluble in mineral oil. Furthermore, at least one manufacturer questions the effects of release of fluorine to the atmosphere. Ford Motor Company, however, considers R-134a to be potentially the best long-term candidate known at the moment, should substitution for R-12 be found necessary or desirable through verification of suspected ozone depletion effects.

Mixtures

The most thoroughly investigated mixture at the present is R-22 plus R-142b, which is currently available at somewhat higher cost than R-12. A problem with any mixture containing R-22 is that it still contains chlorine, and the R-22 could separate during evaporation and
condensation and could selectively permeate hoses, leading to a change in refrigerant concentration. This would cause performance problems and could also invite venting of spent refrigerant to the atmosphere by servicemen who could not determine the concentrations of R-22/R-142b remaining in the system. Other potential problems are the need for new lubricants and questions of flammability (R-142b) and mutagenicity (R-22).

At the moment, R-134a appears to be the best candidate as a substitute refrigerant, should its availability be assured in the future. In the meantime, estimates for converting to use of a refrigerant such as R-22, which would require complete retooling, could be $400 to $450 million for a single large manufacturer, according to General Motors Corporation (possibly $200 million according to Ford Motor Company). This cost might be spread over a total of approximately four million units per year (one to two million per year for Ford); however, because of the more rapid changes in product designs in the automotive field, costs might have to be recovered rapidly. In fact, if R-22 became less readily available in the future, as few as seven years might be a more realistic lifetime for such a product design (following the five to seven years required for it to reach production). Therefore, the capital cost to such a manufacturer, spread over a seven-year period, could amount to about $15 per unit. For a charge of 2.5 to 3.0 pounds per unit, this would be economical only at a cost savings of $5 to $6 per pound for R-22 over R-12.

Of course, the increased cost would be passed on to the customer. Using one manufacturer’s price/cost ratio of three, this could result in a price increase of $45 per unit (up to $75 per unit according to another industry estimate). Clearly, this would not be economically competitive with other mobile air conditioner designs, especially considering that typical units need recharging, or servicing requiring removal and replacement of refrigerant, only once every three to five years. Using these figures, total refrigerant purchased by the consumer at servicing over the lifetime of the air conditioner might be five to 15 pounds. Thus, cost savings from using R-22 over alternative refrigerants would have to be $3 to $15 per pound to offset the higher initial purchase price. In addition, such R-22 units are initially expected to experience somewhat higher maintenance costs, because of the higher pressures and bearing loads in such systems. Therefore, use of R-22 as a substitute refrigerant appears less cost effective than some of the other emissions reductions options.

ASSessment of Product Substitutes

The most viable alternative to a CFC-type MAC system identified previously appears to be a reverse Brayton (air-cycle) system. Although past tests did not demonstrate the feasibility of such a system in automotive use, a low pressure vapor-cycle system that could utilize either CFC or hydrocarbon refrigerants—a more recent development by the ROVAC Corporation—is currently being tested in a Mitsubishi automobile. Although tests by the manufacturer, using an unidentified refrigerant, indicate performance equivalent or superior to that of a conventional Mitsubishi system using R-12, independent tests under a variety of operating conditions must still be undertaken to substantiate the results. Furthermore, the potential hazards of using hydrocarbon refrigerants in an engine compartment, as well as the ultimate costs of utilizing such a system, are yet to be considered.
III. Centrifugal and Reciprocating Chillers

INTRODUCTION

The category of chillers consists of a wide range of systems using a number of different refrigerants. These include units with centrifugal and reciprocating compressors, using R-11, R-12, R-22, R-113, R-114, and R-500. These refrigerants have traditionally been associated with specific applications and capacity ranges of chillers, although the use of certain refrigerants and product types has changed in the recent past and will continue to do so. Therefore, in this section we will consider each specific refrigerant and its contribution to the total, as well as the overall impact of chiller emissions as a whole.

To determine chiller emissions, their significance, and the feasibility of implementing specific techniques to reduce emissions, we will use updated figures through 1980, in addition to those used in the previous Rand study (Palmer et al., 1980). In that study, data covering the period through 1976 were used by IR&T to estimate 1976 emissions and to extrapolate to 1990 emissions. In the present study, we will use more recent data to update emissions estimates and to provide a baseline for evaluating emissions reduction options in the basic categories of control technology, work practices, chemical substitutes, and product substitutions.

Chiller systems are distinguished by two basic types of compressors: centrifugal and reciprocating. Reciprocating chillers are used in the smallest capacity range, from 1.5 to 150 tons. Although these systems were originally designed to use R-12, R-22 designs have been replacing the older R-12 systems since the early 1960s, because of their approximately 60 percent greater capacity within a physically similar system. Furthermore, unitary systems using R-22 have also begun to compete with reciprocating chillers in many applications. With an approximate lifetime of 20 years, the older R-12 systems are rapidly disappearing; therefore, with the exception of servicing and disposal, these older units will play a relatively small part in CFC emissions. Furthermore, with an ozone depletion factor calculated to be only 0.05 for R-22, the ozone depletion potential of current reciprocating chiller systems will be minimal. Therefore, we will concentrate on centrifugal chiller emissions here.

Centrifugal systems are used in the largest building air conditioning applications, ranging from 100 to 10,000 tons capacity. Because of the 100 to 1 ratio of capacities, and the desire to minimize the use of widely differing component sizes, units in different capacity ranges generally use different refrigerants. Thus, for example, a large capacity unit with a more efficient refrigerant may have the same physical size as a lower capacity unit. Therefore, a product line covering a wide range of capacities, but a more restricted range of physical sizes, could all be built within a single plant using common manufacturing techniques. For example, chillers in the largest size range (6,000 to 10,000 tons capacity) use R-22. Since R-22 systems operate at the highest pressure, lowest volume flow rate of any chiller type, such large machines are actually physically similar in size to smaller chiller units using other refrigerants, although they do require higher pressure components.

Table 7.3 shows typical refrigerants used for chillers in various ranges.

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3A ton is a measure of a chiller's capacity to remove heat; it represents the heat required to melt one ton of ice in 24 hours.
Table 7.3

**Typical Refrigerants Used in Centrifugal Chillers**

<table>
<thead>
<tr>
<th>Capacity (tons)</th>
<th>Refrigerant</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;400</td>
<td>R-11, R-113</td>
</tr>
<tr>
<td>400-1,000</td>
<td>R-11, R-12</td>
</tr>
<tr>
<td>1,000-1,500</td>
<td>R-11, R-12, R-500</td>
</tr>
<tr>
<td>1,500-2,000</td>
<td>R-11, R-12, R-114, R-500</td>
</tr>
<tr>
<td>2,000-5,000</td>
<td>R-12, R-22</td>
</tr>
<tr>
<td>5,000-6,000</td>
<td>R-22, R-500</td>
</tr>
<tr>
<td>6,000-10,000</td>
<td>R-22</td>
</tr>
</tbody>
</table>

**Source:** Personal communication from the Carrier Corporation, December 1980, and other sources.

**Chiller Emissions**

To estimate chiller emissions, data on U.S. units manufactured, domestic installations, and total domestic units in service must be known or estimated. Table 7.4 lists U.S. data for production of units both for domestic installation and export from 1970 to 1980. Total production figures are needed to estimate manufacturing emissions, but production figures for domestic use only are used for estimating servicing and disposal-related emissions within the United States.

In addition to these data, the fraction of systems using each type of refrigerant must be determined. Using IR&T's estimates for 1976 to 1990, these fractions for both centrifugal and reciprocating chillers are shown in Table 7.5.

Using the above data, we can first estimate manufacturing emissions. These consist of contributions from leak testing and rework (for which R-12 is used in essentially all units, for an estimated loss of six percent of total refrigerant charge), and "running in" of some final units, each using its own specific refrigerant (estimated to cause loss of about three percent of total charge averaged over all units and manufacturers). For these emissions only, we consider both domestically shipped and exported chiller systems manufactured in the United States.

Using IR&T estimates, we assume an average total charge of 780 pounds per unit for R-11 centrifugal chillers and 2,100 pounds per unit for all other refrigerants used in centrifugal equipment. The resulting emissions estimates for 1980 are shown in Table 7.6. Note that even though R-12 units make up only ten percent of the total, R-12 emissions dominate because R-12 is used for leak testing and rework in virtually all types of units. Using an average charge of 150 pounds for reciprocating chillers, total emissions for reciprocating systems are also shown in Table 7.6. Again, because of lower costs, R-12 is used even in testing R-22 reciprocating units.

In addition to emissions during manufacturing, emissions from new units also occur
Table 7.4

ANNUAL PRODUCTION OF CENTRIFUGAL AND RECIPROCATING CHILLERS, 1970-1980

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Centrifugal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4,056</td>
<td>2,994</td>
<td>3,000</td>
<td>3,350</td>
<td>3,350</td>
<td>4,600</td>
</tr>
<tr>
<td>Exports</td>
<td>1,389</td>
<td>1,261</td>
<td>1,300</td>
<td>1,300</td>
<td>1,300</td>
<td>1,876</td>
</tr>
<tr>
<td>Domestic</td>
<td>2,667</td>
<td>1,733</td>
<td>1,700</td>
<td>2,050</td>
<td>2,050</td>
<td>2,724</td>
</tr>
<tr>
<td><strong>Reciprocating</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>9,180</td>
<td>7,114</td>
<td>8,900</td>
<td>8,100</td>
<td>8,100</td>
<td>9,650</td>
</tr>
<tr>
<td>Exports</td>
<td>3,013</td>
<td>3,001</td>
<td>3,000</td>
<td>3,000</td>
<td>2,600</td>
<td>3,200</td>
</tr>
<tr>
<td>Domestic</td>
<td>6,167</td>
<td>4,113</td>
<td>5,900</td>
<td>5,100</td>
<td>5,500</td>
<td>6,450</td>
</tr>
</tbody>
</table>

**SOURCES:** IR&T data through 1976, and Air-Conditioning and Refrigeration Institute (ARI) and Bureau of Census data. Exports for 1977 and 1978 are estimates.

**NOTE:** The relatively high figures for 1970 represent a period of slow growth and high sales between 1965 and 1975. Although IR&T previously felt that the 1976 figures were anomalously low, subsequent annual data have confirmed a significant dropoff in all chiller sales between 1975 and 1979, with recovery in 1980.

Table 7.5

PERCENTAGE OF CHILLERS USING VARIOUS REFRIGERANTS

<table>
<thead>
<tr>
<th>System and Refrigerant</th>
<th>Percentage of Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Centrifugal</strong></td>
<td></td>
</tr>
<tr>
<td>R-11</td>
<td>80</td>
</tr>
<tr>
<td>R-12</td>
<td>10</td>
</tr>
<tr>
<td>R-500</td>
<td>5</td>
</tr>
<tr>
<td>R-114</td>
<td>4</td>
</tr>
<tr>
<td>R-22</td>
<td>1</td>
</tr>
<tr>
<td><strong>Reciprocating</strong></td>
<td></td>
</tr>
<tr>
<td>R-22</td>
<td>98</td>
</tr>
<tr>
<td>R-12</td>
<td>&lt;2</td>
</tr>
</tbody>
</table>


Table 7.6
CFC Emissions During Manufacture and Shipping, 1980
(Millions of pounds)

<table>
<thead>
<tr>
<th>System and Refrigerant</th>
<th>Percentage of Systems</th>
<th>Average Charge (lb)</th>
<th>Manufacturing Emissions</th>
<th>Shipping and Installation Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Centrifugal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-11</td>
<td>80</td>
<td>780</td>
<td>.086</td>
<td>.026</td>
</tr>
<tr>
<td>R-12</td>
<td>10</td>
<td>2,100</td>
<td>.317</td>
<td>.009</td>
</tr>
<tr>
<td>R-500</td>
<td>5</td>
<td>2,100</td>
<td>.015</td>
<td>.004</td>
</tr>
<tr>
<td>R-114</td>
<td>4</td>
<td>2,100</td>
<td>.012</td>
<td>.003</td>
</tr>
<tr>
<td>R-22</td>
<td>1</td>
<td>2,100</td>
<td>.003</td>
<td>.001</td>
</tr>
<tr>
<td><strong>Reciprocating</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-22</td>
<td>98</td>
<td>150</td>
<td>.043</td>
<td>.014</td>
</tr>
<tr>
<td>R-12</td>
<td>2</td>
<td>150</td>
<td>.088</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

NOTE: The estimate for manufacturing emissions is based on 4,600 total centrifugal units and 9,650 reciprocating units. Manufacturing emissions for each refrigerant are three percent of the total refrigerant charge; for example, for R-11 centrifugal units, this is 0.03 x 0.8 x 4,600 x 780. For each chiller type, R-12 manufacturing emissions also include six percent of the total charge for all units of that type (.288 million pounds for centrifugal, .087 million pounds for reciprocating). For all units, shipping and installation emissions are 1.5 percent of the total charge for each type of refrigerant, estimated from domestically installed units only (2,724 centrifugal and 6,450 reciprocating systems).

during shipping and installation. Since few exported units are shipped with their own charges, we consider only 1980 domestic installations. Using estimates of one to two percent loss, we estimate emissions from centrifugal chillers during shipping and installation to be 25,500 pounds of R-11, 8,600 pounds of R-12, 4,300 pounds of R-500, 3,400 pounds of R-114, and 860 pounds of R-22. Losses from newly installed reciprocating systems would then be about 300 pounds of R-12 and 14,200 pounds of R-22. Thus, for both types of chillers, these emissions represent only about ten percent of manufacturing emissions.

To compute annual leakage from units in service, we must first estimate the total stock of refrigerants in current chillers. Using the shipment figures in Table 7.4, along with IR&T’s estimates of stocks in 1976 (Palmer et al., 1980, Tables 3.E.5 and 3.E.9), we have derived the figures in Table 7.7 for total refrigerant stocks in 1980.

Estimates from the previous Rand study placed leakage emissions at 7.5 percent of total stocks, chiefly from purging and miscellaneous leakage. Using the above table, this places 1980 centrifugal chiller emissions from leakage at 2.52 million pounds of R-11, 0.93 million pounds for R-12, 0.46 million pounds of R-500, 0.375 million pounds of R-114, and 0.092 million pounds of R-22. For reciprocating systems, the leakage emissions are 0.375 million pounds of R-12 and 1.06 million pounds of R-22.
Table 7.7

TOTAL REFRIGERANT STOCKS AND
LEAKAGE EMISSIONS, 1980
(Millions of pounds)

<table>
<thead>
<tr>
<th>System and Refrigerant</th>
<th>Stock</th>
<th>Leakage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Centrifugal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-11</td>
<td>33.6</td>
<td>2.52</td>
</tr>
<tr>
<td>R-12</td>
<td>12.3</td>
<td>0.93</td>
</tr>
<tr>
<td>R-500</td>
<td>6.1</td>
<td>0.46</td>
</tr>
<tr>
<td>R-114</td>
<td>5.0</td>
<td>0.375</td>
</tr>
<tr>
<td>R-22</td>
<td>1.2</td>
<td>0.092</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>58.3</td>
<td>4.38</td>
</tr>
</tbody>
</table>

| **Reciprocating**      |       |         |
| R-22                   | 14.1  | 1.06    |
| R-12                   | 5.0   | 0.375   |
| **Total**              | 19.1  | 1.435   |

Servicing emissions have proven to be the most difficult to evaluate. Servicing emissions occur in several ways, including failure to purge systems before servicing, failure to save refrigerant for reuse, and use of refrigerant to flush open systems. Three different sources have estimated such emissions at 16 percent of refrigerant charge annually (IR&T), six percent of charge annually (the Trane Company), and as two-thirds (+0/-20 percent) of total chiller emissions annually (Carrier Corporation). The latter estimate amounts to twice the total of all other chiller emissions. Including disposal emissions (discussed in the next subsection), total chiller emissions, excluding servicing emissions, are approximately nine percent and 13 percent of total charges for centrifugal and reciprocating systems, respectively. Thus, servicing emissions can be estimated at 18 percent and 26 percent of total charges annually. These numbers are significantly higher than either of the other two figures. We will use a range of six to 16 percent to estimate service emissions from the total 1980 charges in Table 7.7.

Finally, we can calculate approximate emissions at disposal. This first requires estimating total disposals and fractions of various refrigerants used in these units. Assuming average lifetimes of 25 years for centrifugal chillers, and 20 years for reciprocating chillers, Table 7.8 shows the resulting fraction of refrigerant charges (i.e., percentage of each refrigerant in total disposals, not percentage of units using each refrigerant).

Using the above lifetimes and past shipping data, estimated total disposals for 1980 are 800 centrifugal and 6,450 reciprocating chillers. The average charge remaining in such units is about 908 pounds for centrifugal systems, presuming an average initial charge of 1,020 pounds, with five percent lost before disposal, and perhaps six percent recycled. For reciprocating systems, these numbers would be 135 pounds remaining per unit, out of a 160 pound initial charge, with 7.5 percent previously lost and three percent recycled at disposal.
Table 7.8

PERCENTAGE OF REFRIGERANT CHARGES IN DISPOSED OF UNITS, 1980

<table>
<thead>
<tr>
<th>System and Refrigerant</th>
<th>Percentage of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Centrifugal</strong></td>
<td></td>
</tr>
<tr>
<td>R-11</td>
<td>78</td>
</tr>
<tr>
<td>R-12</td>
<td>11.5</td>
</tr>
<tr>
<td>R-500</td>
<td>5.5</td>
</tr>
<tr>
<td>R-114</td>
<td>4</td>
</tr>
<tr>
<td>R-22</td>
<td>1</td>
</tr>
<tr>
<td><strong>Reciprocating</strong></td>
<td></td>
</tr>
<tr>
<td>R-22</td>
<td>22.8</td>
</tr>
<tr>
<td>R-12</td>
<td>77.2</td>
</tr>
</tbody>
</table>

Resulting emissions for centrifugal units disposed of in 1980 are calculated to be 566,000 pounds of R-11, 84,000 pounds of R-12, 40,000 pounds of R-500, 29,000 pounds of R-114 and 7,000 pounds of R-22. Reciprocating chiller disposal emissions are similarly calculated to be about 200,000 pounds of R-22 and 670,000 pounds of R-12.

The above emissions are compared in Table 7.9. Regardless of the estimates used for servicing, Table 7.9 shows that leakage and servicing emissions dominate, followed by disposal emissions. These three categories account for 97 to 98 percent of all chiller refrigerant emissions in 1980.

Among these categories, the emissions from leakage, primarily from faulty purge systems, pressure relief valves, and fittings, are projected to be reduced as a result of improved maintenance; however, the total amount of leakage may still increase as the total number of systems in use increases. Similarly, emissions from servicing may increase on an absolute scale, because of the increased use of chillers. Finally, the great increase in centrifugal chiller sales in the 1950s and 1960s, along with continued strong sales, will result in an increase in the number of older units being replaced and may double the relative importance of disposal emissions in another ten years.

CONTROL TECHNOLOGY ASSESSMENT

In light of the previous discussion, we expect CFC control technology to be important in reducing emissions from chillers. Given the relative amounts of emissions, this appears to be especially promising in the areas of designing to minimize leakage and reduce the initial charge, and recovery and recycling during servicing and salvaging. However, the potential effect of control technology changes during the manufacturing stage appears to be minimal,
### Table 7.9

**Total Chiller Refrigerant Emissions, 1980**

(Millions of pounds)

<table>
<thead>
<tr>
<th>Stage</th>
<th>R-11</th>
<th>R-12</th>
<th>R-500</th>
<th>R-114</th>
<th>R-22</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centrifugal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturing</td>
<td>.086</td>
<td>.317</td>
<td>.015</td>
<td>.012</td>
<td>.003</td>
<td>.145</td>
</tr>
<tr>
<td>Shipping/inst.</td>
<td>.026</td>
<td>.009</td>
<td>.004</td>
<td>.003</td>
<td>.001</td>
<td>.043</td>
</tr>
<tr>
<td>Leakage</td>
<td>2.520</td>
<td>.930</td>
<td>.460</td>
<td>.380</td>
<td>.092</td>
<td>4.380</td>
</tr>
<tr>
<td>Servicing</td>
<td>2.2-5.4</td>
<td>.74-2.0</td>
<td>.37-.98</td>
<td>.30-.80</td>
<td>.07-.19</td>
<td>3.5-9.3</td>
</tr>
<tr>
<td>Disposal</td>
<td>.570</td>
<td>.084</td>
<td>.040</td>
<td>.029</td>
<td>.007</td>
<td>.730</td>
</tr>
<tr>
<td>Total</td>
<td>5.2-8.6</td>
<td>1.8-3.0</td>
<td>.89-1.5</td>
<td>.72-1.2</td>
<td>.17-.29</td>
<td>8.8-14.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage</th>
<th>R-12</th>
<th>R-22</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reciprocating</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturing</td>
<td>.088</td>
<td>.043</td>
<td>.131</td>
</tr>
<tr>
<td>Shipping/inst.</td>
<td>--</td>
<td>.014</td>
<td>.014</td>
</tr>
<tr>
<td>Leakage</td>
<td>.375</td>
<td>1.060</td>
<td>1.435</td>
</tr>
<tr>
<td>Servicing</td>
<td>.30-.80</td>
<td>.85-2.3</td>
<td>1.15-3.1</td>
</tr>
<tr>
<td>Disposal</td>
<td>.670</td>
<td>.200</td>
<td>.870</td>
</tr>
<tr>
<td>Total</td>
<td>1.43-1.93</td>
<td>2.2-3.6</td>
<td>3.6-5.5</td>
</tr>
</tbody>
</table>

In light of the relatively small amounts lost during leak testing, and the possibility of changing from R-12 to R-22 for leak testing in many cases.

Control technology options for reducing leakage during use fall into several categories: designs to minimize purge system leakage, improved relief valves to reduce failures, and leakage detection and warning systems. The previous Rand study indicated some of the possibilities in these three areas and a recent visit to Carrier Corporation provided further information. For example, Carrier discussed ongoing research efforts to reduce the number of spurious openings of pressure relief valves on their systems. Furthermore, they singled out purge systems and the work practices associated with them as major problem areas. Any improvement in either of these areas would not only help reduce emissions from in-service leakage but could also minimize repair service calls and, as a result, could lower emissions from servicing. Finally, the previous Rand work indicated that, subject to better information on actual emissions, detection and warning systems might have little (or possibly a negative) effect on leakage emissions. Considering these factors, a one-third reduction in emissions appears feasible with small to moderate cost and effort, mainly by improving purge systems (work is being done in this area now). Such improvements could result in eventual reductions of about 1.5 million pounds per year for centrifugal chillers, and 0.5 million pounds per year for reciprocating chillers. Since these units include several diverse refrigerants, we can reduce them to a common denominator by using their ozone depletion factors and relating all refrigerants to R-11. The resulting emissions reduction potential in terms of equivalent
pounds of R-11 would be 1.2 and 0.1 million pounds per year for centrifugal and reciprocating units, respectively. Note that such reductions would take many years to realize, considering the typical lifetimes of chillers and the resulting length of time before a significant fraction of current systems could be replaced with improved ones.

Current design trends have already been able to reduce the initial charge in many chiller systems, and it appears that such a trend will continue, possibly through 1980. It is estimated that perhaps a 12 percent additional reduction in charge may be feasible during the next ten years. Since this affects essentially all phases of emissions, from manufacturing through disposal, new designs appear to be a significant emissions reduction option. Using 1980 figures, the ultimate reduction, once all chillers in use were of the newer design, could approach 1.5 million pounds per year for centrifugal chillers and 0.6 million pounds for reciprocating. This produces R-11 equivalents of 1.1 and 0.1 million pounds per year, respectively.

The most significant impact of control technology appears to be in the area of CFC recovery and recycle during servicing and disposal. Since our 1980 estimates indicate that 38 to 62 percent of CFC emissions from chiller systems occur during servicing, this should be our major area of concern. This problem has a twofold solution: first, to implement the technology for in-service recovery and recycling of CFCs and, second, to assure that work practices take advantage of such technology. Since many large chiller systems have their own purging systems with their own receiver tanks, a large part of the problem is lack of adequate work practices during servicing. This will be discussed in the next subsection.

CFC recovery and recycle can be implemented in three ways. First, it is possible to supply more chiller systems that have purge systems with integral receiver tanks. We have found that for large installations, the contractor generally specifies whether a purge system with integral receiver tank is to be supplied as part of the completed system. If the cost or availability of required CFCs were to make recovery a more desirable option, the incentive for including purge systems with receiver tanks should increase. One (1978) estimate of receiver tank cost was $5.00 per pound of refrigerant charge for an 8,500 ton chiller, and $27.00 per pound of refrigerant for a 300 ton chiller. For our 1980 estimates of annual servicing emissions, which are about six to 16 percent of total refrigerant charges, and given lifetimes of 20 to 25 years, this represents a lifetime loss of from 1.2 to 4.0 times the total charge. Assuming that, at most, 80 percent of this loss could be prevented by use of receiver tanks, from 1.0 to 3.2 times the initial charge might be saved. Thus, the cost of a receiver tank would be justified only for refrigerant costs in the range $1.50 to $5.00 per pound for the largest systems, or $8.40 to $27.00 per pound for small chillers. Furthermore, this assumes no added cost for the labor required to purge the system (which we will discuss below), and no cost for reclaiming the refrigerant for reuse. Without these costs, the largest systems, all of which use R-22, would be the only ones for which this approaches cost effectiveness.

Second, removing, purifying, and recycling CFCs used outside recycling plants should greatly reduce CFC emissions when it becomes more economical to save and recycle the used refrigerant rather than purchase it fresh. Finally, portable systems such as the Draf system discussed in Sec. II of this chapter may be useful. However, as pointed out in the previous study, the systems and work practices associated with at least the first two of these options are relatively expensive; Carrier estimated that some of these options might not become economically feasible until refrigerant costs $10 per pound—a number in the range of our above estimates of receiver tank savings.

We estimate that the reduction of emissions for 1980 would be approximately 2.8 to 7.5 million pounds for centrifugal chillers and 0.9 to 2.4 million pounds for reciprocating systems. The corresponding R-11 equivalents are 2.3 to 6.3 million pounds and 0.35 to 0.9 million pounds, respectively, for the two categories.
Finally, some of the same considerations relate to recovery of CFC at disposal of the system. However, the presence or absence of a purge system and receiver tank will not be as important at this stage, since the CFC will have to be removed ultimately whether or not such a tank is present. (Some of the key considerations will be determined by the work practices involved, which will be quite different for recovery at servicing and recovery at disposal. Therefore, we will comment further on this aspect in the next subsection.) We estimate the emissions reduction potential, assuming an 85 percent ultimate recovery efficiency, less an estimated six percent, which is assumed to be currently recovered. The result is a potential recovery of an additional 0.9 million pounds for centrifugal, and 0.7 million pounds for reciprocating chillers—in other words, 0.7 and 0.5 million pounds, respectively, of R-11 equivalent.

ASSESSMENT OF WORK PRACTICES

There are three general areas in which work practices can affect CFC emissions from chiller systems: manufacturing and installation, repair servicing and disposal, and maintenance procedures. Recovery during manufacture and installation, or replacement of halogenated CFCs by other fluids during leak testing, as well as shipping units without initial charges, may all contribute to emissions reductions, but only in a minor way (possibly reducing emissions by 0.3 and 0.1 million pounds for centrifugal and reciprocating systems, respectively).

Of potentially greater impact would be improved procedures for servicing and disposal of chiller systems. Even if systems such as those we discussed in the previous subsection were available for service or disposal, current work practices often militate against recovery. The major problems are discussed below.

First, it may take several days to fully pump down a large system to save the refrigerant. On the other hand, it takes only a few hours to repair typical problems. It is much simpler and, currently, much more cost effective, to release the charge to the atmosphere. One improvement would be to spend a few hours pumping down the bulk of the liquid refrigerant from the system, then vent the remainder to the atmosphere. This approach might be especially inviting to an owner faced with a large establishment that would be without air conditioning during the entire service downtime. Not only would it reduce the cost of servicing but might save some loss of business as well. Thus, there would have to be very large incentives before the maximal recovery of CFC could be realized.

With service charges of $30 to $45 per hour, and an average chiller inventory of about 1,000 pounds for centrifugal units compared with 150 pounds for reciprocating systems, spending four to eight hours purging a system would be only marginally economical for reciprocating chillers but much more so for centrifugal chillers. However, when added to other costs, such as that of adding a receiver tank (if one is not present), and potential loss of business during repair, the costs might not be tolerable. This is an instance where better servicing procedures might be economical in some situations, for example, for large installations where two systems are used, or where an appropriate receiver tank is already present. It may be easier to implement recovery during disposal, since the chiller would not be in operation, and total time for pumping down the system would be of little concern. Trane estimated that 10 to 20 percent of such refrigerant is already recovered and recycled, although other sources indicate that little or none is currently recovered.
Second, one chiller manufacturer (Carrier) pointed out that they typically service less than 50 percent of the units they sell. Many independent service organizations exist, each of which would have to use any improved servicing procedures. However, two factors may help compensate for the difficulty of dealing with a large number of smaller organizations. First, at high CFC costs, smaller organizations may find it more cost effective to recycle refrigerant. Second, should CFC availability decline, servicing companies may find it more difficult to obtain adequate supplies, since manufacturers themselves, as at least one has indicated to us, could afford to buy available CFCs for their own manufacturing use, at any cost. As a result, although the large amount of CFCs lost during servicing and disposal may improve work practices an important area for improvement, it appears that large economic benefits would be required to make it attractive in many cases.

The final area of work practices investigated is maintenance procedures—periodic "servicing" that would attempt to minimize leakage (for example, from relief valves and purge systems), and to prevent gross failures that could result in major losses of refrigerant. However, as indicated in Rand’s previous work, haphazard maintenance at too frequent intervals can actually lead to increased emissions. Therefore, the key to effective maintenance would be to determine optimal maintenance intervals for each type of system, and to develop procedures to pinpoint the most troublesome source of losses, while reducing extra or unnecessary maintenance that might lead to increased CFC emissions.

ASSESSMENT OF CHEMICAL SUBSTITUTES

There are two areas in which alternatives to current CFCs might be used: for testing during manufacturing, and as the actual refrigerant itself. Since, as we have pointed out, emissions during manufacturing and installation are extremely small (about two to three percent of the total during the lifetime of the unit), our work emphasizes the potential for replacement refrigerants. However, we note that R-22 is the most frequently mentioned replacement for the R-12 currently used for all leak testing. Helium is another frequently mentioned candidate. Although helium detection systems using mass spectrometers are already being used for testing absorption systems, and would probably be suitable for use with chillers, the added costs of the system, and the longer time required for the testing process, as indicated by one manufacturer, would probably outweigh any economic savings (helium systems are economically justified for absorption units because of the very low leakage rates required).

As a replacement refrigerant, R-22 appears to be the chief candidate, although R-134a might be used if it becomes commercially available. Since current reciprocating chillers already use R-22, we will concentrate on the possibilities for replacing the fully halogenated CFCs used in centrifugal chillers. As we have already indicated, the introduction of substitute refrigerants in chiller systems will present some problem, because of the wide diversity of refrigerants already in use, even by a single manufacturer. For example, one manufacturer stated that replacing all refrigerants with R-22 would force him to drop some of his product lines, at least in the interim, because the reduced sizes and increased tolerances of components with R-22 as a refrigerant could not be handled in the smaller capacity systems. Alternatively, reciprocating systems might be used to replace these low-end centrifugal units.

\[^8\] We discuss R-134a in more detail in Sec. II of this chapter.
Some of the major questions we address are the problems and costs of such a changeover. Carrier Corporation has estimated what it would entail for them to change all their centrifugal chiller systems over to R-22. Because of the wide range of system capacities, they have determined that three separate strategies might be needed to adapt the units that currently do not use R-22 (that is, units of 6,000 tons or less). For units in the smallest range, R-11 centrifugal systems could be replaced by reciprocating compressor systems in parallel. Those in the intermediate range, in which R-11, R-12, R-114, and R-500 are all used, would require the most extensive redesigning. This would result in a complete new series of units of more diverse size than the current units that use different working fluids. Finally, those in the largest capacity range, currently using R-12 and R-500, would require a more moderate redesign effort.

Carrier has estimated that a 200 man-year effort, and $13 million capital cost expenditure (roughly equivalent to the cost of the engineering effort additionally involved) would be necessary to redesign their entire series in this manner. If all designs could be carried out in parallel, it would take an estimated six years to develop and initially produce the new units. However, since redesigns have been relatively rare in the recent past (Carrier mentions only one major change in the last ten years), it is unlikely that the necessary manpower could be obtained to redesign all capacity ranges simultaneously. If only one capacity range were redesigned at a time, the total time needed would be about 12 or 13 years.

With an assumed capital charge rate of 80 percent (see Chapter 1), and not including engineering design costs, the costs of conversion for a single manufacturer could amount to about $4 million per year, spread over fewer than 1,000 units per year. Thus, to the manufacturer, R-22 costs would have to be at least $4 per pound below those of other refrigerants to keep the new units cost competitive. However, as one manufacturer indicated, the actual increase in price to the customer would most likely be three to five times the manufacturer's cost. At the same time, a unit in use for 20 to 25 years would typically use 2.7 to 6.0 times its initial charge, thus approximately balancing out the increased cost to the customer over the manufacturer's cost. In either case, differential of perhaps $4 per pound would probably be necessary to make such a conversion economically attractive.

The benefits stem from the currently calculated ozone depletion factor of 0.05 for R-22, as compared to the average current factor of 0.85 for all refrigerants used in centrifugal chillers. This could ultimately result in replacing emissions of nine to 15 million pounds per year of CFC with R-22 for centrifugal chillers, thus reducing the ozone depletion potential equivalent to seven to 12 million pounds of R-11 (remember that most reciprocating chillers already use R-22). However, as with several other options, it would be a number of years before enough older chillers were replaced to approach this ultimate total.

Three additional factors to consider are efficiency, reliability, and compatibility. The first is relatively easy to quantify. According to Carrier, R-22 systems would consume about eight percent more energy than equivalent chillers using R-11 and one percent more than R-12 units. The effects on reliability are much harder to quantify. We can only comment qualitatively on two key factors here. First, it is obvious that any new system replacing a chiller that has been in production and use for 20 or 30 years with continuous minor design improvements is likely to be less reliable initially. This could lead to an interim period of increased emissions, though of less consequence to the atmosphere. A new design might not sell well until reliability was demonstrated. The second factor affecting reliability is that R-22 units would require higher tolerances and run at significantly higher speeds (as much as 3:1). For units with design lifetimes of 25 years (some often last 30 or more years), this would be a major area of research and development, especially for the smallest capacity ranges, for
which the R-22 compressor would be smaller, with higher tolerances, than any current designs. Finally, major components from such systems would clearly not be compatible with units in use at the moment. Therefore, a supply of such older components would have to be maintained as replacements for many years to come.

Since the cost of the working fluid is such a small part of the total cost of a refrigeration system (as opposed to the use of CPCs in solvents, or foams, for example), and since chiller systems consume only a small portion of total CPCs used annually, at least one chiller manufacturer has expressed the opinion that they could afford to pay any premium required to obtain sufficient CPC stocks to continue with present systems. That is, unless specific CPCs become totally unavailable, there is some basis for believing that the use of CPCs in chillers, especially R-11 and R-12, might remain relatively unaffected with respect to their use in other applications.

In view of the above considerations, it is unlikely that any chiller manufacturer will change to a partially halogenated CPC like R-22, unless he is certain that it will not also have to be replaced at some time in the future. Although no alternative to R-22 is being strongly considered for use in chillers at the moment, there is the possibility of using a refrigerant such as R-134a in place of R-12 when it becomes commercially available, assuming that it presents no health problems. Under certain operating conditions, there would still be a similar energy penalty (about eight percent), as when changing to R-22; however, compatibility with some of the current chiller systems would be much greater. The chief problem here is the unknown future availability of this potential substitute. Another candidate (for R-11 systems) is R-123, a partially halogenated refrigerant. Here, too, no manufacturing process is yet available. Because of the strong disincentives for changing to R-22, however, substituting either of these, or other new refrigerants, might be more feasible in the future.

One final factor in changing refrigerants is the possibility of going to completely new system designs. The screw compressor has been mentioned as a possible candidate, since it can easily use R-22, or nearly any other potential refrigerant. However, the significant energy penalty, and the newness of the technology, makes the impact of screw compressors uncertain but probably not substantial in the near future.

Our investigations, as well as the previous Rand work, have shown that there will be strong resistance to changing from current chiller designs to those utilizing R-22 as the working fluid.

ASSESSMENT OF PRODUCT SUBSTITUTES

There are few possibilities for product substitutions for current chiller systems. Screw compressors have already been mentioned as candidates in connection with changing refrigerants. The ROVAC Corporation's air cycle system is another possibility. However, design problems, and a limitation to the smallest capacity category, limit its usefulness in the near future. Finally, absorption systems can still be used for some limited applications. Because of their intense use of energy and large physical size, such systems are rarely purchased today (Carrier sells about 50 per year that use lithium bromide). As a result, we do not feel that the area of product substitutions holds significant promise.
IV. Room and Unitary Air Conditioners

INTRODUCTION

Room and unitary air conditioners constitute both single packaged systems and separate, interconnected units, with capacities between about 4,000 and 135,000 Btu/hr, sometimes also with a heating system. They include units built into residences or added on by contractors or consumers, and those used in hotel rooms and small commercial buildings. Since this CFC use category had not been studied earlier by Rando, this section will present information not discussed in the previous Rand report (Palmer et al., 1980).

The major feature of unitary and room air conditioners from a CFC emissions standpoint is that all manufacturers use R-22 exclusively. Therefore, our main concern is to identify ways to minimize use and emissions of R-22 and possible applications to other air conditioning systems that do not use R-22 at the present. Since R-22 is calculated to have an ozone depletion factor of only 0.05, use of substitute refrigerants has not been investigated seriously to date, although Carrier has done some work in the past.

The major types of systems in this category are discussed below.

Room Air Conditioners

These units are single packaged units for cooling and dehumidifying, often with a heating function as well. They are generally mounted in windows, through walls, or on the floor, and have capacities in the range of 4,000 to 35,000 Btu/hr. The Association of Home Appliance Manufacturers (AHAM) certifies such units and compiles statistical information annually.

Unitary Air Conditioners

As defined by the Air-Conditioning and Refrigeration Institute (ARI, 1981),

A unitary air-conditioner consists of one or more factory-made assemblies which normally include an evaporator or cooling coil, a compressor and condenser combination, and may include a heating function as well.

These systems may be either single units or split systems with components mounted both outside and inside, and may be used in residences or commercial buildings. Capacities range from about 5,500 to 135,000 Btu/hr (though they are generally above 13,000 Btu/hr). A certification program is operated by ARI.

Packaged Terminal Air Conditioners

These units are self-contained systems, sometimes with heaters, mounted through the wall. Similar in function to some room air conditioners, these units are largely for commer-

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Some Carrier units used Carene-7 (their trade name product for R-500) in the past.

cial use; they are used in office buildings, hotels, motels, and the like. Sales of these systems currently are less than ten percent of either of the above categories. They are certified by ARI.

Heat Pumps

Heat pumps are essentially reversible air conditioning systems. That is, they provide either cool air or warm air using a single refrigeration system but reversing the flows of warm and cool air. Such systems are available in unitary, room, and packaged terminal configurations. Since some statistics relating to these units are not separated from the appropriate air conditioning categories, we will not discuss them as an individual category.

EMISSIONS

To estimate emissions from room and unitary air conditioners, we first require shipping and installation information. Comparing market data from AHAM and ARI for the various categories, we have compiled the information shown in Table 7.10 for domestic purchase and installation of U.S. built air conditioners. These figures represent reductions from total U.S. production to account for estimated exports of about 25 percent for room air conditioners and ten percent for unitary systems in 1980. Of the remainder, over 95 percent consist of room and unitary systems; therefore we will concentrate on these two categories.

Table 7.10

<table>
<thead>
<tr>
<th>Category</th>
<th>1976</th>
<th>1980</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room</td>
<td>2,300,000</td>
<td>2,400,000</td>
</tr>
<tr>
<td>Unitary</td>
<td>2,160,000</td>
<td>2,130,000</td>
</tr>
<tr>
<td>Packaged terminal</td>
<td>100,000</td>
<td>147,000</td>
</tr>
</tbody>
</table>

*aSome of this information has been compiled by Air Conditioning and Refrigeration News, and by Appliance Manufacturer (1981). Attempts have been made to exclude units exported from the United States. 1976 values used estimates for exports. It should be noted that these figures disagree significantly with Bureau of the Census data.*

Approximately 80 percent of the total market for room and unitary air conditioners is held by six and seven major manufacturers, respectively. Over 50 percent of the market for room air conditioners is held by three manufacturers—General Electric, White, and Whirlpool. The remainder is held by Fedders, Friedrich, and Addison. For unitary systems, 50 percent is held by Carrier, Lennox, and General Electric; Rheem/Rudd, Whirlpool, Heil-Quaker, and Fedders hold the rest.
These estimates allow us to compute total annual use and emissions for such units, using information we have obtained from several manufacturers and market representatives. Typical refrigerant charges for these units lie in the range of one to two ounces per 1,000 Btu/hr for room air conditioners, and two to four ounces per 1,000 Btu/hr for unitary air conditioner units. However, the figures for split-system unitary air conditioners are somewhat sensitive to the separation of the subsystems and the lengths of refrigerant lines connecting them. Therefore, the estimates for unitary systems depend both on capacity and on system configuration. We will use industry estimates of charge averages of 22 ounces of R-22 (eight to 37 ounce range) for room air conditioners, and 80 to 100 ounces of R-22 (48 to 140 ounce range, perhaps going upward to about 200), for unitary air conditioners. Current annual use of R-22 for such units would be approximately 3.3 million pounds for room air conditioners, and 10.6 to 13.3 million pounds for unitary systems.

Emissions from manufacture and testing of air conditioners (including units exported), occur in three ways: from R-22 used in testing, charging, and lost from defective units. Testing is generally done using either helium leak detection systems (G.E. is the major example), or with a combination of R-22 and dry air. In the latter case, losses can range from one to four ounces per unit for room and unitary systems. Losses due to defective units are estimated to occur in one percent or fewer units, and losses in charging may contribute a similar amount. Thus, for manufacturers using R-22 as a test gas (believed to be the majority), the refrigerant lost could range from 1.5 to 5.0 ounces per unit shipped. Including units exported, this could amount to 200,000 pounds annually for room air conditioners, and about 600,000 pound for unitary systems (allowing credit for those units that are tested using He instead of R-22).

Annual refrigerant losses contributed by leakage and servicing can be estimated by considering product lifetimes and industry experience in servicing and replacing such units. Manufacturers' estimates of air conditioner lifetimes range from ten to 14 years; however, several service organizations gave estimates of actual lifetimes of seven to ten years, with ten being considered a reasonable number for a unit that had been regularly maintained. We will use ten years as a rough average. A number of service representatives stated that, within this period, a typical unit (either unitary or room) might require one complete recharge due mainly to major component replacement, or one or more partial recharges due to gradual leakage. One manufacturer judged leakage losses at 50 percent of servicing losses, and all service organizations judged leakage to be less of a problem than servicing losses due to major component replacement. Therefore, to estimate total leakage and service-related losses, we assumed total emissions during the lifetime of a room or unitary air conditioner to be equal to 1.5 times the initial charge, spread out over a ten-year lifetime, and allocated 33 percent to leakage and 67 percent to servicing losses.

We estimate 1980 service-related emissions for room air conditioners by assuming 26 million units in service in 1970, rising to 38 million in 1975 and about 48 million in 1980 (Bureau of the Census, 1979). Thus, total annual emissions would be ten million pounds. Of this, 3.3 million would be from leakage, and 6.7 from servicing losses. These emissions should increase, given the significantly higher number of newer units that will eventually require servicing.

Census data for 1970 and recent estimates for 1980 put the number of unitary air conditioners in service in 1970 at about ten million. By 1980, 14 million units (11 million residential and three million commercial) were in service. Again, using an average based on ten-year lifetimes, total annual emissions would be 10.5 to 13 million pounds, with 3.5 to 4.4 million pounds due to leakage, and 7.0 to 8.8 million pounds from servicing emissions. The figures for both room and unitary air conditioners are significantly higher than numbers obtained from
one manufacturer. However, we will use these higher figures to provide us with a conservative estimate for our total emissions estimates.

Disposal losses can be estimated for room air conditioners by using an estimated lifetime of about ten years, and shipment figures for 1970 of about 5.4 million units (Bureau of the Census data). Thus, on the average, this many units would be expected to wear out at about this time. However, figures for 1978 indicate that closer to two million units were actually purchased as replacements (according to AHAM and Bureau of the Census, 1979) Although the latter figure appears to be a more justifiable estimate for actual numbers replaced, some older units were probably never replaced; some were probably stored, and others disposed of. We will assume that between three and four million units were disposed of. Since industry information indicates that more than half of all replacements result from major component failure rather than from gross leakage, we estimate that 50 to 60 percent of all charge would still remain in units at disposal. Thus, 1980 disposals might account for 2.0 to 3.3 million pounds of R-22 for room air conditioners.

For unitary systems, ARRI estimates annual replacement at 435,000 units in 1980. Again, if the average charge remaining at disposal is 50 to 60 percent, this represents maximum emissions of 1.0 to 1.6 million pounds of R-22. For both room and unitary air conditioners, disposal figures would increase as more units reach replacement age. Note that these numbers have a larger time lag in response to changes in market conditions than do service-related emissions, since disposal occurs later in the lifetime of the unit and reflects purchases made many years in the past. Thus disposal figures represent market conditions roughly twice as old as service emissions do.

Total emissions for all categories appear in Table 7.11. As seen there, disposal-, service-, and leakage-related emissions dominate the figures, with disposal emissions becoming somewhat more important as time lags become less important. In comparing these figures to those in the previous Rand study for other use categories, it is evident that these systems contribute only a small portion of total CFC emissions (no more than seven percent using our assumptions, and perhaps five percent or less). Furthermore, due to the relatively small ozone depletion factor for R-22, the equivalent ozone depletion effect is essentially negligible.

Table 7.11

<table>
<thead>
<tr>
<th>Emissions Source</th>
<th>Room</th>
<th>Unitary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing/testing</td>
<td>0.20</td>
<td>0.60</td>
</tr>
<tr>
<td>Leakage</td>
<td>3.3</td>
<td>3.5-4.4</td>
</tr>
<tr>
<td>Servicing</td>
<td>6.7</td>
<td>7-8.8</td>
</tr>
<tr>
<td>Disposal</td>
<td>2-3.3</td>
<td>1-1.6</td>
</tr>
<tr>
<td>Total</td>
<td>12.2-13.5</td>
<td>12.1-15.4</td>
</tr>
</tbody>
</table>
EMISSIONS REDUCTION OPTIONS

In considering emissions reduction options, certainly, the following factors emerge. First, regardless of refrigerant used, room and unitary air conditioners account for only a small fraction of total CPC emissions. In addition, since R-22, with its low ozone depletion factor, is used almost exclusively as the refrigerant, this contribution is reduced even further.

Second, if additional emissions reductions are desirable, recovery during servicing (mainly during compressor replacement), and recovery at disposal appear to be among the most productive steps, to reduce total emissions. A system such as the Draf device, as discussed earlier, might be useful. However, considering the system cost and labor required (possibly 15 to 30 minutes per use), such a device would not be economically justified for either room air conditioners or unitary air conditioners.

We can estimate, using 1980 figures, the emissions reduction potential of these two options. In each case we assume 50 percent efficiency of recovery. For servicing, we also assume that in two-thirds of the service jobs that result in emissions (mainly from major component replacement), recovery would be possible. Thus, approximately 3.8 million pounds of R-22 annually might be recoverable from room air conditioners, and four to five million pounds from unitary systems. For disposal, we assume that 50 to 60 percent of charge still remains. This results in an ultimate potential recovery of 1.7 to 2.8 million pounds of R-22 per year from room air conditioners and 0.9 to 1.4 from unitary air conditioners. However, it could be quite difficult to actually attain reductions of this size, because of the difficulty of physically obtaining the disposed of units, specifically room units.

Third, because leakage is another major source of emissions, designing to reduce leakage could produce relatively large reductions in emissions. However, there are complicating factors. For example, in the case of room units, user abuse sometimes contributes to damage-related leakage. In split-system unitary units, the relatively long lines from the external to internal subsystems are also potential sources of leakage. It is believed, however, that as much as a 25 to 30 percent reduction in leakage might ultimately be realized at moderate effort by manufacturers, and with additional efforts by service personnel to assure minimal leakage from repaired units. This would translate to emissions reductions of up to one million pounds of R-22 per year for room systems, and 1.0 to 1.3 million pounds per year for unitary systems.

Another option would be to use helium in leak testing. This might be economically feasible for only the largest manufacturers; however, since five manufacturers control about 50 percent of the market, the effect would be noticeable. The effect on total emissions would be very slight, though, due to the small contribution of manufacturing emissions to the total, with perhaps 0.1 million and 0.4 million pounds of R-22 saved per year for room and unitary systems, respectively.

Finally, little work has been done to date on alternative refrigerants and there is little incentive to do so, since R-22 has such a low ozone depletion factor. Therefore, that option is not considered realistic at the moment. In any case, none of the above options would have a noticeable impact in comparison to the mobile air conditioner and chiller categories, due to this low factor. Thus, we consider that the greatest benefits would result from first implementing the most desirable options for these other use categories.
V. Conclusions

On the basis of the preceding discussion, we can enumerate the following conclusions concerning air conditioning systems. First, mobile air conditioners contribute the most to total CFC emissions, both on an absolute scale, and considering the equivalent ozone depletion effect. However, some of the emissions reduction options having the greatest potential effect, namely refrigerant substitution and recovery at servicing and disposal, do not appear feasible at the present. Other options, such as continuing the current trends in reducing initial charges, as well as improvements in servicing techniques and designs to reduce leakage, appear better approaches for further consideration.

Chiller systems rank second in effective ozone depletion effects, although below room and unitary systems in terms of total emissions. The largest potential reduction in ozone depletion effect, obtained by a conversion to R-22 for all chillers, would also be the least feasible and we do not consider it a viable option at this time. However, each of the remaining six options identified in Sec. I of this chapter would be potential candidates for future implementation, although their impact would be less.

Finally, the effect of room and unitary air conditioner emissions is quite small, because of the 0.05 ozone depletion factor of R-22. Since one potential option for chillers and mobile air conditioners is a switch to R-22, a change from R-22 does not seem realistic for room and unitary systems. Furthermore, all other options for these systems would be at least moderately difficult to implement, with very small potential benefits. Therefore, emissions reduction options for these systems do not appear to have significant benefit at this time.
Chapter 8

CHLOROFLUOROCARBON DISTRIBUTION SYSTEMS

I. Introduction and Summary

The distribution of chlorofluorocarbons from manufacturer to consumer involves a number of physical transfers. These transfers can result in CFC emissions and therefore were a subject of inquiry in this study. In addition, this chapter provides some general information about parts of the distribution system, which should be useful to designers of marketable permits.¹

Generally, emissions in the distribution system are low. Wolf (1980) estimated emissions to be two percent of the CFC manufactured each year, and in the present study we found them to vary from one-half percent or less in typical bulk transfers to about four percent in the filling of small containers. There was always a strong economic motivation to minimize emissions, the motto being "that which is emitted can't be sold." This incentive was observed everywhere and is the reason for the low emission rate.

We found no reason to disagree with the previous estimate of two percent emissions, although we recognize that it is virtually impossible to substantiate that estimate industry-wide. The previous study offered no options for emissions reduction in the distribution system, and this study also offers none. Adequate incentives already exist to minimize emissions, and cost-conscious handlers of CFC act accordingly.

The remainder of this chapter describes CFC handling and presents general information about the distribution system.

¹Distribution system emissions are defined as those occurring during movement of CFC from the manufacturer to the consumer. These do not include emissions from the manufacturer of CFC, which were discussed in a previous Rand study (Wolf, 1980).
II. Distribution System Emissions

After chlorofluorocarbons are manufactured, they are distributed by various means to customers who use them as industrial solvents, as refrigeration fluids, as blowing agents in the manufacture of plastic foams, and in a variety of miscellaneous uses. Wolf (1980) estimated roughly that CFC losses in the distribution system averaged two percent; however, no real investigation of these losses was made because of their small size. Further, the distribution system itself was not analyzed to determine whether different systems were employed for different CFCs or whether all product areas shared the same system. If different distribution systems are used, either for each using product area or for each type of CFC, then the emissions characteristics of the various distribution systems might differ. And, emissions might be reduced by transferring some of the efficient practices of the best distribution systems to other systems.

Emissions occurring during the distribution of CFCs from the manufacturer to the consumer can be classified into three categories:

1. Emissions resulting from the loading and unloading of bulk shipments of CFCs;
2. Emissions resulting from packaging CFCs in pressure-tight containers;
3. Emissions resulting from packaging CFCs in non-pressure-tight containers.

The first category is straightforward and includes the shipment by rail or truck of quantities usually over 10,000 pounds. Shipments include those made from the manufacturer directly to the consumer, to a bulk distribution plant, to another manufacturing facility (where the CFCs might be blended or packaged), or to a distributor; these shipments also include those from a bulk distribution plant to any of the above destinations.

The second category involves CFCs that are close to or above their boiling points at ambient temperatures. The CFCs packaged this way include CFC-11, CFC-12, CFC-22, and other CFCs, such as CFC-502, that are used for refrigeration applications. The packaging of these materials is done either by the CFC manufacturer or by companies that specialize in rehousing. The packaging operation itself is usually run under pressure and the containers used are pressure-tight.

The third category almost solely concerns CFC-113 used as a solvent. The boiling point of CFC-113 allows it to be handled like other conventional solvents; in particular, bulk quantities can be rehandled in ordinary five gallon pails and 55 gallon drums. These containers are closed but not pressure-tight, and the filling process does not use sealed and pressure-tight hose and fittings. CFC-113 is rehandled by distributors who specialize in either chemicals, cleaning solvents and chemicals, or the manufacture of cleaning equipment, such as vapor degreasers or ultrasonic cleaners.

These three categories include all product areas; consequently, analysis of the practices in each category covers the emissions from the entire distribution system.

In general, the CFC distribution system links a seller of CFC and a buyer of CFC. Obviously, minimizing emissions losses has a direct economic impact on the seller. Not surprisingly, we found that the transfer of CFC from one place to another, and from one container to another, was generally effected with carefully designed equipment and by trained people who consciously acted to minimize losses. Most of the people we contacted knew their loss rates, since they habitually made material balances to keep a check on lost profits. Because of the
nature of CFC distribution, work practices and improved equipment design are the only means of affecting emissions.

BULK DISTRIBUTION SYSTEMS

We visited bulk CFC shipping points at three locations operated by three different companies. We also visited many receiving locations, ranging from refrigeration and air conditioning manufacturing installations to flexible and rigid foam manufacturers to systems houses and refrigerant repackagers. In all cases, the equipment used incorporated vapor return lines and pressure-tight connectors, and in some cases a vacuum system was used to empty tank cars of even the residual CFC vapors. Stated losses during the transfer of bulk CFC are below one percent and probably are closer to one-half percent. These losses occur when hose couplings are broken and from residual vapors left in the tank trucks and tank cars even after the container is evacuated by vacuum.

Despite the equipment and care used to minimize losses in bulk handling, even these small losses could probably be further reduced if measures were adopted like those to handle poisonous gases. These measures could be made mandatory, but policing their use would be virtually impossible.

Pressure-Tight Containers

About 280 million pounds of refrigerant CFC per year are sold in pressurized containers. These CFCs are primarily CFC-12 and CFC-22, and virtually all of these are destined for refrigerator and air conditioner servicing. About three-quarters of this amount is packaged by the CFC manufacturers; the remainder is repackaged by independent companies who buy bulk CFC from the manufacturers. One source estimated that there are only eight to ten independent repackagers in the country.

Emissions during repackaging into small containers can be a serious economic problem, and consequently the equipment used has become fairly sophisticated. Whereas emissions losses in bulk handling of CFCs were due primarily to coupling and uncoupling the transfer lines, and were very small, exactly the opposite is true in the packaging of refrigerants for the service market. The containers range in size from 12 ounces (“pound” cans) to one ton, and the most popular sizes are 145 pounds or less. Since the connect-disconnect losses must be apportioned to the low weight of the container contents, improper fill system design can lead to high percentage losses. The realities of this situation have led to the design of relatively standard systems that minimize losses. These systems incorporate shutoff valves positioned close to the couplings, and either vapor recovery systems for the displaced gas in refillable containers, or vacuum systems to evacuate new containers before filling. We understand that the transfer losses in the industry probably average about four percent, or about ten million pounds per year. Again, economic pressures are a strong motivation to keep the losses down.

These repackaging losses result almost solely from the equipment that is used, and operator work practices cannot lower the emissions below the capability of the equipment. Nonetheless, two possibilities for reducing emissions exist: One is to adopt even more sophisticated transfer control methods, as was suggested above for bulk transfer; the other is to install emissions collection and recovery equipment similar to that described in Chapter 7.
Non-Pressure-Tight Containers

Probably about 75 percent of CFC-113 is sold through distributors whose customers may buy either in bulk or in 55 gallon drums or five gallon pails. Transfer losses of CFC-113 are not the same as those of refrigerant CFCs because of the relatively low vapor pressure of the liquid at ambient conditions.

Transfers of bulk CFC-113 are made like transfers of other bulk CFCs, that is, using closed systems with vapor return lines. Losses are the same as estimated for other bulk transfers—about one-half percent.

Transfers of CFC-113 to 55 gallon drums or other containers are made without vapor recovery systems, and losses are nominally estimated to be about one percent. In comparison to bulk sales by distributors, sales in drums and smaller containers are relatively small.

ELEMENTS OF THE CFC DISTRIBUTION SYSTEM

We now elaborate on the simple description of the CFC distribution system given above by describing some of the elements of the actual system. CFC-11 and CFC-12 are manufactured by five companies at nine different locations. CFC-113 and CFC-114 are manufactured by two of these same companies at two locations, and CFC-22 is made by the five companies at eight locations.

Shipments of bulk CFC from the manufacturing plants are first made intra-company and inter-company, and to independently owned bulk distributors who are tied contractually to their CFC manufacturer. Intra-company bulk shipments include, at a minimum, shipments between a manufacturer's plants, so that the various CFCs are available even from plants that do not manufacture them, and to specific plants that handle the repackaging of bulk CFC into smaller containers. In addition to intra-plant shipments, a manufacturer may maintain a bulk storage and shipping depot that is not near one of his plants. DuPont, for example, has a bulk depot in Pomona, California, which is supplied from the manufacturing locations.

Inter-company shipments are common because only DuPont and Allied manufacture CFC-113 and CFC-114. All five manufacturers sell these CFCs, but of course they purchase from DuPont and Allied, shipping the CFCs from the manufacturer to the buyers' distribution points.

There is at least one independent bulk distributor in the United States: Industrial Hydrocarbons, in San Dimas, California. This company serves the 11 Western states as the bulk distribution point for Kaiser. Their facility is an analog to the DuPont facility in Pomona, but Industrial Hydrocarbons is an independent company.

The next level of bulk distribution is to customers. The first type of customer buys bulk CFC, stores it in bulk, and then uses it in a manufacturing process. The second type buys bulk CFC for resale and packages it into smaller containers. These latter customers are an analog to the repackaging operations of the CFC manufacturers; their repackaged CFCs are sold in competition with those of the manufacturers, principally for automotive air conditioning servicing.

Bulk CFC customers purchase their products in tank truck to tank car amounts, with 10,000 pounds generally being the smallest shipment. As we have discussed, a bulk customer could receive his CFC directly from the plant at which it was manufactured, from a plant at which it was not manufactured, but which is owned by the manufacturing company, or from
a bulk distribution center that could be either owned by the manufacturing company or independently owned.

For bulk customers who use the CFC in manufacturing, the distribution chain is complete at this point. The CFC is used in flexible or rigid foams, air conditioners, refrigerators, or other products which are then sold. In all of these original equipment manufacturer (OEM) applications, the distribution chain is essentially the same.

Packaged CFCs for refrigeration and air conditioning use originate either with the CFC manufacturer or with a repackager. In general, the repackagers restrict their market to automotive air conditioning uses of CFC-12, and therefore packaged CFC other than CFC-12 almost always comes from a CFC producer, and CFC-12 in packages larger than 30 pounds also almost always comes from a CFC producer.

CFC-12, CFC-22, and other refrigeration CFC packages not destined for automotive use then enter the wholesale distribution network through air conditioning/refrigeration wholesalers. These are sources of parts, supplies, and equipment for air conditioning and refrigeration service organizations. We understand that approximately 45,000 individuals belong to the wholesalers' trade association. The wholesalers sell to the service organizations, who in turn sell to the consumer.

Packaged CFC-12 destined for automotive use is supplied either by the CFC manufacturers or the repackagers in 12 ounce containers ("pound cans") or 30 pound cylinders. Its progress to the eventual user is through the automotive aftermarket distribution system. This usually involves sales of large quantities by a manufacturer's representative to warehouse distributors, then sales to automotive jobbers, such as parts houses, etc., further sales to automobile dealers, and finally sales to the customer. Popular automotive parts houses and mail order organizations, such as Sears Roebuck, J. C. Penney, Montgomery Ward, Western Auto Sales, and Pep Boys, may have entirely different arrangements. Arrangements such as these cannot be characterized in generalities. Large organizations typically negotiate proprietary agreements that differ in each case.

Packaged CFC-113 for solvent use usually originates with a large distributor who purchases in bulk, perhaps on an exclusive contract, or from one of the two manufacturers of this product. These distributors may supply their customers in bulk; they may also supply them in 55 gallon drums or smaller containers. The solvent may also be blended with alcohol, methylene chloride, or other solvents to provide proprietary solvents designed for specific applications.

The transfer of title of the CFC may or may not coincide with the physical movement of the material. There are examples of this in several parts of the distribution system. The clearest example is that although there are five CFC manufacturers, it may appear to a bulk CFC purchaser that there are six. The sixth company is Union Carbide, who once manufactured CFCs but then abandoned the business. However, they kept many of their customers, who still purchase from them. Union Carbide sells DuPont CFC under an agreement between them, and deliveries are made from DuPont bulk shipping points.

Another example is the delivery of bulk CFC-12 to a ship for servicing large scale refrigeration systems. The title passes through a wholesaler, but the CFC may be shipped directly from a bulk shipping point to the ship. This is an example of title to CFC without possession.

A third example involves repackaging for automotive use. We know of one repackager who fills containers on contract for a national company. The CFC-12 is apparently purchased by the national company but is delivered to the packager for canning. It is unclear whether the packager then ships to the national company or to his customers, but the procedure is an example of possession of the CFC without title.
In summary, there is no clear-cut option for reducing emissions in the distribution chain. In addition, losses are so diffuse that enforcement issues would be enormous, should an option be devised.

With regard to CFC physical movement and title transfer, many aspects are straightforward and simple. Others are quite complex and involve numerous intermediate steps between producer and consumer.
Chapter 9

CHEMICAL INTERMEDIATE USES OF CHLOROFLUOROCARBONS

I. Introduction and Summary

A great variety of chemical products, many of them medium and high molecular weight polymers, can be made from chlorofluorocarbons (CFCs). The end-products that are made include elastomers, anesthetics, thermoplastic resins, bearing materials, high-temperature oils, plastic films, fire retardants, dielectrics, and packing materials. In these uses, certain CFCs may be categorized as chemical intermediates. By far the most important use of CFC as a chemical intermediate is in the annual chemical conversion of CFC-22 into 60 million pounds of polymerized tetrafluoroethylene (e.g. DuPont's Teflon™), one of the major uses for CFC-22 at the present time. Other products synthesized from CFC-22 include hexafluoropropylene (used to make fluoroelastomer) and the anesthetic Forane™. 2.2 million pounds of CFC-113 are used to produce polychlorotrifluoroethylene oils, greases, and waxes, as well as the fire retardant 1113. CFC-114 is used to make CFC-115 and FC-116. Vinylidene fluoride is made from CFC-142b.

To a lesser degree, the fluorocarbons FC-23 and FC-152a are also used as chemical intermediates. Vinyl fluoride is made from FC-152a and FC-23 is used to synthesize the fire fighter FC-13B1. CFC-11 and CFC-12 are apparently not used at all as intermediates in the manufacture of other chemicals (although CFC-12 is blended with FC-152a to make the azeotrope CFC-500). Manufacturers of these products have indicated that all the reactions are carried out in enclosed systems from which extremely small quantities of CFCs are emitted. Therefore no significant emission reduction schemes have been identified.

1™ identifies trade name products of the various companies referred to in the text.
II. Emission Control and Work Practices

Industry sources state that all the chemical reactions of the type discussed here are carried out in closed systems under carefully controlled conditions, and that only negligible to very small quantities of gaseous CFCs are released to the atmosphere. The emissions are so low because the major use of CFCs as intermediates involves their efficient conversion to long-chain polymers having virtually no tendency to decompose and emit their CFC monomeric units to the atmosphere. In those minor applications where there is some tendency for a gaseous CFC reactant to escape a reaction chamber, the equipment is designed to recycle the CFC back to the chamber. If a CFC (as an intermediate) is not used at the same plant where it is manufactured, then emissions could occur during transportation. (These emissions are discussed in Chapter 8.)
III. Intermediate Uses of the Chlorofluorocarbon Series

INTERMEDIATE USE OF CFC-22

A major application of CFC-22 is in its chemical conversion to the monomer tetrafluoroethylene (TFE), followed by polymerization to fluoropolymers (poly-TFE). The final products are non-volatile polymers from which CFCs are not regenerated:

\[
2 \text{CHClF}_2 \rightarrow \text{CF}_2\text{CF}_2 + 2 \text{HCl} \quad \text{(CFC-22)}
\]

\[
\text{polymerized} \quad \text{CF}_2\text{CF}_2 \rightarrow \text{poly-TFE} \quad \text{(TFE)}
\]

In this chemical conversion, 1.73 pounds of CFC-22 are needed to make 1.00 pound of product. According to DuPont, in 1979 approximately 60 million pounds of CFC-22 were used in this application—roughly seven percent of total domestic CFC production. The physical and chemical properties of poly-TFE products vary according to their molecular weight and physical form.

DuPont’s fluoropolymers made from CFC-22 include the following products:

- Teflon™ resins, film and tubing, heat transfer products, FEP-coated Kapton™ film, nonstick finishes, and fibers
- Tefzel™ film and resins
- Kairez™ perfluoroelastomers
- Nafig™ products
- Viton™ fluoroclastomers
- Armalan™ felts and fabrics
- Dulite™ finishes
- Silverstone™ nonstick finishes
- Zepeit™ fabric fluoridizer
- Zonyl™ fluorochemical surfactants
- Krytox™ oils and greases
- Vydax™ fluorocarbon telomers

Another monomer made from CFC-22 is hexafluoropropylene. This is polymerized with vinylidene fluoride to make DuPont’s Viton™ Series A fluoroclastomers, or with both vinylidene fluoride and TFE to make the Viton™ Series B fluoroclastomers. These polymers are used in gaskets and sealing devices. Allied Corporation’s brand of poly-TFE made from CFC-22 is called Halon TFE™.

CFC-22 is also used as a chemical intermediate to make an anesthetic called Forane™ (CF₃CHCLOCHF₂).
INTERMEDIATE USE OF CFC-113

Between three and four percent of CFC-113 production (2.2 million pounds in 1976) goes into the manufacture of polymerized chlorotrifluoroethylene (poly-CTFE).

\[
\begin{align*}
\text{CFC-113} & \xrightarrow{\text{polymerized}} \text{CTFE} \\
\text{CF}_2\text{FCCF}_1 & \xrightarrow{\text{polymerized}} (\text{CF}_2\text{FCCF}_1)_n
\end{align*}
\]

In this conversion, 1.61 pounds of CFC-113 are needed to make 1.00 pound of poly-CTFE. Halocarbon Products Corporation of Hackensack, New Jersey, produces a line of Halocarbon™ oils, greases, and waxes for use as lubricants, hydraulic fluids, and the like, in applications where inertness and high thermal stability are needed. Allied Corporation’s brand of poly-CTFE is called Halar™.

CFC-113 is also used to make 1113, a fire retardant, and Ethrane™, an anesthetic (Ohio Medical Products Division).

INTERMEDIATE USE OF CFC-114

The only intermediate chemical use of CFC-114 uncovered during this study is in the production of CFC-115.

\[
\begin{align*}
\text{CFC-114} & \xrightarrow{\text{polymerized}} \text{CTFE} \\
\text{CCF}_2\text{CCF}_2 + \text{HF} & \rightarrow \text{CCF}_2\text{CCF}_3 + \text{HCl}
\end{align*}
\]

In this conversion, 1.18 pounds of CFC-114 are needed to make 1.00 pound of CFC-115.

CFC-115 finds its principal application in preparing the azetropes CFC-502, a refrigerant having the composition 51.2 percent CFC-115 and 48.8 percent CFC-22.

CFC-115 is also used as a chemical intermediate in producing FC-116, a dielectric material.

\[
\begin{align*}
\text{CFC-115} & \xrightarrow{\text{polymerized}} \text{CTFE} \\
\text{CCF}_2\text{CF}_2 + \text{HF} & \rightarrow \text{CF}_2\text{CHCl} + \text{HCl}
\end{align*}
\]

In this reaction 1.05 pounds of CFC-115 are required per pound of FC-116 produced.

INTERMEDIATE USE OF CFC-133a

The anesthetic Fluothane™ is said to be made abroad, but not in the United States, using CFC-133a:

\[
\begin{align*}
\text{CFC-133a} & \xrightarrow{\text{polymerized}} \text{CTFE} \\
\text{CF}_2\text{CHCl} + \text{Br}_2 & \rightarrow \text{CF}_2\text{CHClBr} + \text{HBr}
\end{align*}
\]

According to DuPont, further in-house work on CFC-133a has been terminated as a consequence of adverse toxicological findings.
INTERMEDIATE USE OF CFC-142b

CFC-142b is used to make vinylidene fluoride which is then polymerized to make polyvinylidene fluoride, marketed by Pennwalt Corporation under the trade name Kynar™. Vinylidene fluoride is also copolymerized with hexafluoropropylene or with hexafluoropropylene and TFE to make DuPont’s Viton™ Series A and Series B fluoroclastomers, respectively.

\[ \text{CH}_3\text{CClF}_2 \rightarrow \text{CH}_2\text{CF}_2 + \text{HCl} \]
(CFC-142b) (vinylidene fluoride)

In this conversion, 1.57 pounds of CFC-142b are required to make 1.00 pound of vinylidene fluoride monomer or polymer.

INTERMEDIATE USE OF FC-23

FC-23, a minor by-product of CFC-22 manufacture, is used to make FC-13B1 (also designated as Halon 1301™) by bromination.

\[ \text{CHF}_3 + \text{Br}_2 \rightarrow \text{CF}_2\text{Br} + \text{HBr} \]
(FC-23) (FC-13B1)

FC-13B1 is used as a fire fighter. It is made by Fenwal, Inc., a division of Kidde, Inc., Ashland, Massachusetts. In this conversion, 0.47 pound of FC-23 is required per pound of FC-13B1 produced.

INTERMEDIATE USE OF FC-152a

FC-152a is used to make vinyl fluoride which is then polymerized to polyvinyl fluoride products, such as DuPont’s Tedlar™, a PVF film.

\[ \text{CHF}_2\text{CH}_3 \rightarrow \text{CH}_2\text{CHF} + \text{HF} \]
(FC-152a) (vinyl fluoride)

In this conversion, 1.43 pounds of FC-152a are required per pound of vinyl fluoride monomer or polymer produced.
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