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TECHNOLOGY TRENDS IN CFC AND HALONS REPLACEMENT

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INTRODUCTION

Chlorofluorocarbons¹ (CFCs) were introduced to the world at a meeting of the American Chemical Society in 1930 by Thomas Midgley Jr., head of a team of scientists at the General Motors corporate research laboratory. Although invented to serve the residential refrigerator market, CFCs were first applied in the commercial sector, where Frigidaire (a subsidiary of General Motors) used CFC-12 in ice cream cabinets. Du Pont scientists did much of the early work on CFCs in the 1930's, and it is their numbering system which became the standard for designating different compounds. Since that time, these compounds which are relatively chemically inert and have generally low toxicity have found uses in a wide variety of applications, ranging from refrigeration to use in foam blowing to aerosol propellants.

In the mid 1970's these previously heralded chemicals suddenly became a source of environmental concern. A few years earlier, electron capture gas chromatography measurements started to show that CFCs are present in the lower atmosphere at parts per trillion levels, revealing for the first time that these compounds were accumulating in the atmosphere. The alarm was first sounded in 1974 when Mario Molina and Sherwood Rowland of the University of California at Irvine published an article in *Nature* magazine. The article proposed that several CFCs used around the world can slowly reach the upper atmosphere where radiation from the sun can release reactive chlorine atoms from these molecules. These scientists theorized that these chlorine atoms could then cause a reduction of stratospheric ozone through a series of rapid chemical reactions in which the chlorine atoms are continually regenerated. Such reductions are of concern because stratospheric ozone is known to screen out large amounts of harmful ultraviolet solar radiation before it reaches the earth.

The unusual combination of characteristics of CFC's and halons that these scientists identified include the special ability of these compounds to remain in the lower atmosphere unchanged for years, combined with a reactivity in sunlight reaching the stratosphere--a reactivity yielding highly reactive fragments in the stratosphere, each of which can destroy thousands of protective ozone molecules present there.

By 1978, concern over this stratospheric ozone depletion theory lead several countries, including the United States, Canada, Sweden and Norway, to ban all but essential uses of CFCs in aerosols. Starting in 1979 the United Nations Environment Programme (UNEP) convened a Coordinating

¹ The term 'chlorofluorocarbons' refers to chlorofluoroalkanes (i.e. compounds consisting exclusively of carbon, chlorine, and fluorine. Compounds consisting of these elements plus bromine are referred to as 'halons'. The numbers assigned to CFCs and halons (and related compounds discussed later) reflect the number of each type of atom.

Committee on the Ozone Layer which met at least biennially and published a series of scientific assessments (Pooi, 1988; Jones 1988; Moore, 1989). These activities, along with accumulating scientific data supporting the theory of Molina and Rowland, have culminated in the UNEP Vienna Convention for the Protection of the Ozone Layer in March 1985. Subsequently the Montreal Protocol on Substances that Deplete the Ozone Layer was signed on September 16, 1987 and entered into force on January 1, 1989. To date 51 countries and the European community have signed and/or ratified the Protocol (see Table 1 below).

Table 1. Parties which have approved the Montreal Protocol or indicated they intend to do so.

Argentina*	Finland	Luxembourg	Sri Lanka*
Australia	France	Malaysia*	Sweden
Austria	German Dem. Rep.	Maldives*	Switzerland
Belgium	Germany, FR	Malta*	Syria*
Burkina Faso*	Ghana*	Mexico*	Thailand*
Byelorussian SSR	Greece	Morocco*	Togo*
Cameroon*	Guatemala*	Netherlands	Trinidad and
Canada	Hungary	New Zealand	Tobago*
Chad*	Iceland	Nigeria*	Tunisia*
Chile*	Indonesia*	Norway	Uganda*
China*	Ireland	Panama*	Ukrainian SSR
Congo	Israel	Peru*	USSR
Denmark	Italy	Philippines*	U.K.
EEC	Japan	Portugal	U.S.A.
Egypt	Jordan*	Senegai*	Uruguay*
Equatorial Guinea*	Kenya*	Singapore*	Venezuela
Fiji*	Liechtenstein	Spain	

*Developing nations.

Source: UNEP communication, February 2, 1990.

The Montreal Protocol sets up a schedule for reducing global consumption (and as a consequence, global emissions) of five CFCs and three halons (chlorofluorocarbons also containing bromine atoms). The schedule calls for a freeze in consumption (defined as production plus imports minus exports) at 1986 levels of CFC-11, -12, -113, -114 and -115 beginning July 1, 1989. The freeze on halon-1211, -1301 and -2402 consumption is to begin on January 1, 1992. Beginning July 1, 1993 global consumption of the CFCs is to be reduced by 20 percent, followed by an additional 30 percent reduction beginning July 1, 1998. In addition, the Protocol makes provisions for

reassessing the schedule by periodically reviewing available scientific, environmental, technical and economic information (Montreal Protocol, articles 2,6).

During the same time period that the Montreal Protocol was being negotiated, new evidence of ozone depletion was being reported. In 1985 a group of British scientists published a study reporting significant and unexpected ozone decreases over the Antarctic Continent (an "Arctic hole") each Spring since the mid to late 1970s. There were also preliminary reports, based on measurements by a satellite instrument, that global ozone amounts were decreasing at the rate of about 1 percent per year. These reports led the U.S. National Aeronautics and Space Administration (NASA) to organize the International Ozone Trends Panel to assess ozone data. The Panel's findings, announced in March 1988, raised serious questions about whether the restrictions on CFCs in the Montreal Protocol were adequate to protect stratospheric ozone (McFarland, 1989).

The next meeting of the Montreal Protocol Parties will be held on June 20-29, 1990 in London. Revisions to strengthen the Protocol have been proposed, including: complete phase-out of production and consumption of all fully halogenated CFCs, methyl chloroform, and carbon tetrachloride by January 1, 2000; control of other ozone-depleting substances with an ozone depletion potential (ODP) greater than .01; and the phase-out of production and use of halons (target date to be decided) (UNEP, 1989f)

In addition to their effects on the ozone, CFCs are believed to be responsible for about one fifth of projected global warming. Greenhouse gases other than CFCs include Carbon Dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and tropospheric ozone (O₃). Global warming is being addressed by the Intergovernmental Panel on Climate Change. The Second World Climate Conference will be held in November 1990 and may provide further impetus for CFC replacement (Noordwijk Declaration, 1989).

Thus, there is an ever increasing world-wide consensus that such CFCs and halons be phased out of use as fast as possible. Correspondingly, there is a strong need for appropriate substitutes for these chemicals as they are removed from use. This paper summarizes the status of development of substitutes for CFC and halon to the extent reported in the open literature. As there has been a large and growing market for CFCs and halons, there is likely much research on substitutes that can not be discerned from publicly available documents, and therefore, is not described below.

CFCs, HALONS, AND THEIR USES

CFCs and halons have a special combination of chemical and physical properties, including low chemical reactivity, low toxicity, good organic solvent properties, and a boiling point near room temperature. Moreover, CFCs can be produced with simple chemical reactions and manufactured with high purity, so they are relatively easy to make cheaply in industrial quantities. Therefore, it is not surprising that the use of CFCs has become so pervasive. In 1986, an estimated 1,140,000 tons of CFCs were used worldwide. They are used as blowing agents for foams, refrigerant fluids, solvents, propellants in aerosols, and sterilants (see Figures 1 and 2). Halons are used to a much lesser extent in a few specialized applications.

REFRIGERANTS

CFCs act as the "working fluid" in refrigerators, freezers, air conditioners, and heat pumps. The coils and compressors of these systems transfer heat by compressing and decompressing these compounds to raise and lower their temperature. All of the controlled CFCs, except CFC 113, are used as refrigerant fluids; halon 1301 is also used to a very limited extent in retail refrigeration. Use within the refrigeration sector can be further broken down:

- domestic refrigeration: small refrigerators and freezers generally used in the home which have the highest requirement for reliability and energy efficiency;
- retail refrigeration: large units like those found in grocery stores;
- transport refrigeration: refrigerated cargo and container ships (most of these already use HCFC-22), refrigerated road vehicles, and refrigerated containers;
- commercial cold storage/food processing: warehouses for storing or processing, and distributing meat and other perishables; and
- industrial refrigeration: largely used in petrochemical and refinery applications and for processing and storing volatile liquids or compressed gases (UNEP, 1989g).

Within the air conditioning sector it is the very large chilled water systems, which are mainly centrifugal compressor driven, and mobile air conditioning used in passenger vehicle which use the greatest quantity of CFCs. Earlier in the century, CFCs were hailed as safe replacements for systems that used sulfur dioxide or ammonia as the working fluid. This low toxicity combined with low chemical reactivity and ideal boiling point have made certain CFCs the chemicals of choice for compressor based refrigeration and heating systems.

1986 Global Consumption of CFCs

Figure 1. By Use Category

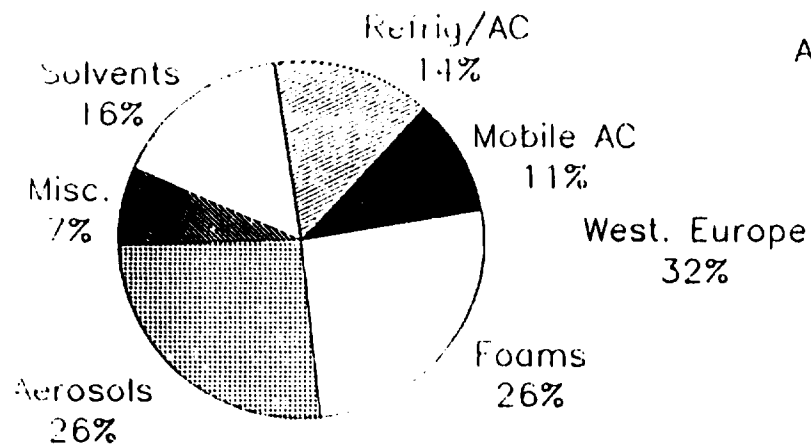
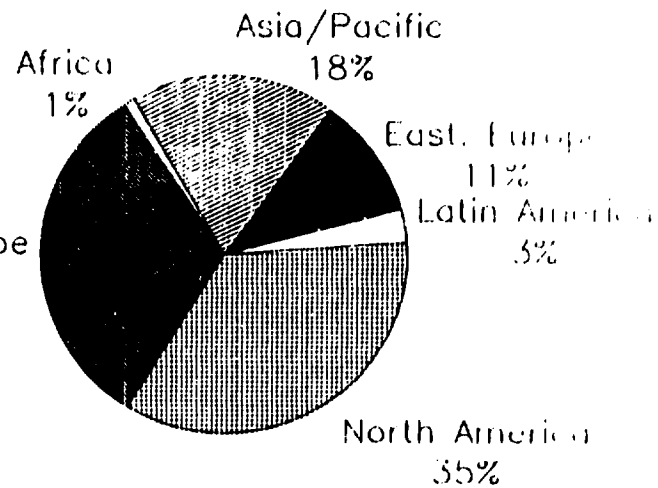


Figure 2. By Region



Source: UNEP, 1989g

FOAM BLOWING

Of all of the sectors using CFCs, the most varied use is in the foam sector where CFCs are used as blowing agents (see Figure 3). The CFC introduced into the liquid plastic forms bubbles and as the plastic solidifies, a cellular foam structure is formed. In some foams the cells are closed, trapping the gas inside (which adds to their insulating capacity), while others are open-celled, releasing the gas. CFCs have the following important properties that make them ideal for use as blowing agents:

- they do not react with the plastic;
- they are sufficiently soluble in liquid plastic, but
- insoluble in the solid plastic; and
- most are easily handled as liquids, which are more convenient to handle than gases.

The many specific types of foam can be grouped into three broad categories: flexible polyurethane, rigid polyurethane, and rigid non-polyurethane. Flexible polyurethane foam is used as a cushioning material. The manufacture of flexible foam uses only CFC-11, all of which is released during the production of the foam. Rigid polyurethane foam is produced with CFC-11 and CFC-12. It has three applications: refrigeration and appliance insulation, building insulation, and packaging. Rigid non-polyurethane foam is made with CFC-12 and CFC-114 and used in both commercial and residential applications. Its uses include packaging for food containers, cushion packaging, and safety and athletic equipment (UNEP, 1989d).

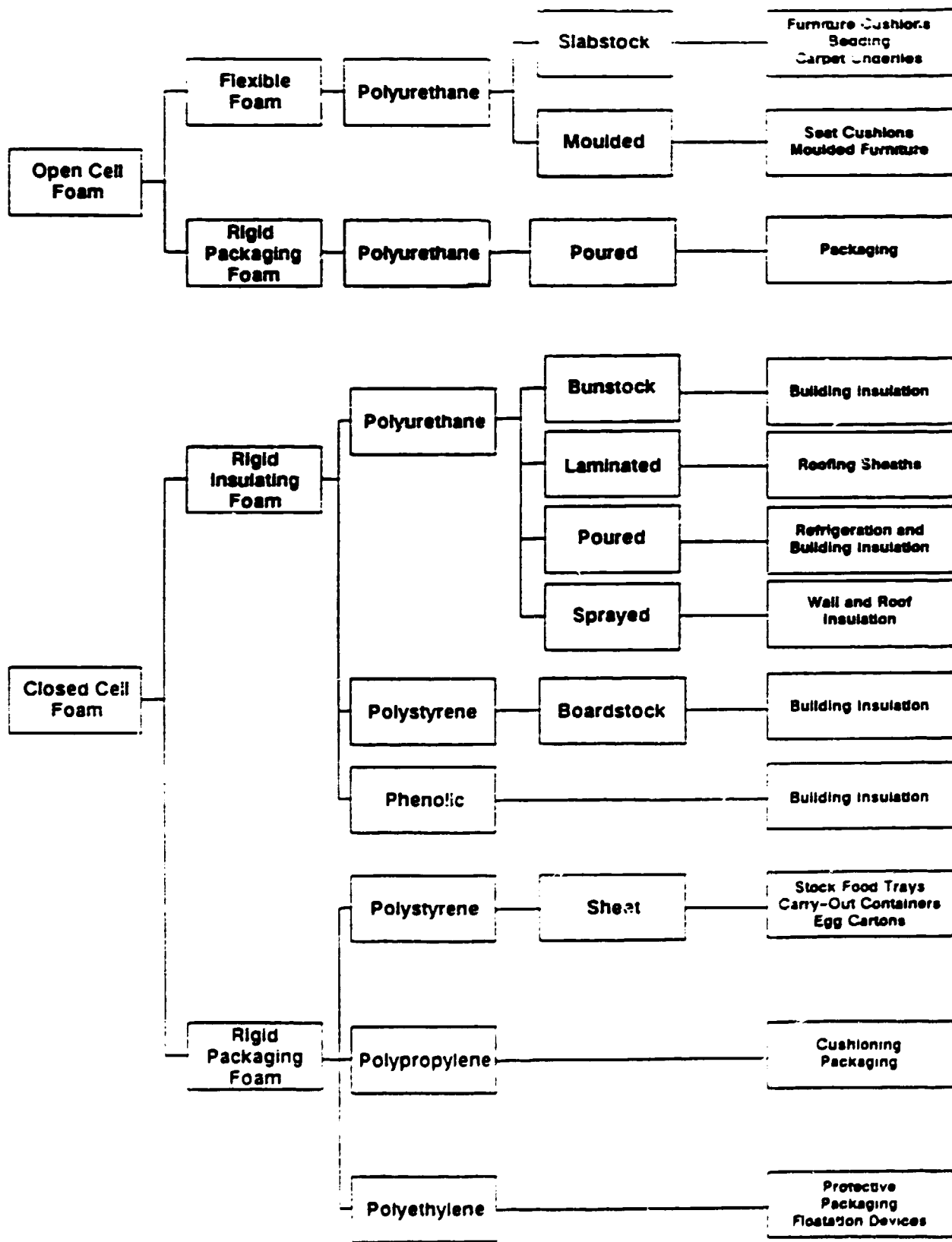
SOLVENTS

CFCs have the ability to perform well as organic solvents and then to evaporate leaving no residue. Therefore, they have received wide use in solvent applications requiring these properties, such as cold cleaning processes (for electronics and precision cleaning) using CFCs at room temperatures and items immersed, sprayed, or wiped with solvent at elevated temperatures. For example, in the vapor degreasing process, items (e.g. precision metal parts) are suspended over a bath of hot solvent, and the condensing vapor dissolves grease and removes it when the solvent drips off, leaving behind a clean metal surface. A small amount of CFC-113 has also been used in dry cleaning fabrics (UNEP, 1989c).

AEROSOL PROPELLANTS

Although several countries banned the nonessential uses of CFCs in aerosols in the late 1970's and 1980's, most nations still use CFCs in aerosols, and consequently global CFC use in aerosol applications remains significant. CFC 11 and 12 are the most commonly used CFCs in aerosols, followed by CFC 113 and 114 for specialized purposes. Their use in aerosols takes advantage of the boiling point of these solvents, their lack of smell, their low chemical reactivity, their non-

Figure 3. Types and Major Uses of CFC-Blown Foam



flammability, and low toxicity. In addition to their use as propellants, they can also be used as a solvent in an aerosol when the product itself requires dissolving. In addition, CFCs can be the active ingredient when used in sprays to provide a chilling effect or remove dust, or when used in fog horns, for example, to make noise (UNEP, 1989a).

STERILANTS

There are a variety of other applications that use a small quantity of CFCs 11 and 12. One of the larger such uses of CFC-12 is as a diluent for ethylene oxide (EO) in hospital and industrial sterilization equipment. Other miscellaneous uses include fumigation, leak detection, and thermostats and thermometers (UNEP, 1989a)

HALONS

The halon compounds controlled under the Montreal Protocol are used almost exclusively as fire extinguishers. Halons are used because they are highly effective, liberating bromine atoms that react with combustion products to extinguish a fire, leave no residue, and cause little, if any, secondary fire damage. In addition they pose little toxic threat to users and fire response personnel. Halon 1301 is nearly always used in automatic fire suppression systems, usually in total-flood applications. Halon 1211 is generally used in streaming systems such as the portable fire extinguishers found in many homes and businesses (Tapscott and Floden, 1989-90). Halon 2402 is used in streaming systems, but its use is in very limited quantities worldwide. (UNEP, 1989e). Halons represent a relatively small part of the total emissions of ozone depleting chemicals, but they are of major concern because their use is increasing rapidly and they are more destructive to the ozone than CFCs (Tapscott and Floden, 1989).

ISSUES ASSOCIATED WITH REPLACING CFCs AND HALONS

The adequacy of any chemical to substitute for a CFC or halon is not determined by its having identical chemical and physical properties. Rather, it is determined by meeting the functions being served by the CFC or halon at a competitive cost, with no unreasonable side-effects (e.g. toxicity, flammability, or ozone depletion capability).

The ideal replacements for CFCs and halons would be chemicals with identical properties, at the same or lower cost to produce, and with few side effects. If such chemicals were available, there would be little need for this paper, as market forces would cause widespread substitution. However, as they do not exist at this time, there is a need to discuss the trade-offs amongst the various alternatives for each application.

Approaches to Substitution

Substitution issues are very different and much more difficult for existing processes and products than for new ones. For example, owners of automobiles and buildings built with air conditioning systems designed for a particular CFC require a chemical substitute with nearly identical properties, if they are to avoid significant and costly equipment modifications. On the other hand, users of purchasers of future automobiles and buildings will care little about the changes in equipment design (e.g. tubing diameters and materials) so long as there are not significant increases in costs nor diminished performance of the modified systems. Thus, the need for a "drop-in" chemical substitute is much greater for existing processes and products than new ones.

In addition to a "drop-in" chemical approach, this paper organizes the spectrum of alternative approaches into three different categories (although each category has many finer gradations within it):

- ± minor process changes (e.g. changes in the operating pressures of sterilizers or changes in the performance of compressors);
- ± major process changes (e.g. going back to forms of ammonia-based refrigeration or steam sterilization); and
- ± completely different ways of meeting functional and cost requirements (e.g. dispensing consumer products through non-aerosol means and the use of food irradiation, instead of refrigeration).

It should be noted that it is easiest to analyze substitution possibilities for drop-in chemicals. As greater and greater process changes are made, the task of accurately assessing substitution possibilities becomes ever greater. When completely different approaches to meeting CFC and halon applications are taken, it becomes nearly impossible to evaluate prospects because the alternatives become very numerous and may come from any of a plethora of different sources (i.e. firms in other than the chemical industry). Thus, while this latter category is likely prove to be the source of the most important CFC substitutes, it is the most difficult to predict.

Many of the currently available chemical substitutes may themselves become subject to restriction under the Montreal Protocol, and therefore must be viewed as a short-term solutions, at best. For example, hydrochlorofluorocarbons (HCFCs)² continue to exert an ozone depletion potential (ODP), albeit a very small one compared with those of CFC-11 and CFC-12. Thus, while HCFCs substituted for fully halogenated CFCs on a pound-for-pound basis would reduce ozone depletion substantially, ozone depletion would continue, although at a slower pace. If the HCFCs are

² CFCs with one or more hydrogen atoms in place of a chlorine or fluorine atom.

viewed as "bridging" chemicals to be used only until chemicals that are completely ozone-safe have been developed, then a second transition period for phasing in those chemicals would occur in the future, with attendant costs and other substitution issues (UNEP, 1989b).

If a chemical is viewed as a short-term or interim solution, providing only marginal benefits, CFC producers say they would have difficulty justifying the significant additional resources that will be needed to develop and commercialize these compounds. Therefore, to avoid a second transition at a later date, some countries may decide not to consider adopting interim chemical alternative, but continue to use CFCs until longer term alternatives are available (Du Pont, 1989).

Recovery and recycling programs for CFCs and halons offer an important potential for reducing emissions in the near term. For example, recycling of CFC-113, used as a cleaning solvent, and of CFC-12, used in mobile air conditioning, has been considered by several countries. Major recycling programs are now under development in many countries. Recycling may also be important source to provide usable CFCs to existing equipment, in order to avoid expensive scrapping in certain application areas (UNEP, 1989b). However, such recovery and recycling efforts merely cut down on the total amount of CFCs and halons produced to service existing equipment. They do not prevent each pound produced from eventually reaching the stratosphere.

Economic Impacts and Innovation

Any substitutions (with similar impacts) caused by market forces are typically considered beneficial by economists. Conversely, any substitution for CFCs and halons that are not caused by market forces will have some economic impacts, generally considered negative from a cost-benefit perspective.

A determination of the negative costs of imposing such CFC substitution is usually difficult for a number of reasons. Determining the cost of phasing out CFCs must take into consideration a number of factors including:

- approaches to substitution chosen by market forces;
- costs of such substitutes and alternatives, including recycling;
- Changes in consumer utility;
- Timing of the phase down of CFCs and introduction of substitutes; and
- One-time transitional costs as labor, capital and resources from reallocated.

Other uncertainties in determining cost include the speed of technological progress in developing possible substitutes, and the use of taxes and incentives for manufacturers. The time-path for required phasing out CFCs can substantially affect costs. A very rapid transition (much less than

10 years) would result in substantially higher costs due to abandonment of capital equipment and plants with remaining years of otherwise effective use.

In addition, monetary costs will vary from country to country. The actual substitution costs in the different application areas depend on many technical and local parameters such as interest rates, energy prices, regulatory costs, etc., which of course means that substitution costs will differ between countries.

The national capital investment to employ new technologies depends on the extent of the change and on whether the country has factories that are currently manufacturing CFC-dependent components or whether they buy such components from foreign suppliers. For example, some refrigerator factories manufacture the refrigerator case, evaporator, condenser, controls, and accessories but import compressors. In such a case, the cost of retooling to change to a new refrigerant is much less since compressor capital investment will be made in other countries.

As more and more manufacturers phase out CFC production, the cost of CFCs will rise. Correspondingly the cost effectiveness of substitutes will improve. Emerging and unpredicted new technologies may further lower the costs of substitutes. Thus, most estimates of economic costs of substitution are likely to overstate the negative impact of substitution.

It should also be recognized that the costs of CFCs normally only constitute a minor part of total production cost of products and processes using them. This means that even a relative large increase in the cost for a chemical CFC or halon substitute will have a relative small influence on the price of the final end-user product, such as a refrigerator. Exceptions include substitution of non-foam insulation for CFC-blown foam or alternative dispensing of CFC aerosols (UNEP, 1989b)

SPECIAL CONSIDERATIONS FOR DEVELOPING COUNTRIES

Developing countries may incur a disproportionate share of the effects of stratospheric ozone reduction, as they contribute only a small amount to the worldwide emissions but sustain a full share of effects. For example, exposure to the ultraviolet radiation light shielded from the sun by stratospheric ozone (UV-B) is a significant cause of degradation of many materials, particularly plastics that are used outdoors. The increased damage will be most severe in tropical locations, where the degradation may be enhanced by high ambient temperatures and sunshine levels. Developing countries in these areas are particularly susceptible to such impacts because of the growing use of plastics in building. Even small decreases in food production from UV-B effects

on agriculture would significantly affect people in areas where food shortages occur even now, which are mainly developing countries. Many developing nations are also dependent on fisheries for protein which may be threatened by increased UV light penetrating the water (UNEP, 1989i).

Under the Montreal Protocol, developing countries³ with annual CFC consumption levels below 0.3 kilograms per capita were allowed to postpone reductions by ten years or until per capita CFC consumption reaches 0.3 kilograms (whichever happens first) in order to satisfy basic domestic needs (Montreal Protocol article 5). To date, approximately one fourth of those designated as developing nations have indicated they intend to ratify the Protocol (see Table 1 on page 2). Countries ratifying the Protocol, however, account for nearly 90 percent of the current global consumption of regulated CFCs and halons (UNEP, 1989b).

Although developing countries now account for approximately 15 percent of global consumption of the CFCs and halons covered by the Protocol, their consumption of products now using CFCs is expected to significantly increase in the next 10 to 20 years, as these nations experience increasing levels of population growth, economic development, and industrialization. Depending on the particular region, this growth is expected to be particularly significant in the refrigeration, solvent and aerosol sectors (EPA, 1989e)

Economic Opportunities for Developing Countries

While developing countries are less able to pay the costs of phasing out CFCs and halons, having other more immediate concerns such as food supply and economic development, a large fraction of the costs of substitution do not affect them. For example, few developing countries have large capital investments in CFC production facilities and will therefore not incur the direct costs associated with a transition to alternatives. Developing countries also benefit from the fact that CFCs make up a small part of the cost of most products in which they are used (e.g. refrigeration and air conditioning).

³ At the May 1989 Meeting of Protocol Parties in Helsinki, the following countries were designated as developing countries (not including Eastern European nations): Afghanistan, Albania, Algeria, Angola, Antigua and Aruba, Argentina, Bahamas, Bahrain, Bangladesh, Barbados, Belize, Benin, Bhutan, Bolivia, Botswana, Brazil, Brunei Darussalam, Burkina Faso, Burma, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Chile, China, Colombia, Comoros, Costa Rica, Cote d'Ivoire, Cuba, Cyprus, Democratic Kampuchea, Democratic People's Republic of Korea, Democratic Yemen, Djibouti, Dominica, Dominican Republic, Ecuador, Egypt, El Salvador, Equatorial Guinea, Ethiopia, Fiji, Gabon, Gambia, Ghana, Grenada, Guatemala, Guinea, Guinea Eissau, Guyana, Haiti, Honduras, India, Indonesia, Iran (Islamic Republic of), Iraq, Jamaica, Jordan, Kenya, Kuwait, Laos People's Democratic Republic, Lebanon, Lesotho, Liberia, Libyan Arab Jamahiriyah, Madagascar, Malawi, Malaysia, Maldives, Mali, Malta, Mauritania, Mauritius, Mexico, Mongolia, Morocco, Mozambique, Namibia, Nepal, Nicaragua, Niger, Nigeria, Oman, Pakistan, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Qatar, Republic of Korea, Romania, Rwanda, St. Christopher and Nevis, St. Lucia, St. Vincent and the Grenadines, Samoa, Sao Tome and Principe, Saudi Arabia, Senegal, Seychelles, Sierra Leone, Singapore, Solomon Islands, Somalia, Sri Lanka, Sudan, Suriname, Swaziland, Syrian Arab Republic, Thailand, Togo, Tonga, Trinidad and Tobago, Tunisia, Uganda, United Arab Emirates, United Republic of Tanzania, Uruguay, Vanuatu, Venezuela, Viet Nam, Yemen, Yugoslavia, Zaire, Zambia and Zimbabwe.

In the near future, countries that have not signed the Montreal Protocol will have few options where CFCs are concerned. Beginning in January 1990, Protocol countries banned the import of CFCs and halons from non-parties. Beginning in 1993, parties are not allowed to export any controlled substances to non-parties. Before January 1992 a list of products containing controlled substances will be developed and within the following year ban the import of those products from non-parties. The Protocol also urges parties to consider import control measures for products produced with, but not containing, controlled substances (Montreal Protocol article 4).

Other countries and industry can be expected to go beyond the restrictions set out by the Protocol. Australia, for example, has already begun cutting its exports of CFCs to encourage developing countries to pursue the development and use of alternative technologies (Australian Environment Council, 1989). CFC producers of the European Community, Australia, and Japan, along with Du Pont in the United States, have made a commitment not to export CFC production technologies to countries which have not joined the Protocol. AT&T, Northern Telecom, and other multinational companies are implementing corporate policy to phase out use of CFCs and halons at all of their facilities, including facilities in nations not yet party to the Protocol (UNEP, 1989b). U.S. CFC manufacturers have indicated they will follow Protocol procedures in their plants, including those in developing nations not yet party to the Protocol (Fay, 1990).

Accordingly, countries which have not signed the Protocol have limited options to pursue continued use of CFCs. They will only be able to import CFCs from other non Protocol countries or manufacture them themselves, provided that they already have the technology. On the other hand, the emergence of CFC-free technologies will present significant trade opportunities to developing countries. From a trade expansion standpoint, firms and nations seeking to enlarge their exports will face a competitive environment far different from that prevailing today. Because of the change in product technology, firms seeking to compete internationally in markets for CFC-free products can start from essentially the same point, if they have access to technology and expertise. Technology for the transition to a CFC-free world will be created largely in the richer countries that until now have been the main producers and consumers of CFCs. Countries that have not yet or only recently have begun to make investments in CFCs need only observe the outcome of the research and development efforts of the high-CFC-use countries; they do not need to make these initial investments of scarce resources themselves. The opportunity to observe this transition to non-CFC-using technology is thus of strategic importance to developing countries considering investing scarce domestic savings or foreign exchange in CFC-dependent facilities (UNEP, 1989b).

APPROACHES TO CFC REPLACEMENT

BASIC APPROACHES TO CFC SUBSTITUTION

As was discussed earlier, one can consider four basic approaches to finding alternatives to the use of CFCs, ranging from "drop-in" chemicals or mixtures that directly substitute for CFCs with no other changes to the process under consideration, to the substitution of a completely different process or product for one based on CFCs. Current estimates suggest that HCFCs and HFCs will replace approximately 40% of current CFC usage, with the remainder being eliminated through conservation practices (30%) and not-in-kind substitution (30%) (Alliance, 1990). Although this discussion presents these four alternative approaches as discrete classes of substitution, the reader should remain aware that there are actually finer gradations of change within each category. In fact, a continuum of changes are possible regarding process changes, and the dividing line between minor and major process changes is somewhat arbitrary.

A "drop-in" substitution involves the direct replacement of a CFC in a process, without other changes in that process. Such a substitution can either employ a single chemical that replaces a CFC or CFC mixture, or can use a mixture of chemicals to replace one or more CFCs. The reader will note, in the following discussion, that true "drop-in" CFC substitutes are rather rare. If, in order to replace CFCs in a particular product or process it is necessary to modify other aspects of the process (such as re-designing a refrigerator compressor to accommodate the properties of a new refrigerant), we have termed the substitution a **minor process modification**. This category would also include such process changes as an increase in operating pressure for a sterilizer, or changes in the conditions (time, temperature, etc.) applicable to foam blowing operations.

Major process modifications are those in which the elimination of CFCs requires a substantially different process than that employing CFCs. Examples would include the replacement of CFC-Ethylene Oxide sterilizers with steam sterilizers, or the use of hydrocarbon propellants for aerosols, which would necessitate the use of explosion-proof filling stations for aerosol containers. The use of alternative products represents an even more extreme change in industrial practice that eliminates the need for CFCs. Among these changes would be the use of pump bottles instead of pressurized can aerosols, the use of fiberglass rather than foam insulation for appliances, the use of cotton or feather padding instead of foam cushions for furniture, or even the use of food canning or food irradiation to reduce the need for refrigeration.

CHEMICAL REPLACEMENTS FOR CFCs

A number of chemical substitutes for CFCs are either currently in industrial and commercial use, in development and near to commercialization, or undergoing research and testing. Some of these chemicals (such as HFCs and HCFCs) are intended to substitute for a broad range of current CFC applications, while others (such as hydrocarbons) are applicable to a more limited range.

Analog Chemicals: HFCs and HCFCs

The Hydrofluorocarbons (HFCs) and Hydrochlorofluorocarbons (HCFCs) are substitute chemicals that are chemically the closest analogs of CFCs. Hydrofluorocarbons involve the substitution of hydrogen atoms for all chlorine atoms in a chlorofluorocarbon molecule, while hydrochlorofluorocarbons involve substitution of only some of the chlorine atoms with hydrogen. Because of the close similarity in structure and physical-chemical properties of both HFCs and HCFCs to CFCs, they are the chemicals most suited to "drop-in" replacement or replacement involving only minor process modifications (UNEP, 1989h).

Table 2. Hydrochlorofluorocarbons and Hydrofluorocarbons

Substance	ODP Relative to CFC-11	GWP Relative to CFC-12	
HCFC-21	Dichlorofluorethane	0.97	0.10
HCFC-22	Chlorodifluorethane	0.05	0.098
HCFC-31	Chlorofluorethane	0.05	0.10
HCFC-121	Tetrachlorofluoroethane	-	-
HCFC-122	1,1,2-Trichlorodifluoroethane	-	-
HCFC-123	1,1-Dichloro-2,2,2-trifluoroethane	0.02	0.0064
HCFC-124	1-Chloro-1,2,2,2-tetrafluoroethane	0.02	0.10
HCFC-131	1,1,2-Trichlorofluoroethane	-	-
HCFC-132b	1,2-Dichloro-1,1-difluoroethane	0.05	0.02
HCFC-133a	1-Chloro-2,2,2-trifluoroethane	0.05	0.02
HCFC-141b	1,1-Dichloro-1-fluoroethane	0.10	0.029
HCFC-142b	1-Chloro-1,1-difluoroethane	0.06	0.11
HCFC-151	Chlorofluoroethane	-	-
HCFC-225ca	1,1-Dichloro-2,2,3,3,3-pentafluoropropane	-	-
HCFC-225cb	1,3-Dichloro-1,1,2,2,3-pentafluoropropane	-	-
HFC-23	Trifluoromethane, fluoroform	0	-
HFC-32	Difluoromethane, methylene fluoride	0	-
HFC-41	Fluoromethane, methyl fluoride	0	-
HFC-125	Pentafluoroethane	0	0.10
HFC-134a	1,1,1,2-Tetrafluoroethane	0	0.039
HFC-143a	1,1,1-Trifluoroethane	0	0.34
HFC-152a	1,1-Difluoroethane, ethylidene fluoride	0	0.0091
HFC-161	Fluoroethane	0	-

Source: UNEP, 1989h.

Chlorine and fluorine provide chemical stability to CFCs, which represents a desirable feature in use, just as it is an undesirable feature from the perspective of atmospheric degradation. The aim of substituting a limited number of hydrogen atoms for chlorine for fluorine atom in a CFC molecule is to retain desirable properties, while decreasing the amount of chlorine that is transported to the upper atmosphere. The effect of adding hydrogen is to make the molecule more susceptible to degradation in the lower atmosphere, thus preventing its migration to the upper atmosphere, where ozone depletion occurs. Removing chlorine from a molecule lessens the damage to the ozone layer; for compounds without chlorine, the threat is eliminated (Pool, 1988).

The substitution of hydrogen for chlorine or fluorine entails disadvantages as well as benefits. One disadvantage of replacing chlorine with hydrogen is that it tends to make a compound more flammable. Compounds with reduced fluorine content tend to be more toxic (Jones, 1988). The limiting case for hydrogen addition is a pure hydrocarbon (discussed separately below), all of which are flammable. Fluorine elimination yields either pure chlorocarbons, such as carbon tetrachloride, or chlorinated hydrocarbons (also discussed separately below), that are generally highly toxic; these compounds are referred to as halogenated solvents.

It is also important for the reader to remember that all HCFCs still have ozone depletion potential, although it may only be one fiftieth that of CFCs. Further, both HFCs and HCFCs are considered to be "greenhouse gasses" that have the potential to contribute to the problem of global warming.

HFCs

Several HFCs are either already in commercial use, or close to commercialization. HFC 152a is already in limited commercial use. It has potential application as an aerosol propellant, and refrigerant.

Acute toxicity testing has been completed on HFC 134a, and results are expected by the end of February, 1990 (Perri, 1990). Potential applications of this compound include use as a refrigerant, foam blowing agent, and aerosol propellant. Its physical properties closely resemble those of CFC 12.

There is already significant industrial development activity for HFC 134a. DuPont⁴ (U.S.) announced on September 26, 1988, that it would invest more than \$25 million to build the world's first commercial-scale plant for HFC-134a. The plant is expected to start up in 1990 and will be used primarily for expanded market development and to provide operational data for a future world-scale commercial facility. On November 14, 1989, Hoechst (Germany) announced that it was concentrating its HFC development efforts on HFC 134a, and that a production facility for 10,000 tons/y is due for completion in 1992-1993.

HFC 125 is also undergoing (acute) toxicity testing, with results expected later in 1990. It is under consideration for use as a refrigerant (Perri, 1990). HFC 143a is also under consideration as a refrigerant. Other HFCs that appear not to have been as fully developed are HFC 23 and HFC 32, both of which have potential as refrigerants (UNEP, 1989g).

HCFCs

Two HCFCs, HCFC 22 and HCFC 142b, have already been commercialized (HCFC 142b is used as an aerosol propellant, while HCFC 22 is primarily used as a refrigerant) (UNEP, 1989h). HCFC 22 is under consideration for additional refrigeration applications, and as an aerosol propellant and foam blowing agent. HCFC 142b is under consideration for these applications as well.

Acute toxicity testing has been completed on HCFC 123 and HCFC 141b, with data expected to be released by the end of February, 1990; similar data on HCFC 124 is expected later this year (EPA, 1989c). HCFC 123 has potential application as a solvent, refrigerant, and possibly as a foam blowing agent. HCFC 124 is being evaluated as a refrigerant and foam blowing agent. HCFC 141b is under consideration as a solvent and possibly as a foam blowing agent. HCFC 225ca and HCFC 225cb are under consideration as replacement solvents for CFC 113. Asahi Glass is testing them for efficacy and toxicity over the next five years.

In November, 1988, Pennwalt (U.S.) announced planned start-up of a plant to produce HCFC 142b in the first quarter of 1989. This plant also has the capability to produce HCFC 141b, and could begin commercial production as early as 1991. Daikin Industries, Ltd. (Japan) announced plans in 1988 to establish a 1000 ton/y supply system of HCFC 142b during 1988 and scale up the supply capacity to 5000 tons/y by 1990.

⁴ Unless otherwise noted, industry product information is taken from company press releases or recent journal articles and referenced in a separate section of the bibliography. Company addresses are provided when possible.

In December of 1989, Allied Signal Inc. announced plans to begin construction in 1990 of a plant to manufacture HCFC 141b. This plant is expected to be in production in late 1991. The company has developed a family of solvents based on 141b.

HCFC 123 can not be produced in existing CFC production facilities, but mass production of this compound has apparently already begun (Asahi glass). DuPont has also announced that it is already operating a pilot plant, is currently producing 1 million pounds per year in Europe and Japan, and plans to locate a commercial scale facility for its manufacture in Maitland, Ontario, Canada. The latter facility will start up in late 1990, and is expected to begin supplying market quantities in 1991.

Hydrocarbons and Related Compounds

Hydrocarbons (propane, butane, iso-pentane, etc.) are already in wide industrial and commercial use, both as fuels and chemical feedstocks. They also have a history of use as aerosol propellants, for which they are the most common substitutes for CFCs. In addition, they may be substituted as refrigerant fluids and as foam-blowing agents. Although hydrocarbons are cheap and efficient, they are also flammable. (UNEP, 1989b) (Harmon and Rhodes, 1988) (UNEP, 1989h) (UNEP, 1989a).

Dimethylether can also be used as an aerosol or refrigerant. It costs more than hydrocarbons, but not more than CFCs. When used as a refrigerant, it offers prospects for reducing energy consumption. It has generally been used when its special properties (such as water solubility) are needed. It is flammable, and currently its availability is geographically limited.

Halogenated Solvents

The halogenated solvents (including carbon tetrachloride, methylene chloride, trichloroethylene, perchlorethylene [tetrachloroethylene], and methyl chloroform [1,1,1-trichloroethane]) are another class of chemicals in widespread commercial use. In addition to their obvious use as solvents, they have the potential of replacing CFCs as foam blowing agents.

Carbon tetrachloride is an excellent solvent, and was once used as a general purpose solvent and grain fumigant in the U.S. Because of its toxicity, it is only used in small amounts in such applications in the U.S. today. The major use of carbon tetrachloride in the U.S. is actually in the manufacture of CFC-11 and CFC-12. Carbon tetrachloride use as a general solvent continues in some areas outside the U.S. (EPA, 1989c).

Methylene chloride is also in wide commercial use, especially in the U.S., both as a solvent and as a blowing agent for flexible polyurethane foams (Harmon and Rhodes, 1988).

Methyl chloroform (1,1,1-trichloroethane) is produced in large quantities around the world for use as a cleaning solvent in vapor degreasing and cold cleaning applications. Small amounts are also used in adhesives, aerosols, and coatings (Harmon and Rhodes, 1988).

Miscellaneous Substitutes

Carbon Dioxide (CO₂) has potential as an aerosol propellant, to be mixed with Ethylene Oxide (EO) for sterilization, and in liquid form for rapid food freezing. Nitrogen N₂ has similar applications. Both have the advantage of being non-flammable, although CO₂ has the drawback of being a "greenhouse gas" that contributes to global warming. Nitrous oxide (N₂O) is another potential aerosol propellant. While it is nonflammable, there is a risk of explosion when it is used as an aerosol propellant.

Ammonia is currently available, and widely used, as a refrigerant in large scale industrial chilling, freezing and cold storage plants. In Eastern Europe, it is used in smaller scale plants as well. Ammonia is quickly biodegradable and is not harmful to the environment, although it is toxic (see below).

There are also a number of other compounds, not easily classifiable, that are under consideration as replacements for specific CFC uses. Examples include polyether polyols and alkali alumino silicate sieves, which are used in foam-blowing applications. Helium is used as a refrigerant in some systems, and a natural solvent derived from oranges and wood pulp has been suggested as a replacement solvent for the electronics industry.

SUBSTITUTION POSSIBILITIES FOR DIFFERENT INDUSTRY SECTORS

Refrigerants

In considering the replacement of CFCs in refrigeration applications, it is important to bear in mind that a significant aspect of the total environmental cost of refrigeration technologies stems from energy consumption. Replacements for CFC refrigerants that impose significant energy costs will be less desirable than alternatives that do not. Energy considerations are especially important in the domestic refrigeration and heat pump sectors (UNEP, 1989h).

Replacement of CFCs in the refrigeration sector must also be viewed in the context of new and existing equipment. In the near term, the very large global stock of existing capital equipment may have to be upgraded slowly, mainly through attrition and retrofitting new chemicals and

refrigeration designs (UNEP, 1989h). More rapid change would entail considerable costs, at least in the developed countries. Accordingly, short term options for refrigerant fluids may rely most heavily on mixtures, especially those that contain CFCs. (The current Montreal Protocol is aimed at decreasing total emissions of CFCs rather than emissions of specific individual compounds.) The appropriate design of refrigeration equipment also requires thermodynamic and transport data on potential refrigerants. At present, this data is only available for HCFC 22 and 142b, HFC 142a, ammonia and hydrocarbons. (UNEP, 1989h)

"Drop-in" substitutions and minor process changes

HCFC 22 is an immediately available substitute refrigerant. It has an ODP of only 5 percent that of CFC-12. HCFC-22 is currently used in air conditioning and refrigeration applications, particularly in low temperature retail food refrigeration (used either alone or as part of a blend with CFC-115), and reciprocating chillers (large air conditioner systems)(EPA, 1989c). It is also the primary refrigerant used for refrigerated ships (UNEP, 1989g). The expansion of its use as a refrigerant to other systems (where it would principally replace CFC 12) must take into account the fact that it requires higher (by 50%) operating pressure, has different lubrication requirements, and has higher permeation rate through elastomer hoses. However, for new retail refrigeration, HCFC 22 could replace all current CFCs, as equipment to use this agent is already manufactured (UNEP, 1989g).

For the longer term, some regard HFC 134a as the most promising substitute for CFC 12 (Harmon and Rhodes, 1988; UNEP, 1989h), although additional testing is needed on this compound (UNEP, 1989g). Its drawbacks include a predicted 5 to 12% increase in energy consumption (Smith and Shapiro, 1989; UNEP, 1989g) and the lack of a compatible lubricant (Smith and Shapiro, 1989; Harmon and Rhodes, 1988). It also tends to migrate (escape) through elastomeric hoses, but Bridgestone Corp. (Japan) has developed a nylon coating hose which will suppress the flow rate of HFC 134a in mobile air-conditioning system to one eighth of that in standard hoses. Assuming an appropriate lubricant could be found, this compound could be incorporated into mobile air conditioners with relatively minor design changes to current CFC 12 systems (UNEP, 1989g). The high cost of the compound may also limit its applicability to liquid freon food freezing operations (UNEP, 1989a). Finally, its use in any application will depend upon the outcome of toxicity testing, which will not be completed until 1993 (Smith and Shapiro, 1989).

Flammable refrigerants (such as HFC 152a and dimethyl ether) represent another CFC replacement possibility, and have the advantage that they could reduce, rather than increase

energy consumption (UNEP, 1989g). HFC 152a should only be considered a medium- to long-term option for domestic refrigerators, due to concern over its flammability (UNEP, 1989a).

Some refrigerant uses of CFCs do not yet have easily identified substitutes. One example is large, centrifugal compressor driven, chilled-water comfort air conditioning systems (UNEP, 1989g). Candidate replacement chemicals under study include HCFC 123 and HFC 134a; HCFC 22 may also be a possibility (UNEP, 1989g; Harmon and Rhodes, 1988). In testimony before the U.S. Congress, DuPont has claimed that "the best candidate to replace CFC 11 in the most energy efficient centrifugal chillers is HCFC 123," and they are actively pursuing its development, as noted above. For refrigerated containers as well, there is no currently available substitute for CFC 12 (UNEP, 1989g).

Mixtures

In addition to single-compound substitutes for currently used CFCs, a number of mixtures of compounds have been proposed as replacement refrigerants. Many of these can be considered interim replacements, in that they require little modification of existing equipment, but retain significant ozone depletion potential. Both azeotropic mixtures (i.e. mixtures that behave as if they were a single compound) and non-azeotropic mixtures have been considered. The latter carry the penalty that they may decompose during use; this could lead to servicing concerns and safety concerns (UNEP, 1989g).

Mixtures currently under consideration include the following:

- CFC 500 (74% CFC 12; 26% HCFC 152a). The high CFC 12 content makes this an unattractive option (UNEP, 1989g).
- CFC 502 (51% CFC 115; 49% HCFC 22). This is currently used in low-temperature retail refrigeration (Harmon and Rhodes, 1988).
- A blend of HCFC 142b (60%) and HCFC 22 (40%) which is currently available is tailored to closely match CFC 12 and has potential for use in domestic refrigeration. Pennwalt has devised a blend of these two HCFCs that may be useful as both a propellant and a refrigerant.
- Akzo (Netherlands) has developed a mixture of dimethylether (13%) and CFC 12 (87%), trade-named Demeon, for use as a drop in replacement for pure CFC 12. It can replace CFC 12 in many applications without major re-tooling and without deterioration of refrigerating performance. Again, this is a mixture with a high CFC 12 content.
- The U.S. EPA is investigating a "ternary blend" (40% HCFC 22, 40% HFC 152a, 20% HCFC 124) (EPA, 1989c).

Road vehicles are already beginning to switch to CFC 500 or 502, and some industrial cold storage plants already use CFC 502. One drawback of mixture systems, particularly those using

CFC 502, is that they can not generally be subsequently converted to non-CFC use. CFC 500 and CFC 502 have only a limited potential for replacing CFC 12 in refrigerated trucks (UNEP, 1989g). Fortunately, however, trucks have short life-span, so when substitute refrigerants become available they can be implemented relatively rapidly.

Major Process Changes

Despite the widespread use of CFCs as refrigerants, they have never fully replaced alternative compounds in a number of applications. For example, ammonia is still widely used in commercial-scale refrigeration (Harmon and Rhodes, 1988; UNEP, 1989g), whether for cold storage or food processing. The key barrier to its further use is the need to guard against the possibility of exposing workers or nearby residents to this acutely toxic compound; such risks can be minimized by remote chilling, or by appropriate location of refrigeration facilities. A similar argument applies to hydrocarbon refrigerants. These may be useful even for domestic refrigeration, providing that safety concerns regarding flammability are addressed.

For commercial freezing of food, there are several alternative processes in commercial use that are available to replace immersion in CFCs. These include cryonic freezing, in which liquid nitrogen or liquid CO₂ is sprayed on the food, and air-blast freezing (Harmon and Rhodes, 1988; UNEP, 1989a).

Other replacement processes that do not involve either CFCs or direct CFC substitutes are currently under development. These include a Stirling cycle system for truck trailer refrigeration that is commercially available (Harmon and Rhodes, 1988) and a bus air conditioning system being developed by Cryodynamics, Inc. (sponsored by the Canadian federal government and the Manitoba provincial government) based on its modified Stirling cycle technology. The latter system uses helium to replace CFC 12.

Albers Technology (U.S.) has developed a prototype air conditioner that operates without CFCs by using proprietary process which manages the temperatures and humidities of air streams. The company says it should sell for the price of existing coolers but, because it has no compressor, operate at about half the energy cost. As of October 1989 Albers was seeking a manufacturer to commercialize the product.

Alternative Products

It is also possible to replace some current uses of CFC-based refrigeration with non-refrigeration technologies. Thus for commercial food processing and subsequent domestic refrigeration, at least partial replacement can be achieved through the use of alternative food preservation

techniques. These include canning, curing, and food irradiation. For some other uses of refrigeration technology (e.g. mobile air conditioning), demand can be highly elastic. Thus reduction of CFC use in this application could be obtained not via substitution, but by changing the cost structure so as to decrease demand for the CFC-based technology.

Solvents

The electronics industry uses the largest amount of CFC-113 worldwide of any industry application area. An estimated 80,000 metric tons of CFC 113 were used to remove flux from printed circuit board assemblies in 1986. Fifty percent of that use is estimated to be dictated by military specifications. According to industry experts, the use of alternative cleaning processes would increase if military specification were changed. The U.S. military is currently undertaking a benchmark testing program toward this end (UNEP, 1989c). The U.K. Ministry of Defence has accepted a new flux standard that will allow the elimination of CFCs in their military electronics production. (UNEP, 1989h) Of course, decreased military expenditures could also lead to environmental improvements in this, as in other, areas.

"Drop-in" substitutions and minor process changes

Apparently, CFC 112 and CFC 113a are currently being marketed as replacement solvents for CFC 113, despite their own high ODP. A more promising option, at least in the short term, is the use of "low" CFC-113 blends which contain 60 to 70 percent CFC-113. In August, 1988, ICI (U.K.) announced the development of non-azeotropic blends of CFC 113 with low boiling point alcohols such as isopropanol and ethanol, creating a highly effective solvent for flux removal. This blend typically contains 25 percent of the alcohol and as such is still nonflammable.

Complete, direct, replacement of CFCs in solvent applications will likely involve HCFC 123 and HCFC 141b (Harmon and Rhodes, 1988). HCFC 123 is a very aggressive solvent, and has a low boiling point, which may limit its use as a solvent by itself (Harmon and Rhodes, 1988). HCFC 141b is flammable, and appears to be a weak mutagen, according to Mobay Corp. Solvent mixtures, such as a combination of HCFC 141b, HCFC 123, and methanol, are expected to be available soon, pending satisfactory toxicity testing results.

In October 1989, DuPont announced a developmental product for metal cleaning that performs better than CFC 113. The product is an azeotrope-like blend of HCFC 123 and 141b. It has no flash point and does not become flammable during boiling or evaporation. Retrofitting will be required to use the blend in conventional vapor degreasers.

DuPont has also developed a blend of HCFC 141b, HCFC 123, and methanol, and another blend which the company says is a proprietary hydrocarbon-based product. Both blends will require redesign of equipment for safe and efficient use. Allied Signal reports it has developed a family of solvents based on HCFC 141b.

Eventually, HCFC 225ca and HCFC 225cb may also prove to be effective replacements for CFC 113.

Major Process Changes

Halogenated solvents represent an alternative to CFC 113 for a number of solvent applications, but these compounds may themselves become subject to the Montreal Protocol, and they are associated with serious toxicity concerns. Currently, they are commercially used in metals degreasing and drycleaning (Harmon and Rhodes, 1988; UNEP, 1989c). White spirits may also be applicable in this context.

For some applications, water-based cleaning procedures may be useful, but in general, water used by itself is of limited effectiveness. Surfactants may improve cleaning performance, but may also cause water treatment or water quality problems when used in water-based system. ICI (U.K.) has developed a "Cleanline-2" cleaning system that combines water and solvent cleaning and drying techniques to provide stain-free removal of contaminants from electrical and electro-mechanical parts.

Another alternative is provided by Bioact EC-7, a natural solvent derived from oranges and wood pulp that can be substituted for CFC 113 in the cleaning of water immersible electronic components. It is manufactured by Petroferm, Inc. and distributed worldwide by Alpha Metals, Inc. Vitronics Corp. (all U.S. companies) has developed a system, tradenamed SA-2150, specifically designed to use the compound. The company reports that it is currently shipping its system to customers in the U.S., Europe and the Far East.

Alcohols and related solvents, such as isopropanol and pentafluoropropanol, are effective cleaners and represent possible substitutes for CFC 113 in electronics and precision cleaning. Both solvents are currently available. However, they are flammable and there may be waste-disposal problems associated with them. In addition, isopropanol has been identified as being toxic (UNEP, 1989c).

A number of hydrocarbon/surfactant cleaning are currently being developed. One such solution, using terpenes, can be used not only for precision cleaning, but for drycleaning and degreasing as

well. There are several problems with terpenes. In addition to the odor associated with terpenes, there are concerns about its flammability. Equipment must be specifically designed for terpene cleaning.

Mitsubishi Electric Co. and Taiyo Sanso Co. (Japan) have developed a system for electronic and precision cleaning which uses the friction of molecular ice grains that are sprayed on the surface. Mitsubishi plans to begin marketing the system in the Spring of 1990.

Alternative Products

Another way to eliminate the use of CFC 113 in cleaning is the development of no-clean technologies. The BOC Group, a world wide industrial gases company operating in more than 50 countries, has developed a no residue soldering process for surface mounting of components onto printed circuit boards and hybrids, thus eliminating the used of solvents. The new soldering process involves a proprietary controlled atmosphere and solder paste. The technology is the result of a collaboration with Airco Gases (U.S.) and Multicore Solders Ltd. (U.K) and is being marketed by Airco Gases. Another no-clean option that is currently available is the AT&T Low Solids Fluxer. This system uses an ultrasonic nozzle (patented by Sono-Tek) to spray a fine mist of low-solids-content flux onto printed circuit boards.

Foam Blowing Agents

Foams have a wide variety of applications, ranging from furniture padding, through protective or insulating packaging, to use as building and appliance insulation. For foam insulation applications, as in the case of refrigeration, it is important to bear in mind the potential energy costs of replacing CFCs.

As noted above, foams can be described in terms of three basic segments of the industry (EPA, 1989c). This distinction, between flexible polyurethane foams, rigid polyurethane foams, and non-urethane foams, will be observed in the following discussion.

"Drop-in" substitutions and minor process changes

Flexible Polyurethane Foams - HCFC 22 is already in commercial use as an alternative to CFC 11 for these foams. It requires minor process changes insofar as it is a gas at room temperature. Both HCFC 123 and HCFC 141b may soon be commercialized as an alternative blowing agents, provided that toxicity test results are favorable (UNEP, 1989h).

Rigid Polyurethane Foams - According to tests conducted by the Mobay Corporation, HCFC 22 can also be substituted for CFC 11 in polyurethane structural foam systems, with very little

modification of the production process. Further work is needed for it to be used in polyurethane integral skin formulations. As noted above, it is available in commercial quantities, and has been reported in commercial use as a replacement for CFC 12 (UNEP, 1989d). HCFC 142b is already in commercial production as well, and may serve as a substitute for CFC 12 in foam blowing as well as aerosol propellant uses (UNEP, 1989h).

HCFC 123 and HCFC 141b represent promising future substitutes for CFC 11 in rigid polyurethane foams, with commercial viability expected around 1993 (Harmon and Rhodes, 1988). HCFC 123 is a less efficient blowing agent than CFC 11. HCFC 141b is more efficient than CFC 11, and should require 15 percent less by weight in polyurethane foams, according to testing by Mobay. It is flammable, but foam manufactured using it performed well in burn tests conducted by Mobay. HCFC 123 and HCFC 141b also have the liability of being aggressive solvents, that may attack plastics if used in appliance insulation blowing (UNEP, 1989d).

Rigid Non-Polyurethane Foams - HCFC 22 has proven to be a viable substitute for CFC 12 in a number of foam-blowing applications, including foam food service items (plates, cups, etc.), and polyolefin (e.g. polyethylene, polypropylene) foams (UNEP, 1989d). DuPont received approval from the U.S. Food and Drug Administration (FDA) to market "Formacel"-S, the trademark for HCFC 22, as a blowing agent for use in food packaging. Fort Howard Corp. (U.S.) announced in January of 1988 that it would begin the process of substituting "Formacel"-S as a blowing agent and planned to have the changeover completed at its first plant within 60 days. Although HCFC 22 is priced about one third higher than CFC 12, smaller amounts are required to achieve similar performance.

HCFC 22 has not yet proven satisfactory in food containers for long-term storage. By itself, HCFC 22 is too volatile for use in dunnage (i.e. plastic peanuts). All HCFCs, with the exception of HCFC 142b, have higher thermal conductivity than CFCs. This may lead to decreased energy efficiency in foams produced using these. In particular, HCFC 22 does not contribute to the insulation properties of polystyrene foam board (it migrates out, and is replaced by air). Given its low boiling point, HCFC 22 would not allow manufacture of thick polyolefin foams (UNEP, 1989d).

Other blowing agents either commercially available or expected in the near term have some drawbacks for insulating foams. HCFC 142b is flammable (UNEP, 1989a), and when used alone, has negative effects in small-scale testing of fire performance of polystyrene insulation boards. HFC 134 is also a possible substitute for rigid non-polyurethane foam, but its high thermal conductivity makes it appear unattractive for insulating foams. As was noted earlier, HCFC 123

may attack plastics if used in appliance insulation blowing. HCFC 124 appears promising for polystyrene board, but only limited information is available (UNEP, 1989d). However, it has sufficiently high diffusivity through foam that it could lead to foam collapse (Harmon and Rhodes, 1988).

Rigid Non-Polyurethane Foams: Mixtures - A number of mixtures have been suggested as blowing agents for non-polyurethane foams, offering a variety of advantages and disadvantages. A mixture of CFC 12 and HCFC 22 is immediately feasible for polystyrene board; it would cause some decrease in insulation efficiency and lower strength. HCFC 22 mixed with hydrocarbons would lead to a significant loss of mechanical strength and insulation properties, as well as higher cost; it does not seem to be a desirable option. Mixtures of HCFC 142b and HCFC 22 could be commercialized more quickly than HCFC 142b alone, but with some expected loss of performance. A mixture of CFC 124 and HFC 134a is under development, and offers promise (UNEP, 1989d).

Major Process Changes

Flexible Polyurethane Foams - Methylene chloride is already in wide commercial use as a blowing agent for these foams, particularly in the U.S. (UNEP, 1989d). A variety of polyether polyols are also under development, including one trade-named "Preminol" (manufactured by Asahi Glass Co. Ltd. of Japan), that is expected to be in production (up to 30,000 tons/y) by June of 1990. The use of polyols as blowing agents tends to increase foam density, although improvement is expected with the development of new polyols. Totally water-blown processes represent another alternative, although these are expected to lead to an increase in the minimum foam density that can be achieved. The AB (formic acid) process is yet another alternative, but some CFC 11 must be used in this process to achieve adequate foam density. This process also generates significant quantities of carbon monoxide, and the blowing mixture is very caustic (pH of 3) (UNEP, 1989d).

Rigid Polyurethane Foams - Polyols are also applicable to rigid polyurethane foams. Bayer AG (West Germany) has developed and is marketing a water-based, non-CFC blowing agent. Trade-named Porofor Z, it is a homogenous paste comprising alkali alumino silicate sieves, water and a polyether polyol. Disadvantages of Porofor Z include: non-solubility and the need for agitation, which limit its use to rigid structural foam systems. Completely water-blown foam is possible for rigid polyurethane foams as well, but unless the foam is completely protected by an impermeable membrane, the use of a completely water-blown process leads to severe losses of energy efficiency. Counterbalancing advantages of this approach is that it yields improvements in compressive strength and thermal aging properties.

Rigid Non-Polyurethane Foams - Hydrocarbons are commercially available, and are suitable for producing extruded polystyrene foam. In fact pentane was the original blowing agent used in making polystyrene foam. Lower operating costs for foams blown with hydrocarbons may be offset by safety/environmental control expenses. Polyether polyols are also under consideration as alternative blowing agents (UNEP, 1989d; Harmon and Rhodes, 1988).

Alternative Products

Flexible Polyurethane, used for furniture padding, can be replaced by a number of non-foam products, including such traditional materials as cotton, down or feathers, and horsehair. Rigid polyurethane insulation foams can be replaced with fiberglass (Harmon and Rhodes, 1988; UNEP, 1989b), but no product appears to be truly competitive with foam for appliance insulation or electronics packaging. The many applications of rigid non-polyurethane foam products have an equally broad range of substitute products, including alternative packaging (paper, foil, sheet plastics) for food, bubble wrap and polystyrene beads for cushioning, rubber, paper, or plastic gaskets, and air filled containers for flotation. It should be noted that for building insulation, all competing products require greater thickness for the same energy efficiency (UNEP, 1989d)(Harmon and Rhodes, 1988).

Aerosol Propellants

"Drop-in" substitutions and minor process changes

HCFC 22 is already commercially available as a propellant for non-medical uses of aerosols, as is HCFC 142b (Smith and Shapiro, 1989; UNEP, 1989h). Pennwalt (U.S.) has developed a 60-40 blend of 142b and 22 as a substitute for CFC 12 in aerosols. Replacing CFCs in medical applications of aerosol sprays may prove to be a difficult and extended process; candidate propellants must meet more a stringent standard of safety for these uses than for general applications.

HFC 134a, and HCFCs 123, 141b, and 124 have all been considered for use as aerosol propellants, but the high cost of these chemicals will probably limit their application as aerosol propellants, where the cost of the propellant represents a larger proportion of total cost than is true for many applications (UNEP, 1989a). A variety of mixtures are also under consideration for aerosol use, including HCFC 22 and HCFC 142b, HCFC 22 and HFC 152a, and dimethyl ether and HCFC 22.

Major Process Changes

Compressed gases (CO₂, N₂, N₂O) are presently used in about 7-9% of the aerosol products. In order to raise that percentage, more efficient aerosol package design will be needed to take care

of problems such as coarseness of spray, drops in pressure in the can, and in the case of CO₂, corrosion in the can (Harmon and Rhodes, 1988). Hydrocarbons are also commercially available as propellants. While much less expensive than CFCs, they do require the use of explosion-proof filling stations. In addition, the requirement by some countries that odorants be added to hydrocarbons for transportation will tend to limit their use as propellants (UNEP, 1989b). Dimethyl ether, while a functional propellant, is not only flammable but also more expensive than CFCs; this will tend to limit its use to cases where its particular chemical properties are important (UNEP, 1989a).

Alternative Products

Several process substitutes currently exist which will reduce or eliminate the need for using CFCs in Aerosol propellants include using finger or trigger pumps which consist of a bottle and a pump valve. Pumps normally provide a wet spray which will not be suitable for some uses (UNEP, 1989b). Two-compartment aerosols separate the product and propellant inside a dispenser by using a piston, an inner bag containing the product or an expanding bag which holds the propellant. The propellant can be a fluorocarbon, hydrocarbon, or compressed gas. Mechanical pressure dispensers systems are another approach. They provide a spray either by the user pressing on the container or, by contraction of an inner bag which was expanded when the product was filled during the manufacturing process. Some of these options may cost more the aerosol dispensers they replace. (UNEP, 1989a)

Sterilants

Much sterilization in hospitals and industrial and commercial contract sterilization of medical equipment is accomplished by using ethylene oxide (EO). In order to reduce the flammability and explosion risks posed by EO, it is often diluted with CFC 12 to a mixture of 12 % EO and 88 % CFC 12. Another diluent currently used is carbon dioxide, which makes up 90% of the mixture. About one half of the sterilizers now using the CFC/EO mixture could use the EO/CO₂ mixture without modification (Harmon and Rhodes, 1988; UNEP, 1989a).

"Drop-in" substitutions and minor process changes

HFC 134 is under consideration as a replacement for CFC 12 in the EO sterilization process. A workable sterilant mixture has not yet been fully developed, but is expected between 1993 and 1995 (Harmon and Rhodes, 1988). Some of the other HCFCs and HFCs also appear to have the properties necessary to be used in diluting EO. One U.S. producer has announced plans to commercialize a HCFC based product in the early 1990's, in cooperation with a supplier of sterilant gases (UNEP, 1989a). Hospital tests indicate that the product can be used as a drop-in for the CFC/EO mixture. This mixture is expected to be more expensive. Allied-Signal (U.S.)

reports that it has developed a fluorocarbon which will replace CFC 12 in sterilization. The new product is part of a family of gases that has the potential to replace CFC 12 in a variety of applications.

Major Process Changes

In addition to replacing the diluent used with EO in the current process, it is also possible to employ EO as a sterilant in an alternative process. One such process involves a system in which the sterilization chamber is purged with nitrogen before sterilizing with pure EO (EPA, 1989c).

A wide variety of chemical sterilization alternatives to EO are already in commercial use or under development. Possible sterilant substitutes currently available include peracetic acid, glutaraldehyde (both of which will necessitate process changes) and formaldehyde. Each of these processes has some disadvantages.

- Peracetic acid is very reactive and hazardous.
- Glutaraldehyde is hazardous and irritating, the process is hard to control, and instruments are subject to easy recontamination, so they can not be stored after sterilization.
- Formaldehyde is already used in Europe as a generally accepted process for sterilization. However, it is toxic and is a suspected carcinogen. For the latter reason, it is subject to regulation in the U.S. by the Occupational Safety and Health Administration (UNEP, 1989a).

Other possible substitute forms of chemical sterilization that are being investigated include gaseous chlorine dioxide and gaseous ozone. Gaseous chlorine dioxide is hazardous; it must be generated on site because it is unstable. Gaseous ozone may cause adverse effects on materials; it may also require major equipment redesigns (UNEP, 1989a).

Non-chemical sterilization is another widely available alternative. Steam or dry heat processes are currently used for sterilizing products that can withstand temperatures of 120 degrees C (steam) or 190 degrees C (dry). Both are safe, effective and relatively inexpensive to implement. Their principal drawback is limited applicability to some modern medical equipment incorporating plastic or other temperature-sensitive components (UNEP, 1989h). Dry heat is probably unsuitable for sterilization of wrapped items. Radiation is another available process, but would require product redesign for compatibility and would be expensive to implement. (UNEP, 1989ab) An acid water scrubber and condensation reclamation process is under review (EPA, 1989c).

Alternative Products

The use of CFC 12 on-site in hospitals can be eliminated by switching either to disposables equipment, or by utilizing an outside contractor for sterilization (Harmon and Rhodes, 1988).

SIGNIFICANT PROBLEMS FOR CFC SUBSTITUTES

The preceding sections of this report have noted specific advantages and disadvantages of various processes for replacing CFC use in several areas of commerce. Economic and technical considerations of the applicability of a given substitute for CFCs must always be considered in the context of a specific industrial process and of the economy in which that process is used. It is important, however, to note some general features of proposed CFC substitutes that influence their environmental and commercial desirability, regardless of the specific application.

HFCs/HCFCs

HFCs and HCFCs, being the chemicals that most closely resemble CFCs, tend to share their disadvantages as well as their advantages. Thus it is important to remember that while HCFCs have reduced ozone depletion potential, they still have some. Further, both HFCs and HCFCs are "greenhouse" gases that may contribute to global warming. Moreover, while initial data indicate that these compounds are relatively non-toxic and environmentally benign, it should be remembered that relatively little data has been obtained thus far. Even with the extensive research efforts currently underway, it will be years before all the important questions are resolved.

Hydrocarbons

Probably the key consideration for hydrocarbons is their flammability. Indeed, most are routinely used as fuels. Because of their flammability, many are subject to regulation (UNEP, 1989h), such as requirements for the addition of odorants to them when they are transported. Such odorants must subsequently be removed before these chemicals are suitable for some uses (UNEP, 1989a). Also, in some jurisdictions, emission restrictions on hydrocarbons could require additional capital equipment (UNEP, 1989d).

Alcohols

Most alcohols also pose questions of flammability, though they tend to present lower levels of concern than do hydrocarbons. Some, however, raise significant concerns with regard to toxicity. For example, isopropanol is subject to testing for neurotoxicity by the U.S. Environmental Protection Agency (OTA, 1989).

Halogenated Solvents

Halogenated solvents have two principal general drawbacks. First, their ozone depletion potential is so high that they may be subject to control under revisions to the Montreal Protocol. Thus they may be of little ultimate value as CFC substitutes. Sources at the U.S. Environmental Protection Agency indicated that they look with suspicion upon suggestions that these chemicals could serve as CFC substitutes. The UNEP solvents panel also noted potential waste disposal problems with all of these compounds (UNEP, 1989c).

Of equal concern are the significant toxic hazards associated with all of the prominent halogenated solvents. For example, carbon tetrachloride, methylene chloride, perchlorethylene, and trichlorethylene are all considered to be probable human carcinogens. Moreover, perchlorethylene and trichlorethylene are degraded in the environment to vinyl chloride, a known human carcinogen. Carbon tetrachloride is not used in the United States or in Western Europe, and the UNEP panel on solvents refused to consider it as an acceptable substitute for CFC solvents (UNEP, 1989c).

Methyl chloroform (1,1,1-trichloroethane) is subject to testing under Section IV of the U.S. Toxic Substances Control Act as a suspected neurotoxicant (OTA, 1989), despite being characterized as having "low toxicity" by a UNEP panel (UNEP, 1989h). Another UNEP panel expressed concern over the market uncertainties likely to result from the prospect of controls for either toxicity or ozone depletion (UNEP, 1989c). It should also be remembered that substitutes exist for almost all uses of methyl chloroform (UNEP, 1989h).

Use of any of these compounds as CFC replacements, in any industry sector, could entail significantly increased investment costs for worker protection (UNEP, 1989d).

Miscellaneous Concerns

Ammonia is flammable and toxic to humans in concentrations above 100 ppm after eight hours of exposure. There is therefore a need for plants using significant quantities to be located away from populated areas, as leaks and accidental discharges of ammonia have caused considerable public concern (see for example *The Community Plume: Air Conditioning, Heating & Refrigeration News*; and Duffy, 1989).

HALON REPLACEMENT

No chemical substitute is currently available to replace halons, and the development of such substitutes is expected to proceed more slowly than for CFCs. An acceptable and known toxicity is proving to be a major obstacle to development of alternative agents. In addition, the

elimination of chlorine and bromine decreases achievable fire extinguishing characteristics. According to researchers there will be no single replacement chemical for halons across the board; they will have to be developed by use category.

Replacements for streaming agents are easier to develop than those for total flood applications. Streaming agents have less restrictive toxicity requirements since contacts between personnel and agent are more limited, and in some instances, can be improved by modification of physical properties to improve streaming performance. Such improvements are not possible for total-flood agents. Replacements for total flood systems are expected to be much bulkier, and much more expensive.

Much of the effort within industry to develop halon alternatives is proprietary, and little detailed information is available. For example, although Japanese companies are known to be working on halon substitutes, no other information is available. Little is known about halon research in the European Community; however, ICI (U.K.) is expected to be the first company to produce a halon substitute. (Tapscott, 1990; UNEP, 1989e) Allied-Signal (U.S.) reports that it is working on sulfur hexafluoride (SF₆) as a substitute for halon 1301. The compound is being tested by the U.S. Navy.

Most of the information available on agent development comes from sources outside of industry. The major nonindustrial effort now in progress in the United States is a program sponsored by the Air Force at the Center for Global Environmental Technology, University of New Mexico. Researchers at the Center have set up a computerized database containing information on more than 650 halocarbons, and divided the compounds into three groups:

- Group 1: compounds for which significant toxicity information is available and could be readily commercialized. Unfortunately, none of these compounds are effective fire extinguishing agents.
- Group 2: compounds for which little toxicity testing has been done, but are expected to have low toxicities. These compounds have better extinguishing capabilities than Group 1 compounds and could possibly be commercialized in the next five to six years.
- Group 3: compounds which are suspected of being toxic, although little toxicity data is available, and must be considered only as long term options. These compounds are expected to be extremely effective fire suppressants (Tapscott and Floden, 1989-90).

A second major program to discover halon alternatives is being developed by the Halon Alternative Research Consortium. The Consortium is being established through the U.S. EPA and includes representatives from both industry and government (Tapscott and Floden, 1989-90;

UNEP, 1989e). The EPA and the Electric Power Research Institute (EPRI) are funding research at the University of Tennessee and at Clemson University on new chemical compounds, mainly three carbon HCFCs and fluoroethers. To date, eight compounds have been synthesized. Some of these compounds may also be applicable as refrigerants or foam blowing agents (Smith, 1990). Remaining efforts in the U.S. include a program at the Battelle Memorial Institute in Columbus, Ohio, U.S.

In the short term, at least, reducing halon emissions will have to rely heavily on changing halon use and improved engineering, rather than chemical substitutes. For example, for certain non-essential computer facilities, water sprinklers could be used. Moreover, new hardware systems, more reliable fire and smoke detectors, localized extinguisher systems, and improved halon transfer systems can help decrease emissions (Tapscott et al., 1989).

ONGOING CFC RESEARCH

In the attempt to find safe and effective alternatives to CFCs, ongoing research efforts are being carried out by industry, government, and cooperative efforts between the two. Under the Program for Alternative Fluorocarbon Toxicity Testing (PAFT), CFC producers from Europe, the Far East, and the United States are pooling their resources to conduct joint toxicity testing on compounds being considered as alternatives to CFCs. Toxicity testing is one of the factors necessary for commercialization of the substitutes, and usually takes about five to seven years, but under PAFT the pace will be accelerated. The toxicity testing program of CFC alternatives began in January 1988 with HCFC 123 and HFC 134a, under the PAFT I program. HCFC 141b was added in September 1988 under PAFT II, followed by HCFC 124 and HFC 125 in July 1989 under PAFT III.⁵ Preliminary results (released in September 1989) indicate that the PAFT I and II chemicals do not show significant toxicity. A final analysis of the acute toxicity test results are expected to be issued by U.S. EPA at the end of February, 1990. Testing on subchronic and chronic toxicity is continuing in eight toxicology testing laboratories in Europe and the United States. Final results on PAFT I and II chemicals are expected to be available in 1992 or 1993 and will be published in peer-reviewed scientific journals (Du Pont, 1988; Du Pont Press Releases on 1/5/88, 9/1/88 and 6/15/89, 9/26/89).

⁵ PAFT I membership includes: Akzo (Netherlands), Allied-Signal (U.S.), Asahi Glass (Japan), Atochem (France), Daikin (Japan), Du Pont (U.S.), Hoechst (Germany), ICI (England), ISC Chemicals (England), Kali-Chemi (Germany), Montefluos (Italy), Racon (U.S.), Showa Denko (Japan), and Ulsan Chemicals (Korea). PAFT II membership includes: Akzo, Allied-Signal, Atochem, Daikin, Du Pont, ISC chemicals, Asahi Glass, Pennwalt (U.S.), and Solvay and Company (Belgium). PAFT III membership includes: Allied-Signal, Atochem, Daikin, Du Pont, ICI, ISC Chemicals, and Montefluos.

Another major industry cooperative is the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS). This study was established in 1988 by 14 companies⁶ to study the environmental effects of the HCFCs and HFCs. Effects studies include ozone depletion potential, global warming potential, decomposition in the atmosphere and resulting products. A draft report of the results was issued in mid-1989, with final publication expected early in 1990 (UNEP, 1989h). Eight of the AFEAS companies followed up with AFEAS II in 1989 to support and participate in the development of information that is essential to complete the studies. AFEAS II will be a three-year, multimillion dollar program focused on research to yield, in the short term, answers to remaining questions on potential environmental effects of the alternatives and their degradation products. (UNEP 1989f, *C&EN*, 1989)

Other research efforts are being coordinated through trade associations. The Polyisocyanate Insulation Manufacturers Association in the United States has organized a foam research and development committee made up of representatives of eight makers of foam insulation board. The committee will evaluate and test new blowing agents. (*FTC Watch*, 1989) In Europe, members of the European Isocyanate Producers Association are conducting research on CFC-free polyurethane products and processes. (*Europe Environment*, 1988)

Several laboratories are conducting research on refrigeration and heat pump substitutes. At the Graz University of Technology (Graz, Austria), a database of 940 substances was systematically screened for optimal working media for compression heat pumps. Out of this number, three substances emerged as possible replacements for commonly used CFC compression heat pump media: ethyl chloride, ethyl bromide and propyl chloride (Narodoslawsky and Moser, 1988).

The Philips Research Laboratory (Eindhoven, Netherlands) is looking at substitutes for CFC 12. The research includes experiments using HFC 152a, dimethylether and cyclopropane in refrigeration (Kuijpers et al, 1988).

In addition to the research they are cosponsoring with the U.S. EPA, the Electric Power Research Institute is also supporting work on refrigerant fluids at the U.S. National Institute of Standards and Technology, and work on home refrigeration design changes in conjunction with New England Electric (Moore, 1989).

⁶ Akzo, Allied Signal*, Atochem*, Daikin Industries, Du Pont*, Hoechst, ICI*, ISC Chemicals, Kali Chem*, La Roche* Chemical (U.S.), Montefluos*, Pennwalt, Racon and SICNG (Greece). (* companies participating in AFEAS II)

The U.S. EPA and Department of Energy are sponsoring a project at the Massachusetts Institute of Technology to better understand the mechanisms of heat transfer through plastic insulation foams and to investigate ways of maintaining or improving thermal performance of foams without using CFCs (Smith and Shapiro, 1989).

Two other research initiatives that have been noted in open literature are taking place in Japan and the United Kingdom. The Japanese Ministry of International Trade and Industry (MITI) is making a budget request for 5.6 billion yen over a five year period, starting April 1990, for research and development of refrigeration fluids. (*Japan Chem Week*, 1989). The government in the United Kingdom plans to invest 10 million pounds over next four years for research on CFC and halon substitutes (*Materials Edge*, 1989).

INVOLVING DEVELOPING NATIONS IN CFC ALTERNATIVES

If developing countries are to avoid the economic and environmental woes associated with continued production and use of CFCs, they will either have to develop alternative technology or import alternative technology already developed by other countries. New technology will be necessary to produce substitute chemicals and manufacture products which use substitute chemicals. Either new technology or existing technology can be used to completely replace CFC-based products and processes. Developing countries may not have many resources to devote to developing new technologies. According to a recent estimate, developing countries account for less than 3 percent of the world's total expenditures on research and development (Stever & Muroyama, 1988). Therefore, it is reasonable to focus attention on technology transfer as the mechanism by which developing nations will gain access to new technology for replacing CFCs.

BARRIERS TO TECHNOLOGY TRANSFER

Potential barriers to technology transfer can be grouped into four broad categories: institutional, technical, cultural/social, and financial. These barriers apply to all technology transfer, and are not specific to alternatives to CFC technology.

Institutional Barriers

Institutional barriers include legal, regulatory or other organizational structures that technology-exporting companies find cumbersome, environmental monitoring and enforcement capabilities that are not equipped to deal with risks posed by the new technology, potentially inadequate patent/copyright protection, or restrictive ownership laws. In South America, for example, industry claims that "anti-colonial" laws and inadequate enforcement of intellectual property rights discourage them from making greater investments. (EPA, 1989f)

Technical Barriers

Some technologies, to be successfully implemented, require the availability of adequate numbers of appropriately trained technical personnel. Many developing countries lack the educational infrastructure to support imported technologies, and face a need to employ foreign technicians, which decreases the net benefits of technology transfer. For CFC alternatives, this may not pose as great a problem as for some other technologies. If a country has a domestic CFC production industry, it should have the technical resources necessary to produce, if not to develop, alternative chemicals. If it has industries that are CFC-dependent, but does not produce CFCs, it may be able to obtain replacement technology products from its current suppliers of CFC-based technology.

As was noted in the preceding discussion of CFC replacement in various industry sectors, a number of alternatives to CFC-based technologies are comparatively "low-tech" (such as the replacement of foam furniture padding with cotton). For such technologies, developing countries may be at an advantage relative to developed countries (not being bound by current capital investments), and may not even require extensive technology transfer. A switch to CFC alternatives derived from natural products may provide a significant economic benefit to developing countries without any appreciable technology transfer. What would instead be required is appropriate international marketing of existing products as more environmentally benign than CFCs.

One crucial consideration for the chemical alternatives to CFCs and halons is that almost all such chemicals have greater toxicity and potential for local environmental damage than do CFCs. Thus it is essential that a country acquiring such technologies be adequately prepared to deal with these hazards, both from an institutional and a technical perspective. For CFC production replacement, one would hope that methods were already in place, as many CFC precursor chemicals, unlike CFCs per se, are highly toxic. Careful consideration should be given, however, to the preparations of CFC user industries to deal with toxic replacement chemicals.

Cultural/Social Barriers

Social and cultural barriers to technology transfer include the difficulty scientists and engineers have in accepting technology from an external source, let alone another nation. In the U.S., this tendency has even received an acronym, NIH (for "not invented here"). Differences in economic systems and work culture must be overcome for collaboration between nations to occur. (Beckers, 1988) Such differences extend beyond the availability of appropriately trained personnel, as discussed above, and also include differing perceptions or awareness of risk. Technology transfer

must also consider language and communication barriers. The tragic incident of organomercury poisoning in Iraq from donated grain treated with fungicides provides clear testimony on the need to consider local cultural factors when transferring potentially toxic technologies.

Financial Barriers

The lack of hard currency or insufficient funds for commercial licenses, equipment and operation and maintenance expenses are continuing concerns for all technology transfer. (EPA, 1989f) It has also been noted that "The desire to preserve domestic employment and to maintain domestic production for reasons of national security are important barriers to international technological cooperation." (Beckers, 1988) Mechanisms to overcome these barriers are in no way specific to CFC alternatives, and are beyond the legitimate scope of this report.

BORROWING TROUBLE

Some newly industrialized countries have indicated that they had already begun investment in CFC-dependent technologies. (Ridley, 1989) Du Pont has testified that at least six CFC plants have either started up or are under construction in "Less Developed Countries" (LDCs) since the Montreal Protocol was available for ratification. Further, that company received five requests from other LDCs for CFC technology or equipment, despite Du Pont's announcement that it would not transfer CFC production technology. (Du Pont, 1990)

EFFORTS TO OBTAIN CFC REPLACEMENT TECHNOLOGY

Developing countries have historically obtained CFC-based goods and services first by importing them and then through a combination of import and local manufacture. In introducing a technology to a developing country, the foreign company or importers usually provide a combination of investment capital and technology, an international lending or development institution may assist with financing, and local business usually provides marketing input and a method of distribution. (EPA, 1989f)

Passive Processes

To some extent, given enough time, the international conversion to CFC substitutes would occur through normal commercial channels. Du Pont, ICI and other multinational corporations now developing chemical substitutes can be expected to evaluate market and other conditions in developing countries and, if they consider doing so to be economically desirable, to convert or build new facilities to produce CFC substitutes. Similarly, AT&T and other multinational corporations throughout the world are likely to assist their subsidiaries and foreign suppliers with the technology, capital and technical assistance necessary to convert, build or operate manufacturing facilities which use the CFC substitutes. As noted earlier, multinational

corporations have continuing concerns regarding compensation and protection of intellectual property rights. (EPA 1989e)

If technology transfer is to be accelerated, development assistance will be required in most cases. UNEP has noted (UNEP, 1989i) that currently available resources to facilitate technology transfer are already strained as a result of the world debt problem and the dire economic situation of many countries, and suggests that funds for financial assistance could be raised by charging for CFC use. The U.S. EPA has also expressed concern that industrialized nations will find that additional incentives are necessary, especially for those developing countries that do not qualify for the ten year grace period under the Montreal Protocol. They, too, argue that financial assistance to developing countries for CFC alternatives should be in addition to current levels of bilateral and multilateral assistance, noting a sensitivity of developing countries to diversion of funds intended for other developmental purposes to support their participation in the Montreal Protocol. (EPA 1989e)

Active Efforts by Developing Countries

Developing countries generally accept scientific evidence indicating the severity of ozone depletion, and most have indicated their desire and responsibility to help protect the ozone layer. However, the developing countries continue to express their concern about the availability and especially the cost of substitute chemicals, products and technologies. (Ridley, 1989) Some of this concern may reflect a narrow focus on direct chemical substitutes currently being investigated in industrialized nations, rather than a consideration of the wide range of technologies that could lessen dependence on CFCs.

Given the capital-intensive, experimental and small-scale nature of current production facilities for direct chemical substitutes for CFCs, it has been suggested that the developing countries may not want to invest in their own production facilities at this time. Instead, they may wish to concentrate on obtaining technologies that are either made with or contain substitute chemicals, while relying on existing producers until the relative promise of alternative replacement technologies becomes clearer (EPA, 1989f)

Efforts by Industrialized Countries

Several countries have called for an international fund be set up to help developing nations with the costs of implementing CFC substitutes. This concept has not yet gained wide support among industrialized nations, and raises issues such as who contributes how much, how will the money be distributed, and who will oversee the fund. Some organizations concerned with implementing

the Montreal Protocol, however, have noted the importance of aid programs in accomplishing this global goal:

"Bilateral and multilateral aid would have important roles to play. Ways of helping developing countries should be a major feature of the review of the Protocol, and should be urgently examined in all appropriate international contexts. It was pointed out that rapid rates of population growth with increased per capita use of resources will pose unique threats to the biosphere. Technical solutions were needed to help solve their human problems. (Ridley, 1989)

"Recommends that, initially, international funding be directed towards funding of a CFC phase-out in developing countries in the context of the Montreal Protocol." (Noordwijk Declaration, 1989)

The US and other industrialized nations are now working with several developing countries in carrying out a series of case studies to serve as the basis for estimating the overall needs of developing countries for support in replacing CFC-based industry. Carried out in Mexico, Egypt, Brazil, China and other developing countries, the studies will help determine each country's current and projected demand for ozone-depleting substances and the projected costs of making the transition to substitute chemicals, products and technologies. Preliminary results from the studies are due by the June 1990 meeting of Protocol Parties in London. (EPA 1989f)

UNEP and EPA have both commissioned studies to evaluate potential financing arrangements. There have been government and industry missions to China, the Soviet Union, Hungary, and Yugoslavia to discuss stratospheric Ozone depletion and potential trade opportunities. EPA is also working with the Association of Southeast Asian Nation (ASEAN) in planning a workshop next year on the use of CFCs as solvents in electronics and other applications. (EPA, 1989f)

In May 1989, the parties to the Montreal Protocol established a working group to develop recommendations on financing and other mechanisms to assist developing countries in implementing the Protocol. The group held a series of meetings last summer and fall in Nairobi and Geneva and will continue to meet this spring in Geneva. It will submit its recommendations for formal consideration at the June 1990 meeting of Protocol parties in London.

INSTITUTIONS FOSTERING THE TRANSFER OF CFC-REPLACEMENT TECHNOLOGY

- the National Environmental Technology Application Corporation, a joint venture between EPA and the University of Pittsburgh to encourage the commercialization and transfer of environmental technologies.

- the International Environmental Bureau has been created by the International Chamber of Commerce to serve as a clearinghouse for information on global warming which could also serve the same function for information on CFC substitutes.

- the International Environmental Technology Transfer Advisory Board (IETTAB), whose purpose is to provide advice and counsel to the Administrator of EPA and other concerned agencies on the transfer of environmental technology and information to developing and centrally planned economies which cannot afford the science and technology involved, and may need assistance in using such environmental technology effectively. (EPA, 1989f)

- Industry Cooperative for Ozone Layer Protection, a consortium of 10 major electronic firms in the U.S. which are working with EPA to eliminate the worldwide use of CFCs. The cooperative acts as a clearinghouse for information on alternative solvents, and will distribute information world wide, particularly to developing countries. (10/10/89 Press Release)

- The European Fluorocarbon Technical Committee has announced the intent of the European Chemical Industry to make alternatives equally available to the industries of all countries, as the technology becomes established. Methods to accomplish this include providing information and technical assistance on the use of alternative products, offering alternatives for sale, and building and operating production facilities for alternatives where appropriate. (UNEP, 1989b)

UNEP is working on barriers to technology transfer and possible solutions - basically, financial resources and proprietary rights (patents). The latter are being reviewed in cooperation with industry through the International Chamber of Commerce or with the World Intellectual Property Organization. (UNEP, 1989f)

RESULTS OF TECHNOLOGY TRANSFER EFFORTS

Thus far, the efforts of organizations attempting to foster technology transfer have not yielded many concrete results. Initial products of such efforts are, however, becoming available. One Example of such technology transfer is the manual published and distributed by Northern Telecom and the U.S. EPA for CFC 113 users in the electronics industry, to help them reduce or eliminated CFC-113 use. The information is based on practices adopted at Northern Telecom that can serve as an example for companies worldwide. (ICF, 1989)

EPA's Air and Energy Engineering Research laboratory has published two reports describing alternatives to CFC usage in aerosol products with a major goal of encouraging other countries to move away from this CFC application. (Smith, 1990, EPA 1989bc)

Du Pont is assisting their customers in development of technology to use HCFCs and HFC. The ability of the users of these alternatives to develop and produce equipment using alternative technology is currently the limiting step to a total CFC phaseout.

CONCLUSIONS

The development of alternative technologies that lead to decreases in the release of CFCs and other ozone-depleting chemicals to the environment is as important, if not more important, for developing countries than for industrialized countries. It must be remembered, however, that it is not necessarily a good idea for developing countries to pursue the same paths as industrialized countries in reducing the production and release of CFCs. Much of current release is occurring in the industrialized nations, and developing nations can, in the near term, contribute to the solution of the CFC problem by not adopting new CFC-based industry.

Further, it should be kept in mind that many of the current alternatives to CFCs developed by the industrialized countries reflect the desire to minimize unfavorable economic impacts that would be incurred if their heavy capital investment in CFC-based technology had to be extensively modified or scrapped prior to the expiration of its normal working life. Nations that have less capital investment in CFC-based technologies may not face similar economic constraints, particularly if they refrain from acquiring new CFC-based industry. The optimal approach for such countries may be to avoid investing in near-term CFC substitution technologies (such as those using HCFCs), which may themselves have to be replaced within the next two decades, and instead to await (or actively attempt to develop) more permanent alternative technologies.

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