

Montreal Protocol

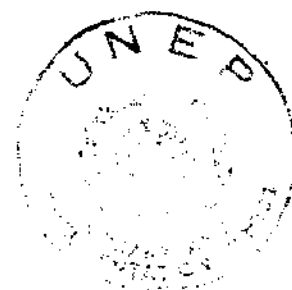
1991 Assessment



Report of the

**Flexible
and
Rigid Foams**

Technical Options Committee



**1991 UNEP FLEXIBLE AND RIGID FOAMS
TECHNICAL OPTIONS REPORT**

**PURSUANT TO ARTICLE (6) OF THE
MONTREAL PROTOCOL ON
SUBSTANCES THAT DEplete THE OZONE LAYER
UNDER THE AUSPICES OF THE
UNITED NATIONS ENVIRONMENT PROGRAMME**

FINAL

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**1991 UNEP FLEXIBLE AND RIGID FOAMS
TECHNICAL OPTIONS REPORT
EXECUTIVE SUMMARY**

Consumption of fully halogenated chlorofluorocarbons (CFCs) by the foam plastics manufacturing industry is extremely varied. An assortment of CFCs, such as CFC-11, CFC-12, CFC-113 and CFC-114, have been used in numerous foam plastic product applications.

In 1990, building and appliance insulation applications consumed about 140,000 metric tonnes, which is equivalent to 80 percent of the CFCs used in foam plastics that year, while the remainder was spread among other product applications, such as cushioning, packaging, flotation and microcellular foams.

This report details the available technical options that can be implemented by each foam market segment to completely eliminate CFC usage known as of 1991. Updates on the progress of each market segment in reducing CFC consumption since 1986 (summarised in Figure ES-1) are also provided.

However, it should be noted that specific technical options and the extent of CFC reduction achieved to date are quite different for each foam application and market sector.

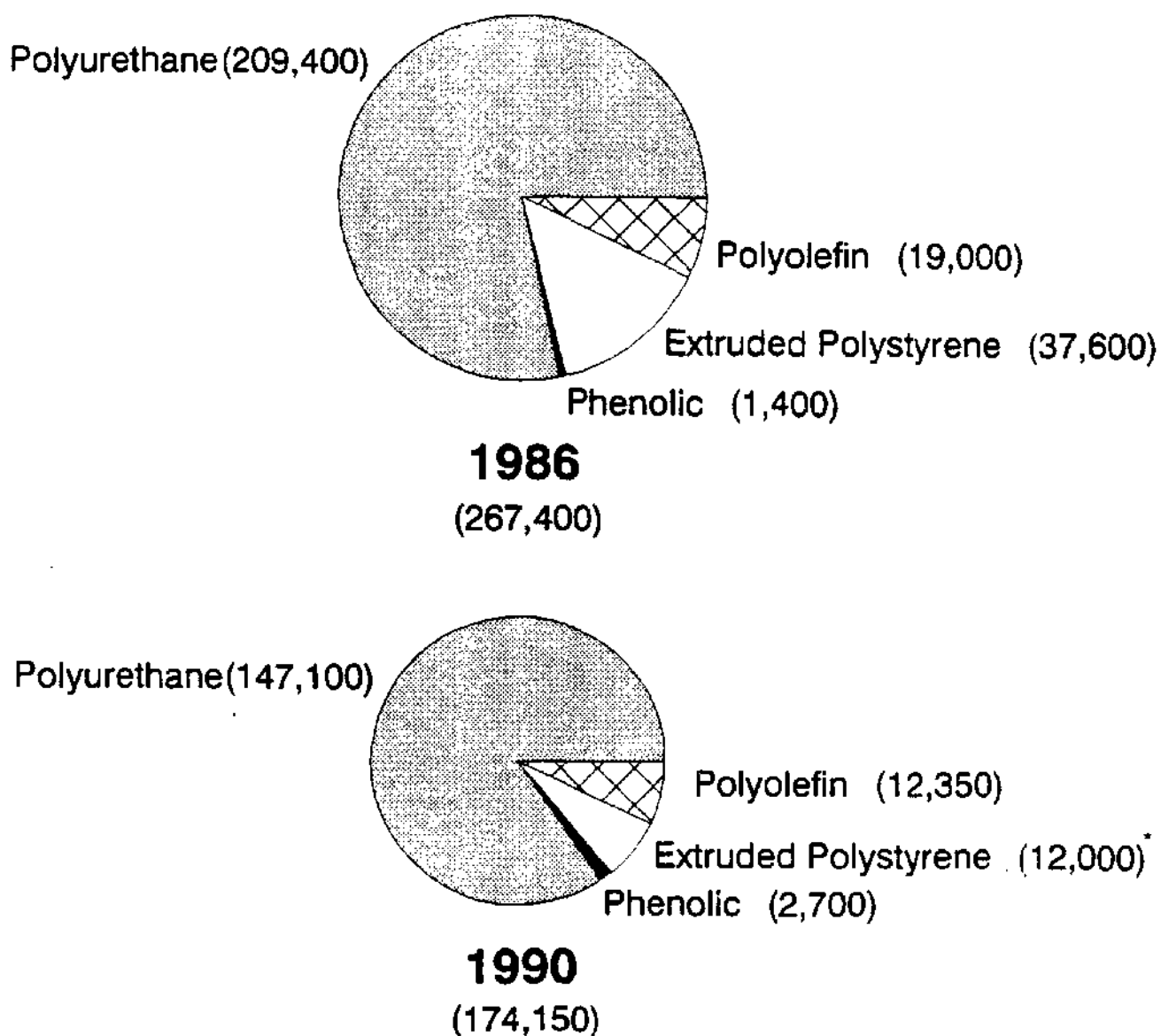
Consequently, key factors affecting the total elimination of CFCs from the foam plastics manufacturing industry are also discussed.

Status of CFC Reductions and Projected Phaseout Schedule

Global CFC consumption has been reduced in every market sector since 1986, despite industry growth during the last five years. Reductions have been achieved by CFC conservation, product reformulation, direct substitution of CFCs with other blowing agents, and the use of new manufacturing technologies.

Global CFC consumption in all foam sectors has declined by about 35 percent, from 267,000 tonnes in 1986 to 174,000 tonnes in 1990. In general, the greatest reductions in CFC consumption have been achieved by developed nations. As discussed later, developing countries also are working to achieve similar CFC reductions but may require additional time as the Montreal Protocol suggests.

Figure ES-1. CFC Consumption by Foam Sector: 1986 vs. 1990
(tonnes)



* This figure represents the amount of CFCs used worldwide in extruded polystyrene boardstock production. A virtual phaseout of CFCs has been achieved in the extruded polystyrene sheet industry in developed countries, while a small undetermined amount of CFCs is assumed to be used for sheet production in developing countries.

Phaseout dates discussed below focus on developed countries. Specific industry sector reductions and phaseout schedules include the following:

An 77% reduction in CFC use for flexible polyurethane foam -- Polyurethane foam industry sectors achieving the highest percentage of reductions include the flexible slabstock and moulded foam, integral skin, and packaging markets. By 1994, the majority of the worldwide producers in these sectors will have eliminated the use of CFCs.

A 6% reduction in CFC use for polyurethane foam insulation -- Despite 20 to 25 percent growth in the polyurethane foam insulation sector since 1986, CFC consumption has been cut by six percent. This equates to an average 30 percent reduction in CFC consumption per tonne of foam. A virtual phaseout of CFCs should be technically achievable by 1995 -- assuming HCFCs are both commercially viable and available.

An average 20% cut in CFC consumption per tonne of foam for phenolic foam insulation products -- The phenolic sector has, in fact, grown in its CFC consumption since 1986, but this has been from a base of less than 2,000 tonnes. Phenolic foam growth has been primarily at the expense of other CFC-containing insulation products. Therefore, to gain a true picture of phenolic foam's contribution to the foam plastic insulation industry's net reduction in CFC usage, evaluations must include a comparison of the respective progress being made with advancing product technologies. The industry estimates that a total elimination of CFCs is possible by 1995, but again this is contingent on both the commercial viability and availability of HCFCs.

A 32% reduction in CFC use for extruded polystyrene boardstock insulation -- Global CFC consumption in extruded polystyrene boardstock insulation foam has been declining since 1988 when the worldwide industry committed to convert from CFC-12 to HCFC-142b/HCFC-22 blends and other alternatives. The industry sector predicts a complete conversion by the end of 1993.

A 35% cut in CFC usage for polyolefin packaging -- It is technically possible to have complete conversion of most polyolefin foam products to new blowing agent systems using hydrocarbons and HCFCs by the end of 1993.

Extruded polystyrene packaging nears complete phaseout of CFCs -- Since 1988, global CFC consumption has been declining rapidly in extruded polystyrene packaging foams. A virtual phaseout has been achieved in developed countries.

Developing Country Issues

Due to the diversity of developing countries, their specific needs will vary. Consequently, even with technology proven in developed countries, some developing countries may

require additional time to achieve CFC reductions whilst other developing nations have committed to phaseout schedules similar to those of developed countries.

The extra time may be needed for some developing countries to:

- evaluate CFC replacement technologies;
- establish national government support and policy; and
- coordinate government and industry activities.

Even when uncertainties surrounding CFC alternatives are resolved, additional time may also be required to facilitate the transfer and implementation of replacement technologies.

Both the capital and operating costs associated with the conversion to CFC substitute technologies should be considered for funding under the Multilateral Fund.

Key Factors Affecting Further Reductions in CFC Use

The global foam plastics industry is evaluating a variety of potential CFC alternatives; however, there are considerable uncertainties affecting several of these options at this time. This section summarises these key factors and uncertainties, and discusses the possible impact on the timing and the rate of CFC replacement.

Toxicity

Concerns over human health impacts of CFC substitutes include:

- worker and consumer exposure to alternative blowing agents; and
- exposure to possible decomposition products formed in foams.

Two of the key short/intermediate term CFC alternatives, HCFC-123 and HCFC-141b, are still undergoing toxicity testing. Final results will not be fully known until 1992-93.

The preliminary toxicity findings on HCFC-123 and the decomposition products from HCFC-123 and HCFC-141b in polyurethane formulations and foams are examples of the uncertainties still existing and affecting the commercialisation of these products.

In addition, some non-HCFC substitutes, such as methylene chloride, have toxicity concerns and are strictly regulated in some areas.

Flammability

Some CFC alternatives, such as HCFC-142b, HCFC-141b, HFC-152a, acetone, pentane and other hydrocarbons, present varying degrees of flammability. The procedure required for their handling will depend on the degree of flammability; in some instances, flammability may limit the use of a CFC substitute.

In order to safely use flammable alternatives, it is necessary to complete the evaluation of these critical areas:

- manufacturing risks from ignition;
- storage and transportation of foam products; and
- finished product fire performance.

Environmental Concerns

It is necessary to consider environmental effects, such as stratospheric ozone depletion, ground level air pollution, global warming, and tropospheric degradation products, when choosing CFC substitutes.

Ozone Depletion Potential

The HCFCs identified or used as CFC substitutes in foam manufacturing have a much lower ozone depletion potential (ODP) than CFCs. However, their unrestricted, long term use would contribute significant amounts of chlorine to the stratosphere.

ODP values vary among the different HCFCs; for instance, the ODP of HCFC-141b had been estimated to be 0.10; however with new scientific data, the ODP may be adjusted upwards. In contrast, HCFC-123 has an ODP of 0.02.

HCFCs are viewed as transitional alternatives to be used while non-ODP, chlorine-free alternatives are developed. In insulation applications, where HCFCs are crucial, efforts are being made to minimise the ozone depleting impact of the blowing agent by judicious foam formulation and to eliminate HCFC use as quickly as possible.

Tropospheric/Ground Level Air Concerns

CFCs are organic chemicals which react negligibly in the lower atmosphere. However, some CFC alternatives, such as pentane, butane, and other hydrocarbons, are classified as volatile organic compounds (VOCs) because they

undergo photochemical reactions in the lower atmosphere and contribute to smog formation.

As a result, even though these alternatives can find applications in many foam sectors, they may be strictly regulated on a regional basis. For example, the US strictly regulates emissions of hydrocarbons. Ultimately, regional regulations may restrict the use of these CFC substitutes even though they are technically feasible options.

The tropospheric degradation of HCFCs and HFCs is being assessed by AFEAS.

Global Warming Potential

The global warming potential (GWP) of a compound is a function of its atmospheric lifetime and its ability to absorb infrared radiation. CFCs have high GWPs.

The leading CFC substitutes have lower GWPs. The relative ability of a CFC substitute to act as a greenhouse gas together with its total emission volume into the atmosphere will affect the choice of alternatives.

While CFCs and CFC substitutes have GWPs, the major contributor to global warming is carbon dioxide produced by the burning of fossil fuels. In their report, the US Department of Energy and AFEAS have determined that the energy efficiency of HCFC-blown foam insulations can reduce fossil fuel consumption sufficiently to decrease the overall global warming effect from use of HCFCs in these foams.

Insulation Efficiency

The use of alternative blowing agents or non-CFC insulation materials in insulation products can impact the energy efficiency of the finished product.

In general, the drop-in replacement of CFCs with HCFCs or other alternative blowing agents resulted in products which were poorer insulators. However, once CFC substitutes had been selected, research and development efforts were focused on reformulation around the chosen substitute and modifications to the foam technology. This effort has resulted in products with equivalent insulation efficiency.

Ultimately, the acceptability of alternative blowing agents is dependent upon the performance, cost-effectiveness and competitiveness of the finished product in a particular application. The market price of any alternative system is often the determining factor as to whether a substitute can be used and sold competitively on the market. This has already been found to be a significant barrier to substitution, particularly in recessionary environments.

For applications requiring high insulation efficiency, the choice of alternatives is more limited. If reliability and commercialisation problems can be overcome, new products, such as composite vacuum panels for refrigerators, could offer both increased energy efficiency and the elimination of CFCs.

National and Regional Legislation

While the global foam plastics industry is committed to totally eliminating CFCs from all product formulations in the minimum practical time-period (as previously detailed on page ES-3), industry efforts may be affected by differing national and regional legislation regulating the phaseout of CFCs. This legislative diversity and inconsistency can create obstacles that impede the implementation of a smooth transition plan to CFC substitutes, particularly for companies serving multinational markets.

Adhering to the regulatory stipulations of international agreements, such as The Montreal Protocol, offers a more effective and efficient phaseout strategy for the industry worldwide.

Conclusions

For the near term, the use of HCFCs presents the quickest path to complete elimination of CFCs in foam plastic product formulations, as presented in Table ES-1. However, uncertainties about HCFCs' impact on human health and ozone depletion may hamper the commercial availability of these alternative blowing agents -- leading to a slow down of the phaseout of CFCs.

For the polyurethane, phenolic and polystyrene foam insulation sectors, such as appliance, boardstock, and other insulation applications, replacing CFCs in the near term will require the commercialisation of HCFC-141b and HCFC-123 and the continued availability of HCFC-22 and HCFC-142b.

The CFC phaseout rate in insulation applications will be dependent upon the ultimate cost of HCFCs and the competition of more cost-effective, CFC-based products still on the market.

In the extruded polystyrene insulation sector, a worldwide transition from CFC-12 to HCFC-142b and HCFC-142b/HCFC-22 blends has been slowed due to the uncertainties surrounding the environmental acceptability of those HCFCs. Consequently, manufacturers in some nations, particularly developing countries, have been reluctant to make capital commitments to the conversion process. Manufacturers are hesitant because they are not confident that this will be the final conversion process.

Similarly, many chemical manufacturers have been cautious about making capital investment decisions to build increased capacity or new facilities for HCFC-141b and/or HCFC-123 due to these uncertainties.

Table ES-1. CFC Alternatives Available to the Foam Industry

Type of Foam	CFC Alternatives		
	Immediate	Short/Intermediate Term	Long Term
Polyurethane:			
Rigid: Appliance	Reduced CFC-11, 100% CO ₂	HCFC-141b, HCFC-123, perfluorocarbon*, HCFC-22, HCFC-22/HCFC-142b blends	HFCs, fluorinated ether, vacuum panels, perfluorocarbon, hexafluorobutane
Boardstock/ Flex-Faced Lamination	Reduced CFC-11, 100% CO ₂ , pentane, 2-chloropropane**, HCFC-22/HCFC-142b blends	HCFC-141b, HCFC-123, HCFC-22, HCFC-22/HCFC-142b blends, perfluorocarbon*	HFCs, fluorinated ether
Sandwich Panels	Reduced CFC-11, 100% CO ₂ , pentane, HCFC-22/HCFC-142b blends, HCFC-22	HCFC-141b, HCFC-123, HCFC-22, HCFC-22/HCFC-142b blends	HFCs, fluorinated ether, vacuum panels
Spray	Reduced CFC-11, 100% CO ₂ , HCFC-22	HCFC-141b, HCFC-123	HFCs, fluorinated ether
Slabstock	Reduced CFC-11, pentane	HCFC-141b, HCFC-123, HCFC-22, HCFC-22/HCFC-142b blends	HFCs, fluorinated ether
Pipe	100% CO ₂ , HCFC-22, HCFC-22/HCFC-142b blends, methyl chloroform	HCFC-141b, HCFC-123, HCFC-22	HFCs, fluorinated ether, 100% CO ₂
Flex: Slab	Extended-range polyols, softening agents, methylene chloride, methyl chloroform, acetone, AB Technology, increased density	HCFCs***	Dissolved CO ₂ , reduced barometric pressure
Moulded	Methylene chloride, increased density, methyl chloroform, extended range polyols	HCFCs***	
Integral Skin	HCFC-22, hydrocarbons, water substitution, methylene chloride, air loading, high active polyol, 100% CO ₂	HCFC-141b, HCFC-123	100% CO ₂ , HFCs
Phenolic	Hydrocarbons, HCFC-22/HCFC-142b blends	HCFC-141b, HCFC-123, HCFC-22/HCFC-142b blends	HFCs
Extruded Polystyrene:			
Sheets	HCFC-22, hydrocarbons, 100% CO ₂ , HFC-152a	HFC-152a, HFC-134a, hydrocarbons, 100% CO ₂	100% CO ₂ , hydrocarbons, Atmospheric gases/resins, HFC-152a, HFC-134a
Boards	HCFC-22, HCFC-142b	HCFC-142b, HCFC-124, HCFC-22	HFCs
Polyolefin	Hydrocarbons, HCFC-22, HCFC-142b, 100% CO ₂	100% CO ₂ , inorganic gases, HFCs, hydrocarbons	

* To be used as an additive or a co-blowing agent.

** Proprietary technology.

*** Not likely to be used.

The use of HCFCs, such as HCFC-141b, HCFC-123, HCFC-124, HCFC-142b and HCFC-22, can immediately reduce the negative impact of CFCs on the ozone layer. At the same time, these alternative blowing agents can offer industries and governments the required time to evaluate the technical feasibility, cost-effectiveness and environmental acceptability of long term options currently under consideration to replace HCFCs.

It must be recognized that not all options being evaluated as long term solutions will be feasible. Concerns related to technical barriers, toxicity, economics, commercial availability, equipment developments, safety or environmental impact may limit or eliminate some options presently being considered.

Failure to allow industry to use HCFCs as transitional substitutes in the near term will result in continued use of CFC-11 and CFC-12 for several more years. This consequence poses more harm to the ozone layer than the introduction of HCFCs with a time constraint for acceptable use.

Estimation of Future HCFC Use by the Foam Industry

Making accurate estimates of the quantities of HCFCs likely to be needed for achieving a quick phaseout of CFCs in the foam industry is difficult because the baseline is constantly changing. Growth in the foam plastics industry (particularly in insulation sectors) has been estimated at roughly five percent annually.

Many companies have been making individual judgements on the best choice of CFC alternatives for their own particular situation. Taking all factors into consideration, especially the uncertainties about the commercial acceptability of HCFCs, some companies have made decisions to move to immediately available non-HCFC alternatives like pentane and 100 percent water blown formulations.

These corporate decisions are often made based on the following criteria:

- the ability of the finished product to be cost-effective and competitive in the market;
- the ability to adjust thickness to compensate for efficiency losses; and
- the impact of national and regional legislation requiring immediate elimination of CFCs in many foam applications.

As noted, estimating an accurate level of current HCFC use or the demand in the future is difficult, but the foam plastic product applications that will rely the most on HCFCs to achieve the quickest phaseout of CFCs can be identified. These applications include polyurethane, phenolic and polystyrene insulation products, and certain polyolefin packaging and polyurethane integral skin for automotive product applications (presented in Table ES-2).

Table ES-2. Importance That HCFC Substitution Will Play in Each Foam Sector

Sector	HCFC Importance in the Phaseout of CFCs	Estimated CFC Phaseout Date*
Polyurethane		
Rigid		
Appliance	★★★	1995
Construction	★★★	1995
Transport	★★★	1995
Packaging	★	1991
Integral Skin	★★	1993
Flexible	★	1993
Phenolic	★★★	1995
Extruded Polystyrene		
Sheet	★	1988** -1990
Board	★★★	1993
Polyolefin	★★	1993

★★★ Very important

★★ Important for some applications

★ Not very important

* Assumes availability and use of HCFCs.

** Portion of industry that converted to HCFC-22 is in the process of phasing out.

It has been projected, based on the current CFC market and the importance of HCFCs in insulation and other special end use categories that 150,000 tonnes of HCFCs per year would be required to achieve a CFC phaseout in foam plastics in the developed countries in 1995.

As stated in the 1989 Foam Technical Assessment, it still is anticipated that a virtual elimination of CFCs worldwide in all foam uses is technically achievable in developed countries around 1995 under the assumption that HCFCs are available and commercialised around 1993.

Without the HCFCs, many foam manufacturers have few other options based on current technology. Foam manufacturers, particularly those that produce insulation products, would have to offer products without CFCs or HCFCs. In turn, the products may have poorer physical properties, poorer fire performance properties, higher cost, and poorer insulating value compared to those made with CFCs.

Chapter One

THE USE OF CFCs IN THE PRODUCTION OF FOAM PLASTICS

This report describes the use of chlorofluorocarbons (CFCs) in the production of foam plastics and foam plastic products. Prepared by the United Nations Environmental Programme (UNEP) Foam Technical Options Committee (committee members are listed in Appendix B), this report also discusses alternatives to reduce CFC use, and includes a compilation of the committee's findings to date.

Foam plastics that are made with CFCs and discussed in this report include:

- polyurethane;
- phenolic;
- extruded polystyrene; and
- polyolefin (polyethylene and polypropylene).

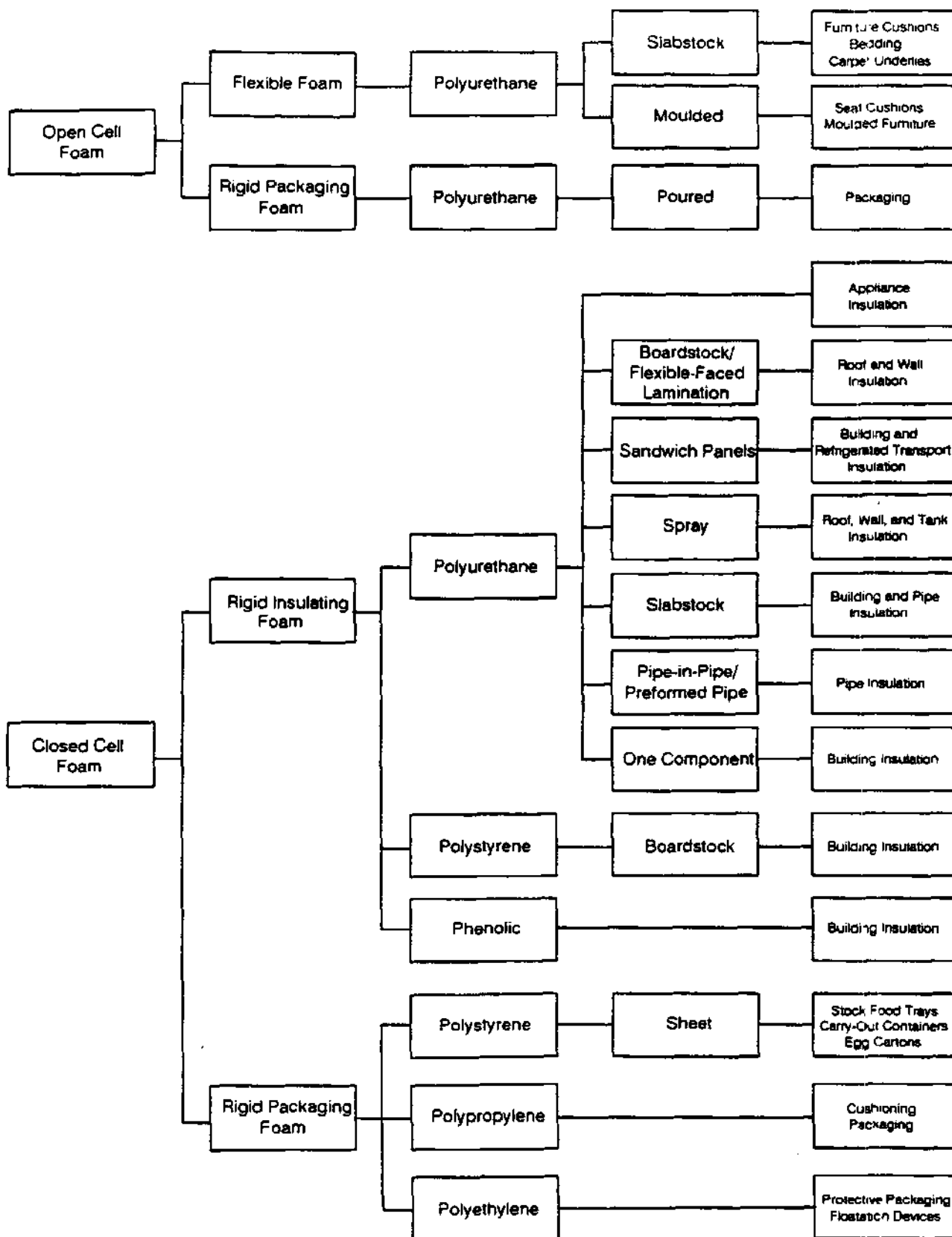
Foam plastics made with blowing agents other than CFCs are mentioned only where they may be product substitutes or where they may clarify the scope of a particular section. Expanded polystyrene and polyvinyl chloride foams are examples of plastic foams which are not made with CFCs.

In this report, a chapter is devoted to each of the four foam types made with CFCs. Each chapter discusses the various types and applications of the foam, the production process, the use of CFCs during production, and alternatives for reducing CFC use in foam manufacturing.

Introduction

Foam plastics can be classified on the basis of composition, chemical and physical characteristics, the manufacturing processes, or product applications, as shown in Figure I-1. The major applications for foam plastics include thermal insulation, cushioning, and packaging.

Figure I-1. Types and Major Uses of CFC-Blown Foam



Foam plastics are produced by using gas or volatile liquid "blowing agents" to create bubbles or "cells" in the plastic structure. Thermoset foam plastics (polyurethane and phenolic) are made by introducing a volatile liquid blowing agent into liquid precursors. During the exothermic reaction between precursor chemicals to form a plastic, the liquid blowing agent volatilises to a gas, forming bubbles which create a cellular structure when the plastic hardens. In contrast, thermoplastic foams (polystyrene and polyolefin) are produced by injecting a gas blowing agent into a molten plastic resin.

In some foam plastics, the resulting cells are closed, trapping the blowing agent inside, while in others, the cells are produced open and the blowing agent escapes.

A number of materials can be used as blowing agents, among them carbon dioxide, hydrocarbons, and chlorofluorocarbons. To be considered a good blowing agent, it is required that they:

- do not react with the plastic;
- be sufficiently soluble in the liquid plastic, but insoluble in the solid plastic; and
- possess suitable boiling points and vapour pressures.

For some foam plastic products (particularly the closed-cell foams), additional blowing agent properties are required to produce specific end-product characteristics or to facilitate the manufacturing process. Product examples include:

- closed-cell insulating foams that require a blowing agent with low thermal conductivity to provide its high thermal insulation efficiency;
- some thermosetting foams (especially the low-density, flexible polyurethane foams) that rely on blowing agents to absorb some of the heat released during production;
- extruded thermoplastic foams that rely on the blowing agent to absorb some of the heat of the molten polymer; and
- resilient closed-cell foams (especially polyolefins) that require the blowing agent to provide dimensional stability during the air-aging period.

In addition, a non-flammable blowing agent is desirable because it helps improve the safety of the foam manufacturing environment and enhances the fire performance characteristics of the end product.

Since they met these requirements and were, until recently, relatively inexpensive, CFCs have been widely used as blowing agents for foam plastics. Historically, the foam plastics industry has used the following CFCs:

- CFC-11 and CFC-113 for thermosetting foams since these blowing agents are liquid chemicals; and
- CFC-12 and CFC-114 for thermoplastic foams since these blowing agents are lower boiling point gases.

This report discusses a second group of blowing agents: partially-halogenated chlorofluorocarbons (HCFCs). Featuring at least one hydrogen atom in the molecule and a carbon-hydrogen bond, HCFCs are less chemically stable than CFCs and tend to break down in the lower atmosphere. Consequently, HCFCs' ability to migrate to the stratosphere and to decompose into ozone-damaging chlorine is much lower than CFCs. Chemicals in this group include:

- HCFC-22;
- HCFC-123;
- HCFC-124;
- HCFC-141b; and
- HCFC-142b.

Currently, HCFC-22 and HCFC-142b are commercially available. The other HCFCs are still undergoing toxicity and technical evaluation, and will require full commercialisation prior to their use.

Significant reductions in CFC use for foam blowing applications can be attributed to the use of HCFC-22 and HCFC-142b. Further reductions are anticipated with the commercialisation of HCFC-123, HCFC-124 and HCFC-141b.

Because recent scientific evidence suggests that depletion of the ozone layer has been occurring over the past decade at a rate faster than previously thought, international restrictions on the production and consumption of CFCs and other ozone-depleting chemicals have been tightened.

In 1990, restrictions under the Montreal Protocol were revised and accelerated to require a complete phaseout in the production of CFCs (CFC-11, -12, -113, -114, and -115), halons (Halon 1211, 1301, and 2402 -- all but essential uses), and carbon tetrachloride by the year 2000, and methyl chloroform by the year 2005.

In addition, the Parties to the Protocol signed a non-binding resolution that discourages the use of hydrochlorofluorocarbons (HCFCs) where other alternatives are feasible. The non-binding resolution also calls for a phaseout in HCFC production by 2020 if feasible, and no later than 2040.

Major research efforts are underway to eliminate the need for CFCs in foam plastics. Much of this effort involves replacement of CFCs with HCFCs or other blowing agents which have low or no ozone depletion potential.

CFCs in foam products are released to the atmosphere at different rates, depending upon the foam type and the molecular weight of the blowing agent. For most open-cell foams, a large portion of the CFCs is released during the manufacturing process. In contrast, closed-cell foams retain most of their CFCs (which have half lives of 100 to 300 years in the foams) during the manufacturing process. Most often, CFCs are released either during fabrication, which may break some closed cells, or gradually over the useful life and disposal of the product.

Replacing CFCs with HCFCs will provide some foam plastic sectors with a transitional period, while manufacturers, raw material suppliers, governments and other researchers work towards developing long-term solutions. Long-term candidates for some current uses are HFCs (partially halogenated fluorocarbons).

Global Consumption of CFCs in Foam Plastic Products

The foam plastics industry used approximately 174,000 tonnes of CFCs worldwide in 1990 to manufacture all types of foam plastic products. This represents a 35 percent reduction compared to the 267,000 tonnes consumed worldwide in 1986. The change in CFC consumption between 1986 and 1990 is presented in Figure I-2.

Technical Options to Reduce CFC in Foam Plastic Products

There are three potential methods for reducing the use of CFCs in the production of foam plastic products:

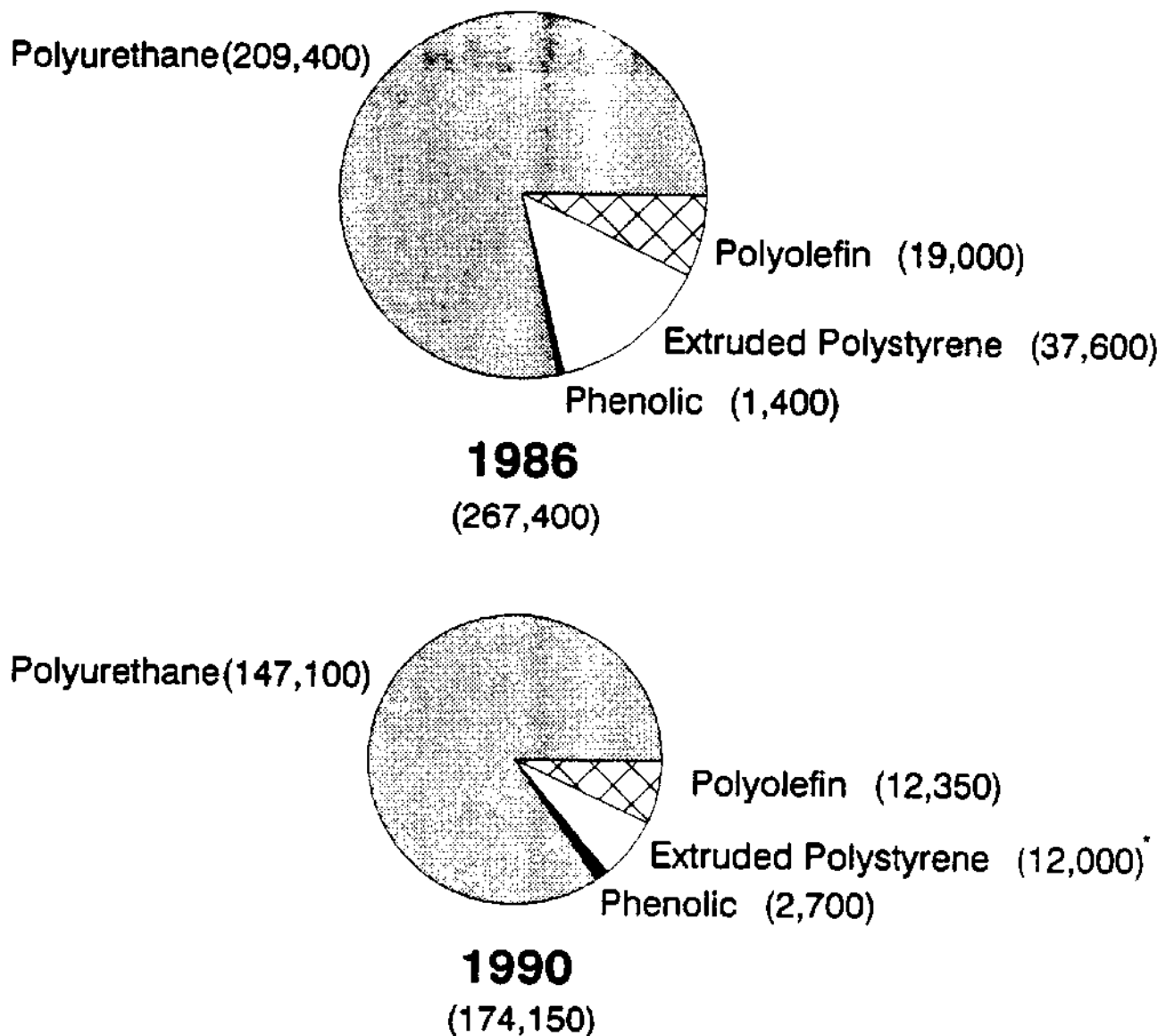
- substituting alternative blowing agents for the fully-halogenated CFCs;
- modifying present production processes or using alternative technologies; and
- substituting foam plastic products with alternative products.

These technical options are briefly described here and are discussed in more detail in the body of the report.

Alternative Blowing Agents

The use of alternative blowing agents, such as HCFCs, HFCs, hydrocarbons and inert gases, has been identified as a way to eliminate CFCs. Alternative blowing agents are chemicals with many characteristics similar to CFCs, but often have significantly lower

Figure I-2. CFC Consumption by Foam Sector: 1986 vs. 1990
(tonnes)



* This figure represents the amount of CFCs used worldwide in extruded polystyrene boardstock production. A virtual phaseout of CFCs has been achieved in the extruded polystyrene sheet industry in developed countries, while a small undetermined amount of CFCs is assumed to be used for sheet production in developing countries.

atmospheric lifetimes and, consequently, a much lower potential for depleting ozone (HCFCs), or no potential at all (HFCs).

Process Modifications and Technological Alternatives

Process modifications and technological alternatives include methods for reducing CFC emissions either by preventing the release of CFCs into the atmosphere during foam production or by reducing or eliminating the need for CFCs.

One method of capturing CFCs during the production process is carbon adsorption. Recovery technologies, however, are more effective for open-cell foams, such as flexible polyurethane foam, because of the relatively high percentage of CFCs released during the manufacturing process. In contrast, carbon adsorption is less effective for closed-cell foams, such as rigid polyurethane and extruded polystyrene, because of the relatively small percentage of CFCs released during production.

Process modifications can also take the form of new chemical systems that expand the present range of foam plastics requiring smaller amounts of CFCs. For example, the use of increased levels of water in the chemical reaction modifies the existing foam production process for polyurethane foams. Changes in polyols and other chemicals used in the foaming part of the production process could also reduce or, in favourable cases, eliminate the need for CFCs in both rigid and flexible polyurethane foam.

Product Substitution

Product substitutes currently compete in all subsectors of the foam market, with the possible exception of appliance insulation. The appliance manufacturing production system is based on direct automated injection of polyurethane foam raw materials between the inner and outer shell of the appliance cabinet, which facilitates the manufacturing process. The foam-in-place technology utilised is a major factor in the structural integrity of the appliance cabinet.

In some uses of flexible slabstock foam, notably the outer layers of furniture cushions and mattress ticking backing (quilting foam), fibrefill materials such as polyester batting are competitive with flexible foam. These materials have the potential to replace at least some portion of slabstock foam, principally the supersoft foams in some markets. Fire performance requirements may be limitations in some applications.

Whilst products such as paper, cardboard and expanded polystyrene can be used in many packaging applications, there are a number of special applications (such as electronic equipment packaging) where protective foam products are the most cost effective choice. Polyurethane, extruded polystyrene and polyolefin packaging materials offer better moisture barrier protection, increased durability and better cushioning protection than more conventional materials.

Foam insulation use in buildings has significantly increased because of its high energy efficiency combined with other physical properties, including excellent combustibility test performance, waterproof characteristics, low density, thin profile and ease of handling. Some polyurethane foam insulation products can be sprayed or poured in-situ. Non-foam plastic insulation products can achieve some of these properties, but not all. In all instances, the substitution of other products would require increases in the thickness of the product to provide equivalent energy efficiency. These insulation products may become more competitive if the choice of alternative blowing agents reduces the thermal conductivity of the foam insulation.

Building design constraints, local building code requirements, and construction costs dictate the choice of insulation material. Because of these factors, it is difficult to generalise the potential substitution of non-foam insulation for foam insulations currently containing CFCs. In some instances, there are substitute products available which can provide acceptable performance. For some applications, however, there is no obvious alternative which would not involve considerable changes in design and construction practice or loss of energy efficiency (Curwell, 1988).

The technical options for reducing or eliminating CFC use in foam are dependent upon each foam type, since each has a distinct set of process and product application needs. Within foam types, options can vary regionally depending upon various factors, including regional product mix, climate, political factors, environmental regulations, and other issues. Discussion of technical options, CFC reductions and the status of evaluating alternatives will be divided into the following categories:

- Immediate -- an alternative which currently has application in a specific end use;
- Short/Intermediate Term -- usually a technically viable alternative that has not currently satisfied all classification criteria but could be implemented in one to three years; or
- Long Term -- an alternative which requires long term research to determine whether it can be implemented or is no longer considered an option. These options are usually considered for implementation after 1997.

As shown in Table I-1, the status of a CFC alternative and the timing for its implementation can be evaluated and classified in one of the above categories by examining:

- 1). Environmental Acceptability. This criterion determines whether the environmental characteristics of an alternative are generally known such that it can be implemented in an environmentally acceptable manner, or whether the characteristics are still under evaluation.

Table I-1. Status of Evaluation of CFC Alternatives for Foams

	Immediate	Short/Intermediate Term	Long Term
Environmental Acceptability	Generally Proven	Under Evaluation	To be Evaluated
Toxicity/ Safety and Handling	Established/ Known	Under Evaluation	To be Evaluated
Stage of Development of Technical Application	Generally Proven	Under Development	Under Research
Availability	Available to Meet Industry Demand	Small Amount Available: Does Not Meet Industry Standards	Only Research Quantities Available
Cost Effectiveness/ Acceptability in the Marketplace	Generally Acceptable	Under Evaluation	To be Evaluated

- 2). Toxicity and Safety. This criterion determines whether the alternative has established toxicity characteristics and known safe handling requirements, or whether it is still undergoing testing and risk characterisation.
- 3). Technical Feasibility. This criterion establishes whether the technology is proven in its application, or if it is still in the early phase of research.
- 4). Availability. This criterion evaluates whether the alternative is available worldwide to meet new industry demand or whether it is being produced in quantities too limited to meet the demands of the whole market, or even select geographic areas or applications.
- 5). Cost Effectiveness. This criterion evaluates whether the alternative can find market acceptability.

HCFC-22 is one example of an alternative which can be considered both an immediate option and a short/intermediate alternative. HCFC-22 has been successfully implemented as an immediately available option in numerous use applications, either alone or blended with other chemicals like HCFC-142b. Foam applications which have recently introduced HCFC-22 based blowing agent systems include extruded polystyrene sheet and boardstock, polyolefin, and polyurethane sandwich panel, spray, pipe and integral skin products.

HCFC-22 is also an attractive short/intermediate term alternative in other polyurethane foam insulation applications, such as appliance foams and slabstock. These uses of HCFC-22 are considered options in the short term because, whilst HCFC-22 is commercially available, it is still undergoing development testing and may take another one to three years for implementation.

HCFC-141b and HCFC-123, principally CFC-11 replacements for polyurethane foam applications, are also considered intermediate strategies. Development work indicates these are technically viable alternatives; however, environmental acceptability in terms of ozone depletion and toxicity is unresolved at present. In addition, there is not sufficient manufacturing capacity to supply the worldwide market (November, 1991 data), and the substitutes' cost-effectiveness (especially HCFC-123) is still under consideration.

However, HCFC-142b, principally used to replace CFC-12 in extruded polystyrene boardstock insulation, is categorised as an immediate option. Although considered a transitional alternative due to ozone depletion concerns, it is generally available in commercial quantities. Furthermore, HCFC-142b has completed toxicity evaluation and has been proven to be technically viable. Identified as an option in 1988, conversions to replace CFC-12 began as early as 1989 and are still underway worldwide. Complete CFC-12 conversion is expected by the end of 1993.

Table I-2 summarises the various CFC alternatives available to the foam plastics industry. Reductions in CFC use will be achieved by using a combination of chemical substitutes, process modifications or technological alternatives, and product substitutes.

Issues Affecting the Phaseout of CFCs

The scheduled reductions of CFCs, which is described in this report for the foam plastic industry, assumes worldwide availability of substitutes and no future regulations that could restrict the ability of substitutes from being adopted on either a global or regional basis. Some of the issues which affect the substitution of CFCs include: rate of conversion, toxicity, safety and environmental concerns, and energy impacts. These issues will be discussed further in the appropriate chapters of the report.

Table I-2. CFC Alternatives Available to the Foam Industry

Type of Foam	CFC Alternatives		
	Immediate	Short/Intermediate Term	Long Term
Polyurethane:			
Rigid: Appliance	Reduced CFC-11, 100% CO ₂	HCFC-141b, HCFC-123, perfluorocarbon*, HCFC-22, HCFC-22/HCFC-142b blends	HFCs, fluorinated ether, vacuum panels, perfluorocarbon*, hexafluorobutane
Boardstock/ Flex-Faced Lamination	Reduced CFC-11, 100% CO ₂ , pentane, 2-chloropropane**, HCFC-22/HCFC-142b blends	HCFC-141b, HCFC-123, HCFC-22, HCFC-22/HCFC-142b blends, perfluorocarbon*	HFCs, fluorinated ether
Sandwich Panels	Reduced CFC-11, 100% CO ₂ , pentane, HCFC-22/HCFC-142b blends, HCFC-22	HCFC-141b, HCFC-123, HCFC-22, HCFC-22/HCFC-142b blends	HFCs, fluorinated ether, vacuum panels
Spray	Reduced CFC-11, 100% CO ₂ , HCFC-22	HCFC-141b, HCFC-123	HFCs, fluorinated ether
Slabstock	Reduced CFC-11, pentane	HCFC-141b, HCFC-123, HCFC-22, HCFC-22/HCFC-142b blends	HFCs, fluorinated ether
Pipe	100% CO ₂ , HCFC-22, HCFC-22/HCFC-142b blends, methyl chloroform	HCFC-141b, HCFC-123, HCFC-22	HFCs, fluorinated ether, 100% CO ₂
Flex: Slab	Extended-range polyols, softening agents, methylene chloride, methyl chloroform, acetone, AB Technology, increased density	HCFCs***	Dissolved CO ₂ , reduced barometric pressure
Moulded	Methylene chloride, increased density, methyl chloroform, extended range polyols	HCFCs***	
Integral Skin	HCFC-22, hydrocarbons, water substitution, methylene chloride, air loading, high active polyol, 100% CO ₂	HCFC-141b, HCFC-123	100% CO ₂ , HFCs
Phenolic	Hydrocarbons, HCFC-22/HCFC-142b blends	HCFC-141b, HCFC-123, HCFC-22/HCFC-142b blends	HFCs
Extruded Polystyrene:			
Sheets	HCFC-22, hydrocarbons, 100% CO ₂ , HFC-152a	HFC-152a, HFC-134a, hydrocarbons, 100% CO ₂	100% CO ₂ , hydrocarbons, Atmospheric gases/resins, HFC-152a, HFC-134a
Boards	HCFC-22, HCFC-142b	HCFC-142b, HCFC-124, HCFC-22	HFCs
Polyolefin	Hydrocarbons, HCFC-22, HCFC-142b, 100% CO ₂	100% CO ₂ , inorganic gases, HFCs, hydrocarbons	

* To be used as an additive or a co-blowing agent.

** Proprietary technology.

*** Not likely to be used.

Rate of Conversion

In the 1989 UNEP Foams Technical Options Report, a number of foam sectors announced plans to convert to available non-CFC short term options. Some are presently in the middle of a worldwide conversion that may take approximately three years to complete. For example, the extruded polystyrene boardstock industry identified HCFC-22 and HCFC-142b as immediately available substitutes in 1989. The industry has been converting to HCFCs worldwide since 1989, and expects full conversion will be complete by the end of 1993. Conversion of plants to handle alternative blowing agents has cost between US\$400,000 and US\$1 million per plant and has taken up to two years to complete, due to delivery times for equipment. Conversely, other foam industries, such as the US and other extruded polystyrene food service and packaging manufacturers, had quickly converted to CFC-12 alternatives in 1988, within one year of decision and approval. The following are important factors which impact the length of time required to completely convert to a technically acceptable alternative:

- economic climate - regionally and globally;
- availability of technical service support;
- regulatory approvals (operating permits);
- product quality evaluation;
- product certification;
- equipment delivery times;
- availability of alternative chemicals in quantities sufficient to meet new demand with acceptable finished product cost implications;
- governmental effectiveness in leading the process;
- successful technology transfer/informational exchange to developing countries;
- national legislation - particularly that which impacts CFCs and alternatives;
- customer preference; and
- patent situations and licensing negotiations.

For example, the usage of alternative blowing agents is dependent on the building regulations (certification rules) of different countries. In some countries insulating foams made with alternative blowing agents can be used without special agreement/permission,

while in others special permission is necessary when using new blowing agents in insulation materials. The process to certify products can impact the choice of alternatives and the rate at which they can be implemented.

Taking into account these factors, implementation of a worldwide conversion to CFC substitutes may require a number of years, once the decision on which alternative to implement has been made.

Toxicity Concerns

Toxicity issues will play a major role in determining when a CFC substitute will be used in foam manufacturing. Concerns over human health impacts of CFC substitutes include:

- worker and consumer exposure to alternative blowing agent; and
- exposure to possible decomposition products formed in foams.

Both issues need to be closely addressed when determining the viability of using identified alternatives, as well as the timing of their implementation.

Clarification of toxicity issues is necessary in order to determine the time frame and ability to use certain CFC alternatives; particularly HCFC-141b, HCFC-123, HCFC-124, HFC-134a, methylene chloride, perfluoroalkanes, and possibly others.

Flammability

Some of the identified CFC alternatives present varying degrees of flammability. These alternatives include HCFC-142b, HCFC-141b, HFC-152a, pentane and other hydrocarbons.

In order to safely use flammable alternatives, it is necessary to complete the evaluation of these critical areas:

- manufacturing risks from ignition. Plant modifications can include increased ventilation and "explosion proofing" to eliminate electrical ignition sources. These modifications require capital investment.
- storage and transportation of foam products. If concentrations of flammable blowing agents are emitted during curing or transportation, care must be taken to identify and minimise the risk of ignition.
- finished product fire performance. Products using flammable blowing agents may need to be reformulated with fire retardants to pass strict fire tests, but in some cases this reformulation may not lead to the required results.

These flammability and safety issues must be addressed when considering flammable alternatives, however many of the problems may be able to be resolved with technical solutions. Many foam sectors have been able to successfully use flammable blowing agents (HCFC-142b in extruded polystyrene boardstock, pentane in a variety of applications) by identifying and minimising flammability risks. In some instances flammability may limit the widespread use of a CFC substitute.

Environmental Concerns

It is necessary to consider environmental effects, such as stratospheric ozone depletion, global warming, ground level air pollution, and tropospheric degradation products, when choosing CFC substitutes.

Ozone Depletion Potential

The HCFCs identified or used as CFC substitutes in foam manufacturing have a much lower ozone depletion potential (ODP) than CFCs. However, their unrestricted, long term use would contribute significant amounts of chlorine to the stratosphere.

ODP values vary among the different HCFCs; for instance, the ODP of HCFC-141b had been estimated to be 0.10; however, with new scientific data, the ODP may be adjusted upwards. In contrast, HCFC-123 has an ODP of 0.02.

HCFCs are viewed as transitional alternatives to be used while non-ODP, chlorine-free alternatives are developed. In insulation applications, where HCFCs are critical, efforts are being made to minimise the ozone depleting impact of the blowing agent by judicious foam formulation and to eliminate HCFC use as quickly as possible.

Global Warming Potential

The global warming potential (GWP) of a compound is a function of its atmospheric lifetime and its ability to absorb infrared radiation. CFCs have high GWPs.

The leading CFC substitutes have lower GWPs. The relative ability of a CFC substitute to act as a greenhouse gas together with its total emission volume into the atmosphere will affect the choice of alternatives.

While CFCs and CFC substitutes have GWPs, the major contributor to global warming is carbon dioxide produced by the burning of fossil fuels. In their report, the US Department of Energy and AFEAS have determined that the energy efficiency of HCFC-blown foam insulations can reduce the overall global warming effect.

Tropospheric/Ground Level Air Concerns

CFCs are organic chemicals which react negligibly in the lower atmosphere. However, some CFC alternatives, such as pentane, butane, and other hydrocarbons, are classified as volatile organic compounds (VOCs) in the US because they undergo photochemical reactions in the lower atmosphere and contribute to smog formation.

As a result, even though these alternatives can find applications in many foam sectors, they may be strictly regulated on a regional basis. For example, the US strictly regulates emissions of hydrocarbons. Ultimately, regional regulations may restrict the use of these CFC substitutes even though they are technically feasible options.

The tropospheric degradation of HCFCs and HFCs is being assessed by AFEAS.

Insulation Efficiency

The use of alternative blowing agents or non-CFC insulation materials in insulation products can impact the energy efficiency of the finished product.

In general, the drop-in replacement of CFCs with HCFCs or other alternative blowing agents resulted in products which were poorer insulators. However, once CFC substitutes had been selected, research and development efforts were focused on reformulation around the chosen substitute and modifications to the foam technology. This effort has resulted in products with equivalent insulation efficiency.

Ultimately, the acceptability of alternative blowing agents is dependent upon the performance, cost-effectiveness and competitiveness of the finished product in a particular application. The market price of any alternative system is often the determining factor as to whether a substitute can be used and sold competitively on the market. This has already been found to be a significant barrier to substitution, particularly in recessionary environments.

For applications requiring high insulation efficiency, the choice of alternatives is more limited. If reliability and commercialisation problems can be overcome, new products, such as composite vacuum panels for refrigerators, could offer both increased energy efficiency and the elimination of CFCs.

Chapter Two

DEVELOPING COUNTRY PERSPECTIVE

Diversities and Similarities

"Developing country" as a general category does not accurately reflect the diversity and specific needs of all countries that fall into this classification.

For example, there will be differences in use patterns of ozone depleting substances (which include CFCs, HCFCs, methyl chloroform, carbon tetrachloride, and others), and the relative ability for individual developing countries to quickly adopt CFC substitutes and alternative technologies. However for this report, developing countries (DCs) will have the following factors in common:

- **Low income levels** -- This factor currently causes large population segments of developing countries to not be served by the most basic applications of ozone depleting substances (ODSs) such as domestic and commercial refrigeration for food preservation. Additional costs associated with a transition away from ODSs might reduce the availability of refrigeration even further.
- **Consumption of ozone depleting substances** -- Though very small on both a total and on a per capita basis, the consumption of these substances is generally associated with very basic societal needs such as food preservation (i.e., refrigeration and insulation). Unfortunately, some ODS applications, including food preservation, may require transitions to non-ozone depleting substances and technologies that are complex and expensive.
- **Growth potential** -- The combination of both having to serve large segments of the population hitherto not catered for and the accelerating expansion which is occurring in many of these countries make developing countries important areas of potential ODS consumption in the coming decades. The challenge is to enable new industries in these countries to adopt environmentally acceptable technologies from inception, thus precluding a subsequent change-over.

- **Products and technologies** -- Products produced, imported, exported, or consumed in DCs are normally based on specifications and technologies transferred from developed countries, adapted to local conditions, and occasionally improved by local experts. The transition away from ODSs threatens local industries with a costly early retirement of equipment and products.

For those DCs possessing ODS-based industries, the transition away from ODSs addresses their ability to serve a population while simultaneously keeping their products cost and quality competitive in the international market. It is likely that these countries will move away from ODSs on a shorter time frame than allowed for DCs under the Montreal Protocol. Countries importing finished goods that rely on ODSs or ODS feedstocks will be forced to move away from ODSs simultaneously with the developed countries from which they import.

Information and Technology Dissemination

The speed and effectiveness of information and technology dissemination into DCs depends upon a number of factors. Examples include:

- an existing base of skilled labour, technicians and technical courses;
- a presence of organised technical forums, such as industry associations;
- a level of government support and commitment;
- a presence of international companies through subsidiaries, representatives, or licensees; and
- a level of cooperation between domestic and international research institutions and industries.

There is no single recipe for designing an effective system to disseminate information. Specific country designs will largely depend upon a combination of the aforementioned factors.

Regardless of the degree to which a current information and technology dissemination network is developed, local governments must play a leading role through their economic and scientific branches in organising national resources. It is only through organised action that the transition process will result in the lowest possible cost to society.

Driving Forces for Moving Away from Ozone Depleting Substances

There are a number of factors that will eventually lead DCs to comply with the ban on ozone depleting substances. This section discusses these factors.

Integration of World Markets

The increasing integration of local markets into a single global market also unifies product and production standards. For instance, today's worldwide markets respond to consumers' environmental concerns by requiring products that are environmentally acceptable.

This environmental concern is slowly and steadily becoming widespread in DCs, thus creating the necessary demand to justify an industrial change-over to non-ozone depleting substances and technologies.

In addition, global consumers are unlikely to continue demanding products made with CFCs because the high tax associated with their use will be included in the purchase price. Consequently, consumers will be more inclined to purchase CFC-free products that cost less.

This anticipated market behaviour also will induce many DC industries to replace CFCs in foam production in order to maintain the competitiveness of their exports. Estimates project that the transition will occur before the expiration of the ten year grace period afforded to DCs under the Montreal Protocol.

Financial and Technology Transfer Mechanisms

Recognising the special situation of DCs, the Parties to the Montreal Protocol have established a Multilateral Financial Mechanism to encourage the participation of DCs and to finance the "incremental costs" incurred by DCs to phase out ozone-depleting substances.

The Montreal Protocol also exhorts Parties to transfer "...the best available, environmentally safe substitutes and related technologies...under fair and most favourable conditions." Both the financial mechanism and the technology transfer provision will play an important role in promoting an orderly and total transition away from ODSs.

It is also likely that international companies operating in DCs through licence agreements, representatives, or subsidiaries will act as powerful tools in disseminating modern, environmentally acceptable technologies.

Successful Initiatives Involving Blowing Agents

Initiatives for reducing or replacing the consumption of ODSs are underway in many countries around the world. In Brazil, a number of initiatives have been undertaken to reduce and eliminate the use of CFCs in the foam plastics industry. The following are brief summaries of some initiatives:

Flexible Foams -- Cushioning

In an example of a cost-driven transition away from ODSs, it is estimated that some 2,500 tonnes per year of methylene chloride have replaced a similar amount of CFC-11 in the production of cushioning flexible foams. Methylene chloride costs approximately 80 percent less on a weight basis than CFC-11. (November, 1991 data).

Food Packaging

In response to corporate directives and in spite of a usually higher investment and variable cost, hydrocarbons and HCFC-22 are replacing CFC-12 in many food service and packaging applications. In the future, alternative fluorocarbon toxicity test results, as well as availability and cost, will determine the timing and extent of an increased transition away from CFC-12.

Rigid Polyurethane Appliance Insulation

In Brazil, appliance insulation made with rigid polyurethane foam is the single most important application of ODSs in foam plastics. Most of the domestic refrigeration units produced in the country are insulated with this material which also contributes to the appliance's structural integrity.

Several initiatives are now underway in Brazil to reduce or replace ODSs in this application. For instance, home appliance manufacturers are working with raw material manufacturers to research and develop alternative blowing agent formulations and technologies. This two-phase programme is investigating the following:

- High water formulations to produce water-isocyanate reactions that generate carbon dioxide as a partial substitute for CFC-11. (Although this alternative can be implemented rather quickly, it does not completely preclude the use of an ODS and is viewed as an intermediate solution only.)
- Low-ozone depleting alternative fluorocarbons such as HCFC-123 and HCFC-141b to replace CFC-11. (Although HCFC-22, a high pressure blowing agent, is being evaluated by appliance manufacturers in developed countries, it has not yet been tested in DCs. The difficulties associated with handling this high pressure material make it less attractive despite its immediate commercial availability and its lower cost relative to HCFC-123 and HCFC-141b.)

For appliance insulation applications, alternative fluorocarbon toxicity testing, environmental acceptability tests, availability, and cost will once again determine the timing and extent of ODS transition.

The Role of Developing Countries in the Process of Replacing Ozone Depleting Substances

In spite of their traditional role as followers when implementing new technologies, DCs can play an important role in the transition away from ODSs.

The industrial base in many DCs, although sometimes sizeable, still has room to grow. This future growth offers the opportunity for an early adoption of environmentally acceptable products and technologies thus avoiding future change-over costs.

The smaller size of existing DC industries offers another unique opportunity to test and certify alternative products and technologies under actual manufacturing conditions. The necessary conditions to make such test programmes in DCs successful include:

- appropriate manpower base;
- technical and financial cooperation of the international community;
- the existence of flexible industries capable of rapidly switching feedstocks, technologies, and products at costs and within time frames comparable or less than in industries located in developed countries; and
- skilled technicians and operators experienced and knowledgeable in new feedstocks, technologies, and products.

Unfortunately, financial resources and technology transfer alone will not ensure a viable transition to alternative substances and technologies in the DCs. For a successful transition, DCs will also require the same access as industries in the developed world to commercial quantities of alternative chemicals and technologies. In addition, DC industries must have, on a competitive cost basis, unlimited access both to commercial quantities of alternative blowing agents and to the technology required to produce these alternatives.

Without the support of DC governments, however, unilateral actions by industry may only lead to incomplete results at potentially high costs to society. DC governments must coordinate, monitor, possibly mandate, and provide incentives for industry actions that will encourage stratospheric ozone protection.

In addition, DC governments can implement such a program under the framework of a National Policy for ODSs. This National Policy should summarise the country's current production, consumption, and applications of ODSs, the country's objectives and priorities in the transition process, and resources assigned to support the transition.

Active cooperation among governmental agencies, scientific institutions, and industry will be instrumental in solving the challenges posed by the transition away from ODSs in DCs

in the near term and will initiate an important working relationship to address other environmental issues in the future.

Key Factors to Success

Successful transition from ODSs is now only a problem of schedule and cost. These issues can be minimised or even turned into an advantage if DCs practice the following:

- **Provide strong commitment and leadership from the government.** Only governmental action can assemble all the important players in a well designed and regularly monitored action plan.
- **Form selection committees and cooperate internationally.** Teamwork and international cooperation are important factors in minimising risks and cost, particularly in light of the immense number of human activities affected by this issue, the difficulties associated with selecting and properly testing alternative chemicals and technologies, and the possible financial penalties associated with incorrect decisions.

All parties involved in the supply chain of products that are manufactured with or contain ODSs should be involved in making decisions regarding choice of alternatives, phase-in schedules, estimates of investments, education and training programs, and other issues.

To reduce transition costs, international technical cooperation is necessary to ensure the rapid dissemination of proven alternative technologies. Several DCs have been receiving technical assistance for the development of National Case Studies and some conversion projects have already been submitted for consideration under the Montreal Protocol's funding mechanism.

Public awareness and the dissemination of acceptable technologies can also be enhanced and expedited by seminars, trade fairs, conferences, and training programmes designed to ensure broad coverage of the issue for all involved parties.

- **Conduct a careful alternatives selection process.** A careful review and selection of strategies, priorities, and alternatives is key to ensuring a rapid transition at low cost. Whenever possible, phased development programmes should be developed to prioritise proven alternatives in terms of technical fitness, environmental acceptability, cost effectiveness, and commercial availability. Testing of exotic, high cost alternatives should be left for a later time.

The impact of alternative technologies on energy consumption should also be carefully analysed. In some instances, the lower efficiency of some alternative substances and technologies will be overcome by improved designs and reformulations. However, care must be taken so that the transition away from ODSs does not increase the energy demand, thereby requiring costly and time-consuming investments in a country's infrastructure.

Conclusion

The transition away from ODSs offers DCs both risks and rewards. The outcome will depend largely on the country's ability to cooperatively develop, promote, and monitor a programme that will encourage ozone layer protection. Governmental commitment and cooperation is absolutely necessary for conducting a successful program to transition away from ODSs and to cope with other environmental issues in the future.

Chapter Three

POLYURETHANE FOAMS

Polyurethane foams are generally based on the exothermic reaction of isocyanates and polyols. By itself, the polymerisation reaction produces a solid polyurethane. During a process known as foam blowing, polyurethane foams are made by forming gas bubbles in the polymerising mixture. The "blowing agent" can be either a gas chemically formed by water or formic acid reacting with the isocyanate, or a physical blowing agent like CFCs separately introduced into the reaction.

Used in a large variety of products, polyurethane foams can be classified into three major categories: rigid, flexible and integral skin. Product application examples include insulating materials for buildings and appliances, cushioning products for furnishings and automobiles, packaging for protection of high-value products, and automobile bumpers and dashes.

CFCs, particularly CFC-11, have been used to produce most of these foam products. In total, 209,400 tonnes of CFCs were used in the manufacture of polyurethane foams in 1986. This figure accounted for approximately 80 percent of the total amount of CFCs used in all foam plastic production. For 1990, CFC use for polyurethane foam production was estimated at approximately 147,100 tonnes, a 30 percent reduction compared to the 1986 consumption figure.

Each type of polyurethane foam, its use of CFCs, and the technical options available to reduce CFC consumption are discussed below.

RIGID POLYURETHANE APPLIANCE INSULATION

Products and Applications

Rigid polyurethane foams continue to be the dominant insulation used in home appliances. There is no detailed breakdown for the relative uses of polyurethanes in appliances. However, it is estimated that approximately 75 to 80 percent is used in refrigerators and freezers, and the remaining 20 to 25 percent is used in other appliances, such as display cabinets, water heaters, portable coolers, commercial appliances, and vending machines.

Production Process

Liquid chemicals are injected between the outer shell and the interior liner of an appliance cabinet and react in situ to form rigid polyurethane foam throughout the cavity. This foam-in-place insulation process, assisted by heated fixtures for the appliance cabinets, allows production lines to be highly automated.

CFCs assist the flow of expanding foam to all parts of the cavity by reducing foam mixture viscosity. The cured foam has high flexural strength and adheres well to the cabinet exterior and interior materials of construction. This contributes to structural performance of the appliance and permits the use of thin-gauge steel for the outer case and thin plastic liners (ABS or HIPS) for the inner liners of refrigerator/freezers. (The use of CFC-11 in appliance foams does not attack most refrigerator plastic liners.)

In addition, CFCs provide excellent thermal insulation properties with long-term performance without thermal bridging. This method of construction is highly cost-effective because it eliminates the previously used, labour intensive, lay-up of fibrous glass insulation into appliance cabinets.

Global Consumption of CFCs in Rigid Polyurethane Appliance Insulation

The global usage of CFCs in appliance foam in 1990 is estimated to have increased to 38,000 tonnes compared to 37,200 tonnes in 1986. The distribution of consumption by geographical region is presented in Table III-1.

In 1986, more than 50 percent of the CFCs used in rigid polyurethane appliance insulation was used in North America and Western Europe. By 1990, many appliances manufactured already implemented major reductions in CFC-11 content where conditions allowed. However in the US, opposing factors, such as energy regulations, have limited the industry's ability to cut consumption.

The main reason for the apparent increase in CFC usage in North America is improved market intelligence, particularly regarding the volume of foam used to insulate water heaters, coolers and display units. The doubling of CFC consumption in Asia Pacific reflects the growth in refrigerator production.

Technical Options to Reduce CFC Consumption

Immediate

Reduced CFC-11 Technology

To achieve immediate reduction in CFC use, the appliance industry has adopted reduced CFC-11 technology featuring a high-water formulation that generates carbon dioxide from the water-isocyanate reaction.

Table III-1. Estimated Global CFC Consumption for Rigid Polyurethane Appliance Foams (1986 vs. 1990)

Region	Tonnes 1986	Tonnes 1990
North America	9,400	11,200
Western Europe	9,900	6,000
Eastern Europe	4,300	3,900
Middle East/Africa	2,000	1,400
Central/South America	2,700	2,300
Japan	4,700	4,600
Asia Pacific	4,200	8,600
Total World	37,200	38,000

The amount of water substitution feasible in appliance foam insulation is dependent upon the selected isocyanate (toluene diisocyanate or diphenylmethane diisocyanate), and the initial energy efficiency value of the insulation. Initial indications are that product quality is not adversely affected; however, there may be slight increases in thermal conductivity (possibly 5 percent) depending upon the amount of water substituted. In addition, energy increases of appliances due to the reduced CFC-11 technology have been estimated at typically up to three percent, well within manufacturing tolerance.

In Western Europe, appliance manufacturers introduced reduced CFC-11 technology in January 1989. Most EC and Scandinavian producers switched their formulations by December 1989; Eastern European manufacturers are also starting to use this technology.

European manufacturers have cut CFC use by nearly 50 percent since 1986. Today, CFC-11 usage in a typical foam formulation has been reduced from 12 to 13 percent to 6 to 7 percent (by weight of foam).

Increased water formulations are also widely practised by North American and Japanese appliance producers. Manufacturing economics and concerns about CFC-11 availability have been the main reasons for the move to greater amounts of water in foam formulations in the United States. While practices vary in the industry, CFC-11 reductions ranging from 10 to 50 percent are common in North America and Japan.

This technology change, however, has a practical limit. Carbon dioxide is not as efficient an insulating gas as is CFC-11 and a balance must be struck in establishing formulations that will still meet appliance energy standards. In the United States, the Department of Energy (DOE) has promulgated new standards effective in 1993 that mandate still higher energy efficiency performance for home appliances.

As another practical difficulty, drastically reducing CFC-11 content in a foam formulation can adversely affect the foam's ability to easily flow and cover the entire appliance cavity. This can result in a weak foam with poor adhesion characteristics.

100 percent CO₂ blowing

One hundred percent CO₂ blowing is achieved by further increasing the water content in the foam formulation, thereby eliminating the need for a physical blowing agent.

Thermal conductivity of foam blown completely with water is 20 to 25 percent greater than that of CFC-11 blown foam. This rise can either significantly increase energy consumption or require adaptations to the units' design and production equipment to accommodate thicker foams, needed to offset the higher thermal conductivity of the foam. And use of different plastics for the refrigerator liner (cabinet interior) may be required to retard diffusion of the CO₂ gas out of the foam, which will decrease the foam thermal efficiency. In addition, an increase in foam density of at least 20 percent will be required to ensure physical stability of foam.

Western European and US manufacturers have already introduced fully CO₂ blown foam in other appliances such as water heaters and vending machines, despite the 20 to 25 percent increase in initial thermal conductivity. This option is considered viable for water heaters and vending machines because in most cases foam thickness can be increased. However, there are cost penalties involved with producing thicker foam and walls, and polyol modifications have been necessary to maintain adhesion.

Short/Intermediate Term

Like other industrial sectors that use rigid polyurethane foam, the appliance industry has evaluated substitutes for CFC-11. HCFC-141b and HCFC-123 have received the most attention.

Field tests by chemical producers, appliance manufacturers, and the Appliance Industry-Government CFC Replacement Consortium (US) have shown that both HCFC-141b and HCFC-123 are viable candidates to replace CFC-11 in rigid polyurethane appliance

foams. Properly formulated foams yield acceptable processing characteristics and final foam properties; however, neither material is currently available in significant commercial quantities.

In addition, toxicology studies on HCFC-141b and HCFC-123 by a consortium of world-wide CFC producers need to be completed in order to know the full implications of their use. Some toxicity concerns include the generation of byproducts when HCFC-123 and HCFC-141b decompose or react with other foam chemicals.

Initial studies have detected some decomposition products of concern. These studies will be completed in 1992 and results will be published in 1993.

The major outstanding technical problem for HCFC-blown foam in appliance applications is its compatibility with ABS and HIPS thermoformed plastic interior refrigerator liners. Compared to CFC-11, the greater solvency of HCFC-141b and HCFC-123 causes cracking and blistering in liners when HCFC-blown foam is the cabinet insulation.

Plastics material suppliers and appliance manufacturers are continuing to explore ways to overcome this compatibility problem. There are encouraging indications that a solution will be found. Particular characteristics of these HCFCs and other immediate options are discussed below.

HCFC-22 and HCFC-22/HCFC-142b Blends

The following factors should be considered when evaluating the use of these substitutes:

- Thermal conductivity of foam blown with HCFC-22 and HCFC-22/HCFC-142b blends may increase by 5 to 15 percent; however with additives (see page III-7), foams with thermal conductivity equivalent to CFC-11 foams have been developed;
- HCFC-22 in the liquid phase is a solvent for liner plastics and new plastic materials may be needed to avoid deterioration. Tests are underway (as of August 1991) to determine the effect of HCFC-22 vapour in simulated use conditions; and
- The low boiling point of HCFC-22 (around -40°C) or HCFC-22/HCFC-142b blends would require processing equipment changes to handle a higher pressure gas.

HCFC-22 is gaining commercial acceptance in frothing applications which once used CFC-12. In addition, initial commercialisation is underway in some product applications, such as hot water heaters, that once used CFC-11. Blends of HCFC-22 with HCFC-142b, HCFC-141b, and HCFC-123 show promise.

HCFC-141b

Extensively trialed, foams using HCFC-141b maintain physical properties, thermal conductivity, and aging characteristics similar to CFC-11 based foams.

Main concerns surrounding HCFC-141b are unresolved toxicological properties, including formation of decomposition products, and potential legislative action based on ODP concerns.

In addition, HCFC-141b is moderately flammable and its use may require some plant modifications.

Based on current (November 1991) price information, foam raw material costs would increase by five percent if HCFC-141b were used.

HCFC-123

This substitute candidate has also been extensively evaluated. Findings indicate that the physical properties, thermal conductivity, and aging of foam blown with HCFC-123 is similar to CFC-11 based foams.

Toxicological concerns, such as the formation of decomposition products, need to be resolved. Further evaluation of worker exposure and completion of toxicity characteristics are required to assess health implications associated with its use.

Based on technical performance and ODP, HCFC-123 appears to be the alternative preferred by appliance manufacturers in Japan and Europe and by some in the United States. However, no firm commitment has been made to commercialise HCFC-123 in quantities needed to fulfil worldwide demand.

Foam raw material costs could rise as much as 25 percent when using HCFC-123, according to price projections as of November 1991.

Perfluoroalkanes

Perfluoroalkanes such as perfluoropentane (C₅F₁₂) and perfluorohexane (C₆F₁₄) have been used commercially for more than 30 years. They also are of low toxicity and are on the TSCA, EINECS and MITI inventory listings. Further testing will be completed in 1992.

Perfluoroalkanes are used primarily in the electronics industry for testing and heat transfer applications, and may prove to have some utility as a replacement for CFC-11 in polyurethane foam blowing.

In applications such as appliances, the use of perfluoroalkanes has received some interest. Preliminary evaluation of the emulsion technology used to disperse

perfluoroalkanes in the foam resins has resulted in foams with finer cells. This reduces radiative heat transfer and compensates for higher gas-phase thermal conductivity.

Perfluoroalkanes have a low reactivity and solvency and, hence, a high compatibility with thermoformed plastic interior refrigerator liners.

And while they have zero ODP, perfluoroalkanes have long lifetimes and a high global warming potential. This factor is one area of concern, but they are likely to be used in very small quantities in this application.

Another concern is the high price of perfluoroalkanes, but it is believed that the blowing agent could be a cost effective additive, used in combination with other blowing agents to promote fine-cell formation. Perfluoroalkanes may therefore find wider scale use as an additive to systems containing HCFCs or other alternative blowing agents. For example, a relatively small amount of perfluoroalkane can improve the thermal properties of the foam blown with HCFC-22, HCFC-123, or HCFC-141b to a level equal to or better than CFC-11 blown foam.

Perfluoroalkanes are available in limited quantities (500 to 1,000 tonnes) for use by the foam industry. Larger scale production capacity is being considered.

Long Term

The ultimate strategy of appliance manufacturers and foam chemical suppliers is to completely eliminate any chlorine-containing blowing agent from polyurethane foam. Currently under consideration is chlorine free insulation in combination with vacuum panels (see Appendix A).

Blowing agent options being researched are discussed below:

HFCs

The HFCs under primary consideration (HFC-125, HFC-134a, and HFC-152a) have, or are believed to have, higher gas thermal conductivities than CFC-11. All three boil at lower temperatures which would require equipment redesign.

At this time, long-term foam performance has not been evaluated, including foam aging.

Toxicological evaluation for HFC-125 and HFC-134a is required prior to commercialisation in foams. HFC-125 and HFC-134a are likely to be expensive blowing agents.

Hexafluorobutane (HFC-356) is an example of a next generation HFC liquid that is currently being evaluated.

Fluorinated Ethers

Fluorinated ethers are a class of compounds in the early stages of evaluation as potential blowing agent alternatives. Substantial development work will be required to determine their ultimate commercial viability.

Product Substitutes

It is unlikely that the appliance industry will return to fibrous glass as a substitute for pour-in-place rigid polyurethane foam insulation. Cabinet design would need to incorporate heavier gauge steel and thicker walls. With a loss of interior space, increased construction costs plus the deterioration of the insulating performance caused by moisture accumulation are additional disadvantages.

However, vacuum panels are one new appliance insulation product. Individual panels have shown excellent insulating properties.

In the longer-term future it may be possible to increase the energy efficiency of refrigerators and freezers by incorporating vacuum panels in the flat-plane sections of these appliances. Designs have been advanced that feature such vacuum panels encapsulated in rigid polyurethane foam in the appliance walls.

However, there are questions about the long-term stability of vacuum panels, the economics of vacuum panel construction, and concern about the resistance of the panels to structural damage.

Vacuum panel technology is being carefully researched by appliance manufacturers and government laboratories. This technology is considered a long term option which may be introduced in some household refrigerator/freezer applications before the year 2000 (see Appendix A).

Recycling

Efforts are also underway to address solid waste issues involving appliance disposal. In many countries, centralized disposal of appliance goods are being established. When disposed of centrally, there are greater economies of scale for disassembling and recycling various refrigerator components. This provides an opportunity for capturing the CFCs trapped in the insulation.

In Germany, there is a programme evaluating CFC recovery from foam insulation of discarded refrigerators. The refrigerator has to be disassembled and the CFCs are

extracted by using condensation and carbon adsorption technologies. Further work is needed to evaluate the effectiveness of this program.

Danish and German programmes have also evaluated the potential for thermal incineration of refrigerators upon disposal, including destruction of CFCs in the foam.

Conclusions

Approximately 29 percent of all CFCs used in polyurethane foam manufacturing is used in the manufacture of appliance insulation. Of this, some 80 percent is estimated to have been used in domestic refrigerator/freezers, with the remainder in water heaters, commercial display units, vending machines and coolers.

Immediate reductions in CFC consumption have been achieved by partial water substitution (CFC-11/carbon dioxide blowing). The actual amount varied depending on initial energy performance of the foam, on the isocyanate base used to manufacture the foam, and on physical property requirements.

CFC reductions in polyurethane appliance insulation of 50 percent have been realised in Western Europe with little effect on product quality or energy performance. Water heaters and other appliances will also be available in Western Europe with 100 percent CO₂ blown foam.

CFC reductions without adverse impacts on the foam properties in Japan and in North America have been estimated to be about 15 to 50 percent.

Provided that HCFC-141b and HCFC-123 are commercialised, it is expected that they will be able to replace all the existing CFC-11 uses and provide a quick conversion away from CFCs. HCFC-123 appears to be the preferred option due to its low ODP and GWP, favourable thermal conductivity and aging characteristics, and non-flammability. However, recent toxicity concerns and availability will be the limiting factors dictating its ultimate use in appliance foam. HCFC-22 is also receiving attention as an intermediate blowing agent option; preliminary testing indicates good results.

In addition, perfluoroalkanes are being considered principally as fine-cell promoters to enhance foam energy efficiency.

Longer term efforts are focusing on eliminating all ozone depleting blowing agents. Options include HFCs, fluorinated ethers, and 100 percent CO₂ blown foam.

Future developments with total carbon dioxide blown foam and/or alternate blowing agents in combination with evacuated panel technology offer the potential to reduce energy consumption. Further research is required to determine the ultimate commercialisation potential for this technology.

CONSTRUCTION - BOARDSTOCK/FLEXIBLE-FACED LAMINATION

Products and Applications

Polyurethane (PUR) and polyisocyanurate (PIR) foam boardstock can be continuously laminated to various facing materials, such as aluminum foil, paper, glass roofing felts, steel and plasterboard. These products are primarily used as insulation in buildings, with some also used as tank insulation and solar collector insulation.

The largest use of laminated boardstock (60 to 75 percent) is in commercial roof insulation. Other uses include insulation for walls of metal buildings and agricultural buildings, cavity wall insulation, and sheathing for residential construction.

Rigid laminated polyisocyanurate and polyurethane foams have penetrated many building insulation markets because these products offer the following properties:

- **Low thermal conductivity** -- High values of energy efficiency can be achieved by using thin layers of foam insulation. Laminated foams with impermeable facers offer the highest degree of long-term insulation value. The low thermal conductivity is derived from the fine, closed-cell polymer structure combined with the use of CFC-11 as the main blowing agent;
- **Fire performance** -- Polyisocyanurate foams provide excellent fire test results under a variety of test procedures;
- **Compressive strength** -- This property is very important in roofing applications because of the traffic that a roof system, including the insulation, must bear;
- **Ease of processing** -- One advantage of laminated boardstock is its ease of manufacturing combined with its excellent adhesion to a whole range of facing materials; and,
- **Ease of use and handling** -- Laminated boardstock products are lightweight, offered in a variety of thicknesses, provide excellent structural rigidity, and can be sealed with hot bitumen when used on roofs.

Production Process

There are two principal types of continuous laminating machines:

- The continuous horizontal laminator used to produce products with two flexible facers, e.g., aluminum foil, paper or roofing felt; one flexible facer and one rigid facer; or two rigid facers, e.g., steel sheet, gypsum board, perlite or wood composite boards; and,

- The inverse laminator variation used to produce one rigid facing in sheet form. The chemical components are metered and mixed from the mixing head onto the pressure conveyor where external heat may be applied to promote faster curing before the foam is moved to the cut-off saw area. This product can also be produced using slabstock production methods.

Global Consumption of CFCs in Construction - Boardstock/Flexible-Faced Lamination

The estimated consumption of CFCs for lamination foams in 1990 compared to 1986 is shown in Table III-2.

Table III-2. Estimated Global CFC Consumption for Rigid Laminated Polyurethane/Polyisocyanurate Insulation Foam (1986 vs. 1990)

Region	Tonnes 1986	Tonnes 1990
North America	21,700	22,700
Western Europe	17,100	10,600
Eastern Europe	4,000	1,200
Middle East/Africa	1,800	100
Central/South America	0	600
Japan	2,600	2,600
Asia Pacific	3,800	500
Total World	51,000	38,300

CFC-11 has been the primary blowing agent for rigid laminated foam insulation. A small amount of CFC-12, approximately one percent, is sometimes used to provide additional nucleation or to create a "frothed," or pre-expanded, foam.

Overall, CFCs have been used because of their ability to physically form the foam as well as to remain in foam cells and provide insulating value. They are also used because they are inert chemicals which do not react with the other chemicals used to manufacture the foams. In addition, they are non-flammable, relatively non-toxic, efficient, and have suitable boiling points.

CFCs have low solubility in the polyurethane polymer, but they do dissolve in and reduce the viscosity of the polyol component. Without CFCs in the production process, the high

viscosity polyol component would make the blending, pumping, and production methods presently used extremely difficult to operate.

Technical Options to Reduce CFCs in Construction - Boardstock/Flexible-Faced Lamination

Immediate

Reduced CFC-11 Technology

The reaction of isocyanate with water to generate carbon dioxide is already used to provide improved flow in some rigid polyurethane foams. This technology increases water levels to reduce the CFC loading.

The amount of water used in the production of laminated foam insulation is dependent upon the type of foam and facer, and the various required characteristics of the foam, such as its combustibility and thermal insulation performance. These product requirements vary on a regional basis, and limit the amount of water that can be used in the formulation.

To date, reduced CFC foam formulations have been trialed by several manufacturers and introduced by some for PUR systems. Some manufacturers, particularly those in Europe, have reduced CFC-11 usage from 12 to 13 percent to 6 to 8 percent for PUR systems. For PIR systems, reductions from 13 to 15 percent to 7 to 9 percent have been possible.

In North America, manufacturers can reduce CFC usage by 15 percent with reduced CFC formulations.

While physical properties of the foam remain unchanged, increases in thermal conductivity are expected to be a maximum of 10 percent for both initial and aged foam values.

There may be a slight increase in manufacturing cost.

100 percent CO₂ Blowing

One hundred percent CO₂ blowing is accomplished by further increasing the water content of the foam formulation, thereby eliminating the need for a physical blowing agent.

Increases in initial foam thermal conductivity have been estimated at 20 to 25 percent. Without impermeable facers, there is a further rapid increase in thermal conductivity to a value of 0.030 to 0.032 W/mK. However, additional

impermeable facers are being developed to partially offset changes in energy efficiency.

When using 100 percent CO₂ blowing, a foam density increase of 10 to 35 percent is necessary to maintain dimensional stability. The required density change will depend upon the starting density and therefore may vary from region to region.

Longer post-storage of boards may be necessary to compensate for increased cure time. Especially for thicker boards, the higher exotherm temperature may increase cure time and necessitate a reduction in conveyor speed, thereby reducing the production rate. Scorching may also be a problem.

Significant cost increases will occur because more isocyanate must be used; thicker sections must be made; and production rates must be reduced. One hundred percent CO₂ blowing has been introduced into production for some product lines, particularly in Europe.

Pentane blowing

Pentane is being extensively evaluated, particularly in Europe, since it is relatively inexpensive and widely available worldwide.

Pentane-blown foams will have 15 to 20 percent higher thermal conductivity. However, these foams have aging characteristics similar to CFC-11 foam products; other physical properties of the final foam product are acceptable.

Because of pentane's flammability, the behaviour of foam in large scale fire tests is under investigation. In addition, its combustibility may require considerable modifications at high capital cost to processing equipment and the post-production board storage area.

Pentane also is a volatile organic compound (VOC). Its emissions have to be controlled because of air pollution concerns in some countries.

Succinctly, pentane is considered a pragmatic short term CFC substitute that may be used immediately, particularly in Europe. In fact, pentane blown products have satisfied several European building codes.

Pentane is currently not being actively considered in North America and Japan.

HCFC-22 and HCFC-22/HCFC-142b Blends

Since toxicological studies are complete and the decomposition problem appears to be negligible, some manufacturers are beginning to use HCFC-22 and blends of HCFC-22 and HCFC-142b.

Using these substitutes will increase thermal conductivity by approximately 10 percent as compared to CFC-11 foams. Further rapid aging of these foams and increases in thermal conductivity, particularly with HCFC-22 which permeates from the foam, may occur over time if impermeable facings are not used. In addition, plant modifications are required to use gas blowing agents with low boiling points.

Cost increases may occur due to increased thickness and blowing agent cost. However, the cost of HCFC-22 is expected to be lower than other HCFCs, such as HCFC-123 and HCFC-141b.

2-Chloropropane - "LBL 2"

Being used by one European manufacturer, 2-chloropropane has minimal ODP and GWP. However, it is flammable and its use will require modifications to processing equipment.

Currently, product availability is limited, because 2-chloropropane is a proprietary technology and hence a license may be needed for full-scale production.

In addition, cost of producing boards will increase when using 2-chloropropane.

Short/Intermediate Term

HCFC-141b and HCFC-123, the primary CFC replacement candidates, have shown to be technically feasible alternatives, but require commercialisation prior to their use in boardstock insulation.

HCFC-141b

Extensively evaluated, HCFC-141b blown foams provide the same physical properties and thermal conductivity as foams blown with CFC-11. In addition, the rate of aging HCFC-141b foam is similar to that for CFC-11.

Main concerns surrounding its use include ODP and unresolved toxicological properties, such as the formation of decomposition products. The moderate flammability of HCFC-141b may require some plant modification.

In addition, production costs would increase by five percent.

Based on technical performance and cost-effectiveness, HCFC-141b appears to be the alternative preferred by the PIR industry in the US.

HCFC-123

The use of HCFC-123 as a blowing agent has been extensively evaluated. The physical properties, thermal conductivity and aging of foams blown with HCFC-123 are similar to CFC-11 blown foams.

The main concerns surrounding HCFC-123 are unresolved toxicological behaviour, including formation of degradation products, and uncertainty as to the availability of commercial quantities.

Estimated price levels could possibly result in an uncompetitive product.

Perfluoroalkanes

Perfluoroalkanes are being examined for use as an additive to promote fine cells and reduce thermal conductivity.

Long Term

Several blowing agents are being examined, including HFC-125, HFC-134a, HFC-152a and fluorinated ethers. All such evaluations are in the early stages.

Recovery/Recycle

Given the minimal emission of CFC at the time of manufacture (5 to 10 percent of the CFC is emitted), carbon adsorption recovery equipment would not have very high efficiency rates in capturing CFCs, and is not considered cost-effective.

In fact, the manufacturing process is designed to capture as much of the CFCs put into the system as possible. As a result, 90 to 95 percent of the CFC-11 charged into the manufacturing line is retained within the foam insulation.

There are only three potential emission points:

- During the manufacturing process (5 to 10 percent of CFC input) at the foam head/chemical laydown, edge trimming and cutter areas;
- During product use -- Short-term studies conducted at the University of Oregon (Rasmussen) on unfaced product show that the half-life of CFC-11 emission is about 160 years for 5 cm thick sections. (The half-life is inversely proportional to the square of the thickness, and is also affected by facers.) Since laminated foam insulation is almost always covered during its lifetime by completed roofing systems or sidings on residential construction and remains in place during the lifetime of the building, the annual emission of CFC-11 is extremely small.

- During building demolition -- Because buildings have very long lifetimes, potential emission of CFC from foam insulation due to building demolition is extremely limited. To recover CFC-11 from laminated foam insulation during building demolition would require that every foam cell would have to be totally crushed and the CFC recovered.

Product Substitutes

Many non-CFC insulation products are currently available for use as roof insulation materials. These products include expanded polystyrene, fibreboard, fibrous glass (mineral fibre), and cellular glass, and have always competed for market shares with CFC-based insulation products.

It is extremely difficult to predict the percent replacement of rigid laminated insulation by CFC-free insulations. CFC-free products do not offer all of the properties of laminated foams; therefore, it is not always easy to substitute directly.

When a substitution is made, the alternative material will have a higher thermal conductivity per unit thickness, and will not insulate as efficiently as the CFC-blown foam of equal thickness.

The main difficulties in substituting non-CFC insulation materials for CFC insulation in buildings and industrial applications are cases where there is a need for waterproof characteristics, building code compliance and insurance requirements, combustibility requirements, or building design constraints. In these instances, it is not always easy to substitute directly. If a substitution was made, it would require considerable changes in design and construction practice.

Substitute insulation products may become more competitive if the choice of alternative blowing agent reduces the thermal conductivity or substantially increases the cost of the foam insulation.

Summary

Globally, approximately 26 percent of the CFCs consumed by the polyurethane foam industry is used to produce rigid laminated polyurethane/polyisocyanurate boardstock foam insulation.

In North America, the use of CFCs in production of laminated polyisocyanurate foams could be reduced by a maximum of 15 percent by reformulation with water to increase carbon dioxide blowing. These reductions are possible without adverse effects on product quality or energy efficiency.

In Europe, the use of water in laminated foam products based on polyurethane foam chemistry has reduced CFC-11 use by up to 50 percent. The actual amount of water,

which replaces CFC-11, will be dependent upon a number of factors, including facer type, the initial insulating value of the foam, and the product combustibility requirements in different regions.

In regions where a quick reduction in ozone depleting chemicals is required, manufacturers are using a variety of immediately available options, including pentane, 100 percent CO₂ blowing, HCFC-22/HCFC-142b blends, and 2-chloropropane. While eliminating CFCs quickly, these options may not be able to be implemented globally due to environmental or flammability concerns, and adverse impacts on foam properties -- especially thermal conductivity.

HCFC-141b and HCFC-123 have been identified as the blowing agent options of choice, particularly HCFC-141b because of its cost advantage. It is expected that these products could completely replace CFC-11 immediately following their commercial introduction. Research and development work is being directed at minimising some of the adverse affects of these blowing agents.

In addition, HCFC-22 is currently under study to replace CFC-11 and CFC-12. If technical developments are successful, HCFC-22 could be a means for a quick reduction in CFC-11 and CFC-12.

Long-term options to eliminate HCFCs are currently being pursued, and include HFCs and fluorinated ethers. The status of their potential implementation is uncertain, because they have not been proven to be technically feasible, cost-effective, commercially available and, in some instances, environmentally acceptable.

CONSTRUCTION AND TRANSPORT: SANDWICH PANELS

Products and Applications

Sandwich panels have foam cores between rigid facings. The facings are often profiled to increase rigidity. Facing materials are typically steel, aluminum or glass fiber reinforced plastic sheet.

The panels are increasingly being used in the construction industry for applications such as:

- cold stores: for frozen and fresh food storage;
- retail stores: including the cold rooms for food storage within them; and
- factories: particularly where hygienic and controlled environments are required such as in electronics, pharmaceuticals, and food processing.

The panels are also used in the transport industry for the manufacture of insulated trucks and reefers.

In all applications, the insulating property of the foam is used in conjunction with its strength and self-adhesive capability. The panels are components of high quality modular construction techniques.

Production Processes

The panel thickness, depending on application, varies from 30 to 200 mm and products over the entire range can be made by either continuous or discontinuous processes.

Continuous Process

The continuous process uses a horizontal laminator similar to that used for the production of boardstock/flexible-faced laminates. However, additional plant is installed to convert coiled sheet steel to profiled facings which are fed into the laminator.

Discontinuous Process

In the discontinuous process, pre-profiled or flat facings are assembled, with appropriate spacers, in single- or multi-daylight or in oyster processes. The foam is injected at multiple ports or a lance withdrawal technique is used.

Global Consumption of CFCs in Construction and Transport - Sandwich Panels

The estimated consumption of CFCs for sandwich panels was 24,100 tonnes. Consumption on a regional basis is provided in Table III-3.

Table III-3. Estimated Global CFC Consumption for Sandwich Panels in 1990

Region	Tonnes 1990
North America	5,900
Western Europe	9,500
Eastern Europe	1,600
Middle East/Africa	800
Central/South America	500
Japan	3,800
Asia Pacific	2,000
Total World	24,100

Technical Options to Reduce CFC Consumption

Immediate

Reduced CFC Technology

Reduced CFC formulations are achieved by increasing water content to produce CO₂ by water/isocyanate reaction. Several manufacturers have already reduced CFC-11 usage by up to 50 percent with this technology.

While the physical properties of the foam product can be maintained by appropriate formulation modifications, some increase in thermal conductivity (up to 10 percent) with HCFC-22/HCFC-142b blends and with HCFC-22 does occur.

In addition, there may be a slight increase in manufacturing cost.

100 percent CO₂ blowing

One hundred percent CO₂ blowing is possible by further increasing water content. Currently, this option is being used in production by some manufacturers, particularly in Europe.

Increases in initial foam thermal conductivity have been estimated at 20 to 25 percent. However, the presence of impermeable facers greatly reduces changes in thermal conductivity of the foam as it ages, but may not totally eliminate this

effect because of unfaced edges. In addition, adhesion to facers, particularly in polyisocyanurate foam formulations, is a problem for 100 percent CO₂ blowing.

A density increase of up to 10 percent also may be necessary to maintain dimensional stability and maintain the foam's structural contribution to panels.

Significant panel cost increases are attributed to the need for more isocyanate in the foam formulations and thicker foam sections required to provide the same insulation value. With the thicker boards, the higher exotherm temperature may increase cure time and necessitate a reduction in conveyor speed (continuous process) or a longer jig time (discontinuous process). In either case, this would cause a reduction in production rate.

Initial flammability tests indicate that the foam product blown with 100 percent CO₂ does not meet ASTM E84 smoke requirements, which may limit its use.

Pentane Blowing

Since it is relatively inexpensive and widely available worldwide, pentane is being extensively evaluated, particularly in Europe.

Pentane-blown foams are poorer insulants than CFC-blown foams; an increase in foam thermal conductivity of 10 to 15 percent is indicated. However, other physical properties of the final foam product are generally acceptable.

Because pentane is flammable, the behaviour of pentane-blown foam in large scale fire tests is under investigation. In addition, its combustibility may require considerable modifications at high capital cost to processing equipment and the post-production storage area. Other flammability issues which need to be further explored are the risks during transportation and shipping, cutting and storage.

Pentane also is a volatile organic compound (VOC). Emissions from VOCs are stringently regulated in some countries.

HCFC-22 and HCFC-22/HCFC-142b Blends

These blowing agents have been evaluated and introduced by some manufacturers. Their use will increase foam thermal conductivity by up to 10 percent. However, other foam physical properties appear to be acceptable.

Plant modifications also are required to cope with the low boiling points of HCFC-22 and HCFC-142b. These panels are not typically manufactured by using HCFC-22 for frothing.

In addition, cost increases are expected due to increased thickness and incremental blowing agent costs. However, the cost of HCFC-22 is expected to be lower than other HCFCs, such as HCFC-123 and HCFC-141b.

Short/Intermediate Term

HCFC-141b

Extensively evaluated, HCFC-141b blown foams provide the same physical properties and thermal conductivity as foams blown with CFC-11.

Main concerns surrounding its use include ODP and unresolved toxicological properties, such as the formation of decomposition products. Current ODP is estimated at 0.10, however new data suggest that it may be adjusted upwards. The moderate flammability of HCFC-141b also may require some plant modification.

In addition, production costs would increase by five percent.

Overall, the use of HCFC-141b is technically considered a good intermediate term option.

HCFC-123

The use of HCFC-123 as a blowing agent has been extensively evaluated. The physical properties and thermal conductivity of foams blown with HCFC-123 are similar to CFC-11 blown foams.

The main concerns surrounding HCFC-123 are unresolved toxicological behaviour, including formation of degradation products, and the lack of firm plans for commercial scale manufacture.

No production equipment changes are foreseen when using HCFC-123.

However, estimated price levels indicate that HCFC-123 blown foams may not be competitive with other insulation products in the market.

Long Term

Several blowing agents are being examined including HFC-125, HFC-134a, HFC-152a, and fluorinated ethers. All evaluations are at an early phase. Significant capital changes would be required to handle low boiling point gases. Vacuum panels may also serve as an alternative for this sector, provided issues associated with long term reliability and manufacturing processes are resolved.

SPRAY FOAM INSULATION

Products and Applications

Sprayed foams are used for in situ application of rigid thermal insulation. Their major use is in roofing applications, especially in the US. Worldwide, sprayed foams are used for residential and commercial buildings, industrial storage tanks, piping and ductwork, and refrigerated transport trailers and tanks.

Production Process

Spray foam is applied using a hand-held pressurized spray gun, in which separate polyol and isocyanate streams are metered under pressure, mixed together, and then dispensed. Different formulations impart specific properties to the foam, such as increased compressive strength, better dimensional stability at high heat and humidity, and greater thermal stability. The ability to adjust foam properties is beneficial, given foam's application in a variety of climates and environments.

The foam is sprayed directly from the mixing head onto the surfaces requiring insulation. This method of application facilitates coverage of large and complex surfaces. For those applications where a thick layer of foam is needed, multiple thin layers of foam are applied to create the thick layer. The sprayed foam needs to be highly reactive, especially for adhering to vertical surfaces during application.

Global Consumption of CFCs in Spray Foam

The estimated consumption of CFCs for spray foams in 1990 was 12,800 tonnes. Consumption on a regional basis is provided in Table III-4.

Table III-4. Estimated Global CFC Consumption for Spray Foam in 1990

Region	Tonnes 1990
North America	6,000
Western Europe	1,500
Eastern Europe	500
Middle East/Africa	500
Central/South America	500
Japan	2,300
Asia Pacific	1,500
Total World	12,800

Technical Options to Reduce CFC Consumption

Immediate

Reduced CFC-11 Technology

Reduced CFC-11 blowing is achieved by increasing water and isocyanate content of spray foam formulations. Depending upon the level of reduction, machinery changes may be necessary to deal with an isocyanate stream or polyol stream ratio different from 1:1.

100 percent CO₂ blowing

One hundred percent CO₂ blowing is already being evaluated by several systems houses and spray foam applicators. Currently, the mechanical properties of foam blown with 100 percent CO₂ are similar to those based on CFC-11.

However, preliminary testing indicates that the initial thermal conductivity of the foam increases by 20 to 25 percent and aged thermal conductivity increases to 0.030 to 0.032 W/mK (as measured at 10°C).

In addition, polyol modifications are necessary to reduce friability and to maintain adhesion. Machinery modifications also have to be made to handle higher viscosities and unequal isocyanate and polyol streams.

Cost increases are expected due to higher isocyanate content and the increased foam thickness required to maintain insulation value.

HCFC-22

HCFC-22 and blends of HCFC-22 with HCFC-142b, HCFC-141b, and HCFC-123 are being considered for spray foam applications which once used combinations of CFC-11 and CFC-12.

Short/Intermediate Term

HCFC-141b

HCFC-141b provides spray foam characteristics similar to those for foams blown with CFC-11. However, the main concerns surrounding HCFC-141b are unresolved. These are the toxicological behaviour of the blowing agent and of potential degradation products, and possible increase in the ODP of HCFC-141b.

In addition, minor modifications to processing equipment may be required to handle the moderate flammability of HCFC-141b.

Use of this blowing agent is expected to increase foam costs by approximately five percent.

HCFC-123

HCFC-123 also provides spray foam characteristics similar to those of foams based on CFC-11, but it requires no modifications to processing machinery.

The main concerns surrounding HCFC-123 are unresolved toxicological behaviour, including degradation products, and the lack of firm plans for commercial scale production.

The estimated price range of HCFC-123 would increase foam costs by approximately 20 percent. This could make the end product uncompetitive in the market.

Long Term

Several potential alternative blowing agents which are being investigated in other polyurethane rigid foam evaluations should prove equally suitable for spray foam. These include HFC-125, HFC-134a, HFC-152a and fluorinated ethers.

OTHER RIGID POLYURETHANE FOAM APPLICATIONS

Other rigid polyurethane foam applications include slabstock, pipe-in-pipe, and one component foams.

Global Consumption of CFCs in Other Rigid Polyurethane Foam Applications

The estimated consumption of CFCs for other rigid polyurethane foams was 11,300 tonnes. Consumption on a regional basis is provided in Table III-5. The data was reported in aggregate for all subsectors (i.e., slabstock, pipe-in-pipe, and one component foam) because data for the individual subsectors was not available.

Table III-5. Estimated Global CFC Consumption for Other Rigid Polyurethane Foam Applications in 1990

Region	Tonnes 1990
North America	1,300
Western Europe	7,700
Eastern Europe	1,000
Middle East/Africa	200
Central/South America	200
Japan	400
Asia Pacific	500
Total World	11,300

SLABSTOCK

Product Applications

Rigid polyurethane slabstock is used as insulation for pipes and storage tanks, as insulation boards, and can be the insulating material for refrigerated transport containers. Rigid slabstock is manufactured in a variety of product shapes and forms.

Production Process

Rigid slabstock is produced using either the discontinuous or the continuous manufacturing process. CFC-11 has served in both processes as the blowing agent, although water and/or CFC-12 are sometimes incorporated into the mixture.

Discontinuous Process

In the discontinuous method, the chemical components of a slow-reacting foam system are weighed and hand-mixed, after which they are poured into a wooden or cardboard mould. Fitted on top of the foam, a floating lid rises with the expansion of the foam. The lid serves to level the top surface of the foam block that is being produced. The output of the discontinuous method can be increased by using mechanical stirrers and agitators to replace the hand-mixing stage, or by machines that both mix and dispense the foam reaction mixture into the mould.

Continuous Process

In the continuous process, the foam reaction mixture is dispensed continuously into a trough lined with paper or polyethylene film and located on a moving conveyor belt. The foam expands as it moves forward on the conveyor belt. Some belts are fitted with equipment that produces a foam with a flat top surface, similar to the floating lid used in the discontinuous process.

In production by either method, the foam rises and cures. Then it is cut into sections for use in the applications and products listed above. In general, rigid slabstock does not have either a facer or an impermeable liner attached to it.

Technical Options for Reducing CFC Consumption

Immediate

Immediate and short term options for slabstock are very similar to those for flexible-faced laminates/boardstock.

Reduced CFC-11 Technology

Reducing the amount of CFC-11 in the foam formulation is feasible and has been introduced by some slabstock producers. However the higher exotherm is a critical problem in slabstock foams and limits the reductions which can be achieved.

In addition, an increase in the thermal conductivity of the foam, up to 10 percent, may occur when using reduced CFC-11 formulations.

Pentane Blowing

Pentane blowing is a feasible option that has been evaluated by manufacturers, particularly in Europe.

Since pentane is flammable, safety precautions are required for the production equipment, production area and post-production storage area.

To reduce flammability risks further, precautions are also necessary for foam cutting by fabricators and customers when they handle foam products blown with pentane.

Short/Intermediate Term

Intermediate options for slabstock are the same as for flexible-faced laminate/boardstock.

HCFC-22

HCFC-22 and blends of HCFC-22 with HCFC-142b, HCFC-141b, and HCFC-123 are being considered as replacements for CFC-11 and CFC-12 in certain slabstock applications.

HCFC-123

The use of HCFC-123 as a blowing agent produces foams with very similar properties to those based on CFC-11.

HCFC-141b

HCFC-141b also produces foams with very similar properties to those based on CFC-11. In addition, HCFC-141b is a preferred option because of its lower estimated price, relative to HCFC-123.

New polyols also may be required to combat the solvent effect of the HCFC-141b blowing agent.

Long Term

Several potential alternative blowing agents which are being investigated in other polyurethane rigid foam evaluations should prove equally suitable for slabstock foam. These include HFC-125, HFC-134a, HFC-152a and fluorinated ethers.

PIPE-IN-PIPE/PREFORMED PIPE

Products and Applications

Foam-insulated pipe-in-pipe sections typically have an inner steel pipe which is surrounded with foam insulation which, in turn, is protected by a plastic outer skin. These pipes are installed underground and are used to transport hot water from a central boiler to surrounding dwellings. Similar pipes and others insulated with preformed pipe sections are used in production units and chemical plants for the transport of hot or cold fluids.

Production Processes

Pipe-in-pipe sections are produced by injecting the foam chemicals into the cavity between the inner and outer pipes. Preformed pipes are produced by pouring or injecting the foam chemicals into half-section moulds.

Technical Options to Reduce CFC Consumption

Immediate

100 percent CO₂ blowing agent

One hundred percent CO₂ blowing is the preferred option being implemented by pipe-in-pipe and preformed pipe fabricators in most countries. Many fabricators have already switched or are in the process of converting to this technology. Key considerations for using this option include:

- the construction of the pipe-in-pipe assembly minimises aging of the foam thermal conductivity; and,
- a zero ODP option was required at an early stage in Scandinavia, which has a significant share of the world market for the product. Certification for such systems has been obtained.

One hundred percent CO₂ blown foam has better compressive strength than CFC blown foam. Accelerated tests show that 100 percent CO₂ blown foam can withstand temperature and time better than CFC blown foam.

The thermal conductivity of 100 percent CO₂ blown foam for pipes has increased by 5 to 15 percent. However, changes in thickness and construction practices (two carrier pipes in the same insulation and outer casing) can compensate for the increased conductivity.

HCFC-22, HCFC-22/HCFC-142b, and Methyl Chloroform

HCFC-22, HCFC-22/HCFC-142b and methyl chloroform have also been introduced in piping products. The thermal conductivities of foams using HCFC-22, HCFC-142b, or methyl chloroform are 5 to 10 percent higher than CFC-blown foams.

Intermediate/Long Term

It is feasible that both HCFC-141b and HCFC-123 could be used in formulations designed to give better insulation values than those offered by the immediate/short term options. However, costs would increase by about 5 to 15 percent.

Many manufacturers are implementing immediately available options like 100 percent CO₂ blowing, which can be used for the long term. As described previously, the foam manufactured with this process has better compressive strength, aging, and other properties. Therefore, it is possible that in the long term, manufacturers will focus on developing new blowing agents or foam formulations to target increases in foam thermal efficiency since ozone depleting compounds have already been eliminated in most cases.

ONE COMPONENT FOAM

Products and Applications

One component foams are used by both the building industry and the do-it-yourself market in a variety of applications. These include draught-proofing around pipes, cable runs, doors, and windows; sealing doors and window frames; and joining together insulating panels, roofing boards, and pipe insulation. One component foams are preferred because they are portable and easy to apply, and offer both thermal and sound insulation properties.

Production Process

One component foams are MDI-based prepolymer compositions that contain dissolved CFC-12. CFC-12, which has a lower boiling point than CFC-11, has been used because it acts as a propellant and because it produces "frothed" foam, thereby preventing the material from flowing away from the site of its application. Additionally, one component foams do not generate enough heat to volatilise CFC-11.

One component foams are supplied in pressurized cylinders and aerosol cans fitted with a nozzle that extrudes the product in a thin strip of material. After application, the foam expands at room temperature in conjunction with the vaporization of the CFC-12, and cures by reacting with moisture in the air. This characteristic is unique to one component foams.

The foam continues to cure internally after becoming dry to the touch as moisture traces diffuse into the foam. The total length of time needed for the foam to cure depends on several factors, including temperature and the humidity level.

Technical Options to Reduce CFC Consumption

Immediate

HCFC-22 or HCFC-22/HCFC-142b blends

HCFC-22 or HCFC-22/HCFC-142b blends can produce one component foam with characteristics similar to foams containing CFC-12. In fact, some manufacturers have already introduced these blends into product formulations.

Butane or Propane

Hydrocarbons, such as butane or propane, have been introduced by many one component foam manufacturers because they have zero ODP. However, changes are required in the foam packaging plant because of the flammability of the blowing agent/propellant.

Dimethyl Ether (DME)

DME, which contains no chlorine, is currently being used as a blowing agent in one component foam. However, its flammability also may require changes in packaging machinery.

Intermediate/Long Term

The need for intermediate or long-term strategies may depend more on application needs and product characteristics rather than on environmental issues. For instance, DME and hydrocarbons eliminate the need for chlorine containing blowing agents.

The search for long-term options may be dictated by blowing agent solubility characteristics. Prospective replacements can include many low boiling compounds including HFC-125 and HFC-152a.

FLEXIBLE POLYURETHANE FOAMS

Flexible Polyurethane Foam Chemistry

Flexible polyurethane foam has become an important cushioning material since its commercial introduction in the late 1940s. The material is made by the intensive mixing of different raw materials at room temperature during which the polymeric product is

formed and simultaneously expanded with a self-generated carbon dioxide (CO_2) blowing agent. The liquid mixture is poured and starts creaming and rising. The production process may happen on a conveyor belt (e.g., continuously-poured slabstock) or in a mould (e.g., individually-moulded items, such as automotive seats).

There are limits on the foam properties that can be achieved with CO_2 as the sole blowing agent. Auxiliary blowing agents are therefore used in some formulations to provide cooling, reduce foam density and increase softness. CFC-11 is one of the auxiliary blowing agents currently used in the flexible foam industry.

A small number of isocyanates and a range of polyols of different molecular weights and functionalities are used to produce a wide spectrum of materials. The relative rates of the reactions are controlled by specific catalysts. Some catalysts have more influence on the polymerisation; others influence the CO_2 formation. Typical catalysts used include tertiary amines and organometallic salts. In addition, surfactants are added to help mix physically incompatible components of the reaction mixture, which stabilise the fine cell structure, promote cell opening, and ensure uniform cell size. Specific additives are also included in the formulation to meet specific customer requirements such as colour, weight, and fire performance.

The function and types of blowing agents used in flexible foam manufacturing can roughly be divided into two classes:

- Chemical blowing agents -- These react with the isocyanate, one of the chemicals used in the polyurethane chemistry. The best-known example of a chemical blowing agent is water. In fact, water is the most "natural" and most widely used blowing agent in polyurethane chemistry.

When water reacts with the isocyanate, carbon dioxide is generated. Carbon dioxide provides the foaming action which expands the forming polymer network. The greater the volume of CO_2 formed, the more expanded the polymer network, and the lower the resultant density. However, the increased use of water and the resulting increase in CO_2 formation has limitations:

- 1) The heat developed by using more water to generate greater quantities of CO_2 can cause the temperature inside the foam to reach conditions under which the polymer starts to degrade. The exothermic reaction can lead to spontaneous auto-ignition of the foam. If the foam product does not ignite, the degradation will be marked by a brownish discoloration (scorching) of the foam interior.
- 2) Hard urea segments develop in the foam polymer network as a byproduct of the water/isocyanate reaction which forms the CO_2 . This urea formation establishes a natural limit to the softness of the foam. As the water level is increased to release more CO_2 and to

produce a lower density foam, the hardness of the foam is automatically increased. Therefore, where soft foam properties are desired, water alone cannot be used.

- Physical blowing agents -- These are usually inert products that have physical properties which make them suitable for use with polyurethane chemicals. Auxiliary blowing agents are used to absorb the heat energy of the foam reaction and to provide foam properties that the chemical blowing agent alone cannot provide. They are typically introduced into the manufacturing process when super soft or low-density foams are required.

Physical blowing agents are used in a range of formulations to reduce foam density and/or increase softness. They volatilise (absorbing heat energy) during the foaming process and the vapour that is produced supplements the gas volume created by the generation of carbon dioxide (therefore the name "auxiliary" blowing agents).

The introduction of CFC-11 as an auxiliary blowing agent in the early 1960s allowed a tremendous increase in the spectrum of physical foam properties achievable, including density and firmness. A liquid at initial mixing temperatures and inert to the polyol, isocyanate, water, catalysts, and surfactants, CFC-11 quickly converts to the gaseous form when the exotherm of the water/isocyanate reaction is initiated. The heat of vaporisation of the CFC-11 provides a desirable cooling effect upon the exothermic reaction.

By the early 1970s, methylene chloride was identified as an auxiliary blowing agent. As a result, both CFC-11 and methylene chloride have shared the market as auxiliary blowing agents. It is estimated that by 1986, CFC-11 use comprised 80 percent of the global market. In certain markets, like the United States, methylene chloride was more widely used.

Today, acetone and methyl chloroform are also being utilized as auxiliary blowing agents. However, certain limitations are associated with their use. For instance, use of acetone, a flammable liquid, necessitates that extra precautions be taken to ensure worker safety. Methyl chloroform faces production and use restrictions as a regulated substance under the recently revised Montreal Protocol, as well as restrictions based on the extra heat absorption that influence the process negatively.

Products and Applications

Slabstock Foams

Polyurethane flexible slabstock foams include both polyether- and polyester-based foams used to produce low density, supersoft, high-density, high-resilience (HR), and combustion modified high resilience (CMHR) type foam cushion products.

Slabstock foams are widely used in furniture, bedding, carpet underlay, and automotive interiors. Available in a range of densities and firmness, the foams are produced in large blocks which are cut for use in individual applications.

In applications requiring combustion modified foams to meet fire safety standards, the foams include melamine, graphite, or alumina trihydrate to improve the foam's performance. Greater amounts of auxiliary blowing agents are normally used in these foams to offset the increased hardness and density resulting from the introduction of these solid additives.

Combustion modified foams are mainly used in upholstered furniture and bedding applications. In some countries, they are used principally in prisons, institutions and mass transit; however, in other countries, such as the UK, their use is compulsory for all upholstered furniture and bedding. Most of the technical options available for flexible slabstock foams can be used in combustion modified foams as well, except where noted.

Moulded Foam

The most significant use of flexible moulded polyurethane foam is in the automotive field for seat cushions, back cushions, and headrests. Flexible moulded foams are used in seating applications for other transportation, such as trains, buses, and airplanes. A specialty market is the sound dampening in cars by backfoaming of the carpet. Together, these uses account for at least 90 percent of the flexible moulded foams used worldwide. The other 10 percent of moulded foams is used for non-automotive or furniture applications.

Production Process

Traditional Slabstock Method

In a typical continuous slabstock foam production line, the slabstock foam is produced on an enclosed continuous conveyor belt, called a "foam tunnel", that can be over 60 metres long.

Liquid chemicals are metered to a mixing head. Feed formulation varies for different foam grades and between different foam producers.

The discharge stream from the mixing head is dispensed with a traversing pattern across the width of the initial inclined portion of the conveyor belt: this is termed the "lay down". The conveyor belt is lined with polyethylene paper or polyethylene film to make a "U" shaped retainer for the rising foam mass as it descends the slope.

As the polymerisation reactions proceed and bubbles form, the foam rises and the blowing agents are volatilised due to internal heat generation. Within six metres of the lay down, the foam mass generally reaches its point of maximum expansion.

The foam can be as high as 1 to 1.25 metres and up to 2.5 metres wide. From its maximum expansion, the foam starts to release its blowing agents and some unreacted chemicals. A ventilated tunnel, typically covering the first section of the conveyor system, exhausts these emissions and thereby controls workplace concentrations.

The continuous slab of foam moves through the production tunnel to a cut-off saw which slices it into blocks for curing and storage. These blocks can be as short as 1 meter or as long as 60 meters. The exothermic chemical reaction continues within the foam mass while in the curing area. The natural insulating qualities of the foam maintain the heat for a period of several hours. Slowly, the heat dissipates while air penetrates the block and replaces the blowing agent.

The conventional slabstock process is less economical than newer methods; consequently, the use of this process is on the decline. In addition, processing is generally more critical, and the introduction of CFC alternatives is more problematic. However, the process is still the primary choice for polyester foams and many other specialty products.

Maxfoam/Varimax

Developed in the early 1970s, the Maxfoam/Varimax process differs from the traditional method in lay down and foam expansion. The discharge from the mixing head is moved directly into a trough, which is nearly level with the ultimate height of the foam slab.

The rising foam mass expands and spills over the front edge of the trough and is drawn away on a sloped fall plate. This slope is kept similar in shape to the rise profile of the foam, thus allowing a downward expansion, giving the resulting foam slab a nearly rectangular shape.

Currently the process of choice for most manufacturers, the Maxfoam/Varimax process for flexible foam production is less complicated and more efficient than conventional foaming.

Other Foaming Equipment: Vertifoam

The Vertifoam process produces foam vertically rather than horizontally. This results in full-sized blocks at a far lower foam chemical throughput rate and a slower production rate than conventional equipment. This more controllable rate is suited to small to medium manufacturers, since it allows efficient operation from 500 to 3,000 tonnes per year.

In addition, the foam blocks produced are accurately shaped and cut-off losses are low. Both square blocks and round blocks can be produced.

The Vertifoam process differs substantially from conventional horizontal foam machines that need high chemical throughput rates to produce large foam blocks. The high

chemical throughput rates of conventional foam machines result in high capital costs and large space heating and ventilation requirements.

The reductions in floor area achieved with the Vertifoam process are very substantial -- up to 85 percent reduction has been reported. The lower chemical throughput of the process means that a large reduction in the extraction system is possible, which in turn means air conditioning/heating costs are reduced.

In countries where legislation may in the future require blowing agent recovery and/or fume scrubbing, the low air extraction rate substantially reduces the capital and running costs of recycling and/or scrubbing equipment.

Moulded Foams

As in slabstock manufacturing, a precise mixture of polyol, isocyanate, water, and other raw materials is delivered at a specified temperature in the production of moulded flexible foams. Following mould cleaning and application of a release agent, the moulds are filled, sometimes manually, and then closed.

As the foam reactions occur within the mould, the polymer forms and simultaneously expands to fill the mould cavity. Many moulded products are manually flexed and/or precrushed by rollers upon removal from the mould, which opens some of the remaining cell windows. In some cases, the newly-demoulded part is heat-treated to further cure and harden the skin.

Generally, within the automotive field, flexible moulded foam can be produced by either "hot cure" (approximately one third of production) or "cold cure" (approximately two-thirds of production) on a worldwide basis. Hot cure foam production is used exclusively for automotive seating and headrests. Cold cure or high-resilience moulded foams are used in both automotive (seating, headrests, carpet ticking backing) and non-automotive (furniture) uses.

CFC-11 has typically been used in supersoft grades (for back cushions) and in the low-density grades (25 kg/m^3). In 1986, approximately 10 percent of all moulded foam production used CFC-11 in manufacture. In formulations using high resilience foam, auxiliary blowing agents are essentially phased out.

Consumption Patterns of Auxiliary Blowing Agents

Slabstock Foams

Approximately 46,750 tonnes of CFC-11 was used worldwide in 1986 in the production of flexible slabstock foam. At the time, this figure represented 17 to 18 percent of all CFCs used in the production of foam plastic products.

The use of CFC-11 in the production of flexible foams has declined substantially worldwide since 1986. The estimated consumption of CFCs for flexible polyurethane slabstock in 1990 is shown in Table III-6.

Table III-6. Estimated Global CFC Consumption for Flexible Polyurethane Foam (1986 vs. 1990)

Region	Tonnes 1986	Tonnes 1990
North America	11,150	1,350
Western Europe	10,800	5,900
Eastern Europe	4,400	800*
Middle East/Africa	6,200	1,200*
Central/South America	5,300	1,000*
Japan	2,000	900*
Asia Pacific	6,900	1,300*
Total Slabstock	46,750	12,450
Total Moulded	13,700	1,500
Total World	60,450	13,950

* Estimate.

Moulded Foams

Approximately 13,700 tonnes of CFC-11 were used in the production of flexible moulded foam worldwide in 1986. In 1990, it is estimated that 1,500 tonnes were used, all of it in Japan. This figure represents about 5 percent of all CFCs used by the foam sector.

There has been a trend towards using less CFC-11 in moulded foam applications as automobile manufacturers increase densities of the foam seats. In moulded foams, however, the CFCs are used not only for density reduction, but also for flowability of the foam system in the moulds.

Technical Options to Reduce CFCs in Flexible Polyurethane Applications

There are a variety of potential technical options for reducing CFC-11 emissions and use in flexible foam production. There is no single solution, rather a combination of technologies will be required, depending on the particular product mix of each

manufacturer. Available options include improved housekeeping and maintenance, product modifications, process modifications, chemical modifications, chemical and physical blowing agent substitutes, and product substitution.

The most viable options for reducing CFCs are discussed in more detail in the following sections. The potential for many of the options to reduce CFC usage will be dependent upon the grade and density of the foam being manufactured.

Housekeeping and Maintenance

Certain housekeeping and maintenance activities will help minimise blowing agent emissions. Particularly important activities include the routine maintenance of pumps, pipe fittings and flanges, pressure relief devices, sampling and delivery connections, storage tanks and dispensing lines. Blowing agent emissions can also be reduced by following these other housekeeping procedures:

- unload only with closed loop systems; and,
- avoid using CFC-11 for flushing the mixing head and troughs and for cleaning of machinery parts.

Process Modification

E-Max

An intermittent production approach now in its first production use, the E-Max process is a blend of Maxfoam (slabstock) technology and moulding technology. Foam is poured through the Maxfoam process into a slab-sized mould, which is closed immediately after pouring. The mould is connected to a closed loop exhaust system, including both a sacrificial pre-filter and a carbon adsorption unit. This system traps all emissions and allows subsequent recovery of the blowing agent.

The metering technology is extremely important and should approach those of the moulding technology in precision and directness for the following reasons:

- the production of a mould of foam is essentially identical to a run of slabstock foam; and,
- the yield of the run is directly related to the run length.

Although a successful recovery rate of 85 percent for CFC-11 was achieved on pilot scale, the rate should be improved on an industrial scale. A full size, commercial unit has been installed and is operational in the US. It is expected to be operational and open for demonstration later in 1991.

Hypercure/Envirocure

Hypercure is an add-on technology for the Vertifoam process. The Vertifoam technology produces a foam block with a thin, porous skin allowing CFCs to be emitted at a faster rate than in the traditional or Maxfoam processes, which produces a foam with a relatively thick skin.

Benefits of the hypercure/envirocure technology, which involves forced air recirculation through the foam, include the following:

- it permits rapid curing under continuous controlled conditions, which quickly cools foam blocks to ambient or safe handling temperature;
- it provides an opportunity to terminate unreacted isocyanates under controlled conditions; and,
- it allows carbon adsorption for efficient recovery of the auxiliary blowing agent (85 to 90 percent).

Add-On Recovery Systems

For existing traditional and Maxfoam manufacturing units, add-on recovery systems are effective in the recovery of blowing agents from the process exhaust, but are unproven in their efficiency on capturing emissions from the curing area. However, with increased encapsulation of the production line and curing area, complete capture of blowing agent emissions could be expected. A technology using the reversed "Braysorb Cycle" may reduce the need for extensive and expensive carbon beds. Adsorbents other than activated charcoal may prove to be more effective under diluted vapour concentrations.

Although theoretically possible, recycling the air that contains the blowing agent, has proven to be technically difficult and cost prohibitive. However, ongoing development in this area combined with future broader regulations on air emissions may turn the tide in favour of this type of conservation.

Recovery and recycling deserve continued attention, in an era where emissions are subject to scrutiny and conservation efforts are increasingly important,

Catalytic Oxidation

Thermal oxidation or incineration is a common method for the disposal of industrial gas wastes. This process is at least theoretically applicable for the elimination of CFC-11 emissions. However, a number of major technical and economic obstacles make its application to the foams industry rather difficult.

Chief among the obstacles are the low heat of combustion which requires considerable supplemental fuel, the relatively low blowing agent emission concentration, and the presence of chlorine which tends to poison catalytic systems. With an abundance of other, more viable options, it is unlikely that this process will ever be applied in the flexible polyurethane foam industry.

Product Modification

Density Restrictions

The three functions of an auxiliary blowing agent are to control foam hardness, absorb heat from the exothermic foam reaction, and decrease the foam density. Of these, density reduction is the most significant in terms of the amount of auxiliary blowing agent used.

Low density foams (21 kg/m^3 or less) can only be manufactured with the help of auxiliary blowing agents. Limiting foam production to the higher densities (greater than 21 kg/m^3) would limit the function of the auxiliary blowing agent to hardness control and would eliminate approximately two-thirds of the current auxiliary blowing agents. The polyurethane foam industry in Sweden has already entered into a voluntary agreement with Swedish government to practice such a restriction.

Reformulation

Quick and significant reductions in the use of CFC-11 can be achieved by reformulation. Formulations should be reviewed and modified to allow for the lowest amount of auxiliary blowing agent (CFC) use to obtain the desired physical properties. For example, some foam formulations use relatively high amounts of isocyanate (TDI) for processing convenience; however, this tends to cause hardness or boardiness in the foam. Additional CFC use is therefore required to soften the foam. Elimination of such practices has already saved many foam manufacturers up to 10 percent of total CFC use.

Chemical Modification

Extended Range Conventional Polyols

Extended range conventional polyols expand the range of foams that can be made with carbon dioxide as the sole blowing agent. These polyols are either used to replace the current conventional polyol or are blended with it. Their use significantly reduces the need for CFCs or other auxiliary blowing agents for softness in all densities of foams, and eliminates that need in some foams.

However, extended range polyols commercially available do not yet allow the total elimination of CFC-11 from all grades of conventional foam. Some of these

polyols allow a six to eight parts CFC-11 reduction by weight. Others allow the total elimination of CFC-11 from supersofts but are not capable of making the intermediate grades of foam.

These polyols can be used with existing foam machinery; however, their use may require capital investment for storage and metering equipment, and is likely to increase chemical costs by approximately 15 percent.

Extended Range HR Polyols

Extended range polyols for high resilience (HR) foams allow the production of a wide range of densities and IFDs without the use of blowing agents. A dual polyol system consisting of a high resilience polyol and a conventional filled polyol is required for this system.

The densities are limited to about 21 kg/m^3 due to "exotherm control" considerations. Foam grades from supersoft to high load can be produced. Lower density HR foams still require auxiliary blowing agents with a high heat capacity to prevent the foam from being scorched by the heat generated in the foam reaction.

This technology makes it possible to successfully replace auxiliary blowing agents at virtually no cost wherever higher resilience foams are used.

Softening Agents

A softening agent is an additive that lowers the foam hardness and therefore allows the reduction of CFC-11 use. Several chemical manufacturers have products available that allow foam production with only six to eight parts CFC-11. In all cases, however, the lowest foam density achievable without the need for auxiliary blowing agents is 21 kg/m^3 due to foam exotherm considerations.

Alternative Auxiliary Blowing Agents

Reducing hardness in high density foams (down to densities of approximately 21 kg/m^3) without the use of an alternative blowing agent is not a difficult problem. Many practical feasible methods are described above. Decreasing density, however, without the use of such blowing agents is a much more difficult problem. When densities below 21 kg/m^3 are required some auxiliary blowing agent is, at present, required.

Alternative auxiliary blowing agents to CFC-11 include: methylene chloride, methyl chloroform (1,1,1-trichloroethane), HCFCs, acetone, and carbon monoxide (CO) generated by a formic acid - isocyanate reaction (the technology is known as the "AB" process). Assuming that factors such as toxicity and environmental acceptability prove to

be satisfactory, these alternatives hold some promise for eliminating CFC use in the flexible polyurethane foam manufacturing industry.

Methylene Chloride

The substitution of CFC-11 by methylene chloride in slabstock production is both a technically and commercially feasible immediate option. Methylene chloride has been used successfully for many years in the production of conventional grades of flexible slabstock foam.

In the US, approximately 70 percent of the auxiliary blowing agent currently used is methylene chloride. In the UK, a major switch to replace CFC-11 in flexible foam with methylene chloride has occurred. The cost of methylene chloride is significantly less than CFC-11.

Methylene chloride can technically eliminate between 80 and 100 percent of CFC-11 usage in flexible foam slabstock production. However, there may be a technical limit for very low density supersoft foam production. The main limiting factor in the substitution of methylene chloride is the restriction of its use due to local environmental and safety concerns.

Methylene chloride is emitted from slabstock foam later than CFC-11, so modifications in the plant ventilation systems are needed to handle emissions at the cut-off saw and in the foam cure area.

The use of methylene chloride raises a number of controversial environmental and safety issues:

- **Health Effects** -- Short-term health effects from repeated inhalation of excessive amounts of methylene chloride vapour include anaesthesia, possible organ injury or death. Permissible eight hour exposure levels vary from country to country; the current range is 50-500 ppm, and, in general, regulation of methylene chloride exposure is becoming more stringent.

Long-term health effects from methylene chloride exposure are also of concern. The International Agency for Research on Cancer (IARC) has classified methylene chloride as a possible human carcinogen. This assessment is being challenged by the European Chemical Industry Ecology and Toxicology Centre (ECETOC) on the basis of recent research reports. The controversy surrounding long term health effects has yet to be resolved.

Therefore, worker exposures must be well controlled. This may require substantial capital investment in ventilation systems and material handling equipment. In many countries, automatic block handling in the foam curing and initial storage areas means that employee access does not occur.

Capital costs will vary depending upon the existing ventilation system in the plant and the layout of the existing line, cure area, and storage areas.

Environmental Impacts -- The ozone-depletion potential for methylene chloride is negligible because it has a very short atmospheric lifetime. The contribution of methylene chloride to acid rain is insignificant and it has negligible smog and global warming potentials.

Methyl Chloroform

More than 10 percent of the auxiliary blowing agent used in flexible slabstock in the US is methyl chloroform.

Methyl chloroform is particularly used in areas where methylene chloride use is restricted. Although methyl chloroform has an ODP of 0.1 compared to 1.0 for CFC-11, its large global use as a cleaning solvent has led to a scheduled phaseout of its production by the year 2005 under the Montreal Protocol.

As a result, the use of methyl chloroform is only considered a short term bridge from CFC-11 to other solutions. In addition processing is rather cumbersome because of its higher - and sometimes too high - heat capacity.

HCFCs

Hydrochlorofluorocarbons, or HCFCs, are a family of compounds composed of carbon, hydrogen, chlorine and fluorine. Two HCFCs, HCFC-123 and HCFC-141b, have boiling points and heats of vaporisation close to that of CFC-11. Laboratory and plant scale evaluations suggest that they can fully replace CFC-11 as auxiliary blowing agents in flexible polyurethane foam with only minor adjustments to formulations. The ODPs of HCFC-123 and HCFC-141b are 0.02 and 0.10, respectively.

HCFC-123 has the advantage of being non-flammable, while HCFC-141b is moderately flammable. The possible need for plant modification to accommodate HCFC-141b is presently under investigation.

The commercialisation of HCFC-123 and HCFC-141b is not anticipated until about 1993. Toxicological studies are still not completed.

Reductions in CFC usage by HCFCs will be dependent upon a number of factors, including the timing of commercialisation, use of other technical options, and the cost of the HCFCs. The potential cost may make HCFCs uncompetitive in most flexible foam markets.

It is possible that the HCFCs may be used by a small portion of the market which may not be able to eliminate CFCs by the time HCFCs are commercialised. For

example, HCFCs may be necessary for use in combustion modified and low density supersoft foams.

However because of the chlorine contained in HCFCs, additional limits may be imposed on the production and use of HCFCs. In the US, for example, a ban on non-essential uses of HCFCs may take effect at approximately the same time that HCFCs become commercially available in large quantities. Therefore, it seems realistic not to consider these chemicals as an option to be used in flexible foam manufacturing.

Acetone

All flexible polyurethane foam grades produced using CFCs can be produced using acetone as the auxiliary blowing agent. Acetone does not have an ozone depletion potential, and it exhibits a negligible contribution to acid rain, smog, and global warming. In addition, the cost of acetone is significantly less than that of CFC-11.

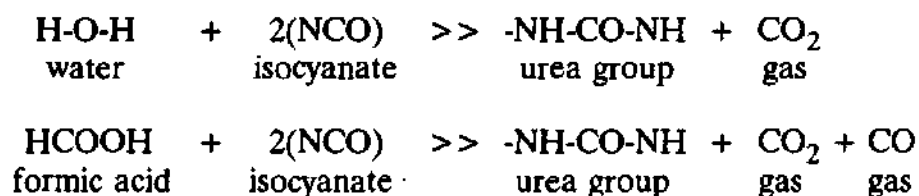
Nevertheless, acetone's relatively high flammability requires that special precautions be taken when it is used as an auxiliary blowing agent. Because the use of acetone is patented, licensing is required to use this chemical as a blowing agent.

AB Technology

AB technology employs formic acid in conjunction with water as the blowing agent for producing flexible polyurethane foam. The process is based on using the reaction of formic acid with an isocyanate to produce carbon monoxide in addition to the water/isocyanate reaction normally used to generate carbon dioxide gas for the expansion of foam.

The formic acid reaction doubles the gas quantity generated by the reaction of isocyanate. Since the reaction yields two moles of blowing gas (CO and CO₂) instead of one, it is more efficient than water as a blowing agent. In fact, this additional gas formation reduces the need for inert blowing agents such as CFC-11.

This process is depicted in the following equations:



Because only half the amount of urea groups (the "based segments" in a foam) are formed for a given volume of gas in the AB process, the AB foams are therefore softer than all water-blown foams. A variety of density/hardness grades can be produced with less dependence on inert auxiliary blowing agents such as CFC-11. No CFCs or other auxiliary blowing agents are used for most conventional foam grades above about 21 kg/m³, while reduced CFC levels may be used in many lower density grades.

The AB Process generates 50 percent carbon monoxide as the chemical blowing agent. Carbon monoxide is highly toxic and is a cumulative poison. In many countries, the permissible levels of exposure are 50 ppm or below for an eight hour exposure, with short term 10 minute levels of 400 ppm or below.

The generated carbon monoxide concentrations do not represent a major problem in the main conveyor section of a flexible foam slabstock machine, where ventilation is highly efficient to maintain safe workplace levels of TDI. Concentrations of CO in this section of the conveyor can be a few hundred parts per million. However, a substantial percentage of the CO is emitted at the cut-off saw, foam cure, and storage areas, where ventilation is not as efficient as on the foam line itself.

Care must be taken to insure the safety of operators from exposure to carbon monoxide. Automatic analytical monitoring equipment for carbon monoxide is essential both for fixed area monitoring and portable monitoring to ensure that the produced carbon monoxide does not exceed threshold levels. Additional ventilation systems would need to be installed in most factories. Ideally, mechanical handling in large open-sided storage areas is the solution, but for many plants the climate of the area and limitations imposed by plant layout prohibit this solution.

Equipment and procedure modifications are also generally required to store and handle the acid mixture. Vessels, pumps, and pipework must be made from acid resistant steel or appropriate plastic.

Carbon monoxide is a flammable gas, but the concentrations released in the AB process do not approach the levels representing a fire hazard.

Investment costs will depend upon the existing facilities and the design and layout of the foam plant. Foam manufacturers will need to invest in process equipment, protective equipment for workers, environmental controls, and ventilation. Depending upon the plant, investments in capital could be substantial.

In 1988, one manufacturer estimated that it had reduced its usage of auxiliary blowing agents by 60 percent with the AB technology and expected to attain a 70 percent reduction in 1989. Generally, reduction possibilities will depend upon the product mix, but a CFC-11 reduction of up to 50 percent is feasible.

Future Options

Use of Dissolved Carbon Dioxide as a Blowing Agent

The main blowing agent in the production of flexible polyurethane foams is carbon dioxide released from the liquid reactants by the exothermic reaction of TDI and water. There are, however, drawbacks involved with using CO₂ as the only blowing agent. These include:

- The high exotherm developed by the TDI/water reaction limits the lowest density achievable to approximately 21 kg/m³. Generation of greater quantities of CO₂ causes the internal temperatures of the foam block to rise to levels leading to scorching or auto ignition;
- The reaction of TDI and water to produce CO₂ is a more expensive method of forming CO₂ than dissolving CO₂ into the liquid foam materials; and,
- The formation of hard urea segments in the polymer result in a harder foam and limits the ability to make soft grades.

As a result, there has been increased interest in establishing alternative methods for releasing gas into the reacting foam mix. It is known that substantial quantities of CO₂ can be dissolved into the liquid foam ingredients.

Another method of CO₂ introduction is via the formation of CO₂ with some of the liquid reactants. Among the problems encountered with this method has been the need to keep the liquid reactants under pressure and the rapid release of the CO₂, when the reacting liquid leaves the mixing head.

With the possible future non-availability of CFCs and an increased price for TDI, the practicality of using dissolved gases will likely be reevaluated.

Operation at Higher Internal Block Temperatures

Technology is now becoming available that will allow the attainment of internal block temperatures of 170°C or even 175°C without the danger of scorching or ignition. This is especially significant in light of the problems associated with the exothermic heat developed when CO₂ is generated from the TDI/water reaction. This new technology may allow low density foams (below 21 kg/m³) to be produced without the need for CFCs to control scorch.

With higher internal block temperatures achievable, it also seems probable that this would allow a reduction in density of approximately one to two kg/m³.

Operating the Foaming Process Under Reduced Barometric Pressure

It is an established fact that atmospheric pressure variations, especially the reduction in average pressure due to altitude, have a significant effect upon foam density. In fact, the density of a slabstock foam from a particular formulation is directly proportional to the atmospheric pressure at the time of manufacture.

For each 100 meter increase in altitude, the average barometric pressure decreases by about 1,330 Pa (1 cm of mercury). This change decreases density by approximately three percent and a firmness by approximately six percent. There are several foam manufacturing plants operating at high altitude where foam densities can be up to 30 percent lower than would be attained at sea level.

European Patent Application No. 81303253.9 gives some details of how density and blowing agent reduction is possible by reducing barometric pressure. When foamed at 710 mm mercury, one foam formulation gave a density of 24.5 kg/m³; when foamed at 350 mm mercury, the same formulation gave a density of 14.1 kg/m³.

The Patent Application also discloses that to achieve the reduced density of 14.1 kg/m³ without the use of reduced barometric pressure meant introducing substantial quantity of CFC-11 (15 parts per 100 parts polyol) and a greatly increased quantity of toluene diisocyanate (TDI). This results in a significant increase in the cost of the foam.

Although the capital costs of equipment operating under reduced pressure would be higher, the operating costs would be substantially lower because of the elimination of blowing agent costs and the reduction in diisocyanate usage.

The operation of flexible foam block plants under reduced pressure poses very high development and capital costs and has not yet been achieved. Future interest in this approach may be revived depending on the increased cost of foam chemicals and blowing agents, and the non-availability of blowing agents.

Product Substitution

The majority of flexible polyurethane foam is utilized for comfort in furniture, bedding, and automotive applications. Although it competes with polyester filament and steel springs, the product has achieved a very high market penetration because of its durability and variability. This market penetration could be reduced or halted if technology adopted to eliminate CFC-11 usage increases the price of the product significantly.

For some uses, most notably the outer layers of furniture cushions and mattress ticking backing, polyester batting, other fibrefill materials and natural latex foams compete with flexible polyurethane slabstock foam. These materials have the potential to replace at

least some fraction of slabstock foam, principally the supersoft foams, in some markets. Fire performance requirements are limitations for some applications.

Other applications of polyurethane flexible foam include acoustical, filtration, gasketing, packaging, etc. In most of these applications, polyurethane foam has achieved a much lower degree of penetration and a multitude of viable alternatives are available. Although foam may be a relative small part of the overall product price in these applications, the chance of replacement is more viable and therefore price sensitivity may be greater.

Conclusions

Slabstock Foams

In 1986, between 17 and 18 percent of all CFCs consumed in foam manufacture globally were used in flexible polyurethane slabstock production. Substantial reductions in CFC use have already occurred.

By using a combination of the options outlined in this section, it is likely that flexible polyurethane slabstock manufacturers can eliminate CFC consumption by 1993, provided availability and acceptability of the alternatives.

At present, the low density segment of the flexible slabstock industry and combustion modified high resilience foams using melamine or graphite present the greatest challenge for eliminating CFCs.

Raw material suppliers are evaluating many alternative processes and process modifications which could allow the manufacture of low-density foams without the need for an auxiliary blowing agent like CFC-11.

The use of HCFCs in flexible foam manufacture will depend on regulatory acceptance of these substances for flexible foam production as well as time of commercialisation and cost/performance. At most, they are likely to capture 5 to 10 percent of the market.

Moulded Foams

Around the world, there has already been a significant trend to move away from CFC-11 blowing in flexible moulded foam. In so called "cold cured" foam manufacturing, CFCs are already completely phased out. This is the process of choice in North America and many other countries.

CFCs will be eliminated by 1993 from all moulded foam applications worldwide through increases in water, use of new polyol technology, and increases in densities, to at least 30 kg/m³. Unlike slabstock foams, there are no competitive cushioning materials for automotive seating which provides the same performance and ease of applications. The

particular technical option chosen and the rate of substitution will depend on precise circumstances in the local market, the cost of CFC-11, and the regulatory environment.

INTEGRAL SKIN AND MISCELLANEOUS FOAMS

Products and Applications

This section includes the many types of polyurethane foams which do not fall into the rigid or flexible category. The list of applications is long and varied.

Integral skin and miscellaneous polyurethane foams include:

- rigid integral skin foams for computer cabinets, skis, and tennis rackets;
- flexible (or semi-rigid) integral skin foams for steering wheels, headrests, armrests, shoe soles, beer barrels, etc;
- microcellular high-density foam for the exterior body parts of automobiles;
- energy-absorbing foams for dashboards and bumpers of automobiles;
- dunnage foam for automotive plants;
- low-density foam rigid packaging;
- floral foams; and,
- rigid floatation foams.

The principal benefits of polyurethane use for these applications are performance, ease of processing, and cost. CFC-11 was previously used in most of these foams, typically in small amounts.

Production Process

In the production of integral skin and miscellaneous foams, CFCs were useful because they have appropriate boiling points and contribute to the flowability of the chemical components. For the integral skin foams, CFC-11 was used because it condensed at the mould surface during the moulding operation to create the "self skinning" effect.

CFC-11 is retained in the closed cell rigid integral skin and floatation foams; however, its low thermal conductivity is irrelevant in these products. For all the other types (flexible integral skin, microcellular, energy absorbing, packaging, and floral foams), most of the blowing agents used in manufacture is emitted to the atmosphere during the foaming

reaction or very soon thereafter. The applications where CFCs are quickly released to the atmosphere are generally categorised as open cell polyurethane foam products.

Global Consumption of CFCs in Integral Skin and Miscellaneous Foams

According to global estimates, 17,700 tonnes of CFCs were used in integral skin and miscellaneous polyurethane foam manufacturing in 1986. At that time, this figure represented seven percent of CFCs used in all foam production. In 1990, global estimates placed CFC use at between 7,400 and 9,900 tonnes in these applications. A regional distribution of global consumption for 1986 and 1990 is presented in Table III-7. The available global data is not comprehensive enough to apportion CFC consumption totals to each integral skin and miscellaneous foam category.

Table III-7. Estimated Global CFC Consumption in Polyurethane Integral Skin and Other Foams (1986 vs 1990)

Region	Tonnes 1986	Tonnes 1990
North America	4,500	2,500
Western Europe	7,600	2,500-4,200*
Eastern Europe	2,000	700-1,100*
Middle East/Africa	500	200-300*
Central/South America	900	800
Japan	900	300
Asia Pacific	1,300	400-700*
Total World	17,700	7,400-9,900*

* Estimate. Ratios used to estimate 1990 consumption in these regions are based on the reduction in CFC consumption from 1986 to 1990 in North America and Japan. There is no proof that actual consumption lies within a given range.

Technical Options to Reduce CFCs in Integral Skin and Miscellaneous Foams

Immediate/Short Term

Rigid Integral Skin

Recent studies indicate that it is technically possible to totally eliminate CFC-11 use by water-blowing. Suitably reformulated systems have been successfully introduced into the German market. It is also possible to produce rigid integral skin foams by using HCFC-22. The use of HCFC-22 will require investment in processing equipment, but will not result in the need for large capital investments.

Based on a combination of these approaches, at least 80 percent of the CFC-11 used in this application can be eliminated in the near-term.

Flexible (Semi-rigid) Integral Skin

Recent tests indicate that 15 to 20 percent of CFC-11 can be replaced by water. The limiting factor is the decrease in skin thickness.

HCFC-22 has been shown to be a viable substitute for CFC-11 in flexible integral skin applications.

Hydrocarbon blowing agents, such as isopentane and butane, have been evaluated and found to be technically acceptable as replacements for CFC-11. The disadvantages of these chemicals are flammability and photochemical reactivity. Additional ventilation and other plant modifications would be required to handle these flammable materials safely. And, their use may be limited or even prohibited in areas which regulate photochemically reactive, volatile organic compounds that contribute to smog formation.

Microcellular

The majority of microcellular products, including those moulded by the RIM process, do not use CFC-11 as a blowing agent. In the few processes where it is used, air loading of the polyol component can provide a satisfactory technical solution.

Low-Density Packaging

The primary blowing agent for packaging foams is CO₂ produced by the water - isocyanate reaction, but CFC-11 is used to some extent. With appropriate reformulation, it is expected that the technical barriers to removing all of the CFC-11 from these foams will be overcome.

Costs involved in modifying the manufacturing process include installing equipment to handle higher viscosity chemicals and the need for additional inventory during the changeover. It is estimated that, for all open cell packaging polyurethane foam applications (80 to 100 percent), reformulating with water will eliminate CFC usage in the near term.

Energy-Absorbing, Floral, Floatation

CFC usage can be eliminated from energy-absorbing, floral, and floatation foams without difficulty by reformulating with water, HCFC-22, or other options.

Short/Intermediate Term

While HCFC-123 and HCFC-141b will technically work as CFC-11 substitutes, the main factors determining their future use will be their cost and performance characteristics. It is expected that they will not be needed in the longer term for rigid integral skin and miscellaneous polyurethane foam uses.

Flexible (Semi-rigid) Integral Skin

In flexible, semi-rigid integral skin foams, CFC-11 can be partially replaced with methylene chloride, although more work is needed to determine the precise reductions achievable in view of the stringent performance requirements in the automotive industry. Again, other environmental and health effect concerns may limit the use of methylene chloride in certain countries.

Long Term

It is estimated that 80 to 100 percent of the CFC-11 used today will have been eliminated from rigid integral skin and other rigid foams in the intermediate term, by 1993. For applications where eliminating CFCs/HCFCs with immediate and intermediate term options cannot be accomplished, manufacturers are looking at HFC chemicals such as HFC-152a, HFC-134a, and HFC-125.

Summary

According to global estimates, 17,700 tonnes of CFCs were used in integral skin and miscellaneous polyurethane foam manufacturing in 1986. At that time, this figure represented seven percent of CFCs used in all foam production. In 1990, global estimates placed CFC use between 7,400 and 9,900 tonnes in these applications.

By using a combination of options (complete water substitution, HCFC-22, methylene chloride, hydrocarbons and air loading of the polyol component), 80 to 100 percent of the CFCs used for rigid integral skin and other rigid foams will have been eliminated by 1993.

CFC-11 usage could be eliminated in 50 percent of flexible integral skin foams by 1993. This is the most critical long-term area. HCFC-22 and pentane (in Germany), as well as new HCFCs and HFCs, appear to be adequate substitutes provided that some reformulation of the system is carried out.

The main factors in determining whether HCFCs will be used in integral skin and other foam applications will be their cost, performance characteristics, and the ability to eliminate CFCs by other options prior to the commercialisation of the HCFCs.

Chapter Four

PHENOLIC FOAMS

Products and Applications

Phenolic foams currently represent well under five percent of the foam plastic insulants used worldwide. However, since 1986, this market sector has grown in excess of 100 percent, although there are substantial regional variations. The prime cause of growth has been the availability of processes to produce highly thermal-efficient, closed-cell products to compete with the polyurethane- and polyisocyanurate-based equivalents.

Phenolic foam products are gaining acceptance in most commercial, and some residential construction. Their excellent generic fire properties (particularly their extremely low smoke emissions) are establishing these products in many of the applications previously dominated by polyurethane (PU) and polyisocyanurate (PIR) products.

Although there is significant regional variation, the greatest proportion of substitution is occurring against PU and PIR based materials in the flexible faced laminate sector. Such laminates are widely used for wall and roofing applications, including the growing single-ply roofing market.

There is some substitution against fibrous products where strength, thermal efficiency, cleanliness and moisture resistance can be offered without unnecessary loss of fire performance. This is typical in the building services sector (H&V), where insulation is often exposed. Pipe laggings are an example. However, cost rules against phenolic foams in Europe when considered for domestic, or residential, applications.

Less thermally efficient, conventional open-celled phenolic foams are also used as prime insulation in some countries, most notably the USSR. However, contrary to the understanding at the time of the previous Technical Options Report, these are not typically blown with CFCs. Like many others, the Soviets are currently seeking to improve their energy conservation abilities and are expressing great interest in newer closed-cell CFC-blown phenolic technologies, which may lead to increased CFC consumption, in the absence of substitute alternative blowing agents.

There is still some residual usage of open-celled phenolic foam for non-insulation applications. A prime example of this is its use for floral arrangements. The unique wetting properties of this particular product make it virtually irreplaceable. However,

these properties are not reliant on the use of CFCs and most production has already switched to hydrocarbons on the basis of cost.

Production Processes

Closed-cell phenolic foams can be made by either discontinuous or continuous processes.

Discontinuous Processes

Several discontinuous processes have been developed for closed-cell foams, but undoubtedly the most prevalent is the block or bun process.

This specific process has been particularly dominant in Europe because block production lends itself to the varied requirements of the building services market. Complex computer-controlled cutting equipment optimises yields from blocks when cutting pipe sections. Despite this, yields can be as low as 50 percent for the more awkward shapes.

Other discontinuous processes include the manufacture of rigid faced panels by injection (normally referred to as "pour-in-place"). Multi-daylight and oyster-press routes have been followed, but investment in these more recent routes has been curtailed pending the development of thermally efficient CFC-free technology.

Most, if not all, discontinuous processes have used CFC-11 and/or CFC-113 to obtain their high thermal efficiencies. Accordingly, most plant technologies and their associated installed units are unable to handle low boiling blowing agents. Additionally, few plants are explosion-proofed. These factors have inhibited the move to alternative blowing agents, particularly the low boiling HCFCs and HFCs. Furthermore, appropriate plant and process technologies for this purpose are likely to be difficult to achieve and, therefore, still seem some way off.

Continuous Processes

Within the range of continuous processes, lamination with flexible facings has been the major development over the last five years. Lamination with rigid facings and continuous block processes have received less attention. When CFC-free technologies become available, these continuous processes may be developed more fully.

The machines used for continuous lamination are more capable of processing a variety of blowing agents, although the explosion-proofing limitations remain similar in most cases. Consequently, CFC-114 has been a common constituent within several technologies in addition to the more traditional CFC-11/CFC-113 combinations. It should be stressed that the process, not the machinery per se, facilitates the use of low boiling materials. Therefore, it is unlikely that much of the associated technology will be transferable to the discontinuous operations.

Global Consumption of CFCs in Phenolic Foams

The requirement for high thermal efficiency naturally drove the phenolic foam industry towards CFCs during the early to mid 1980s and several closed-cell technologies were developed around that time. However, it is now evident that the global consumption figures given in the previous Technical Options Report were over-estimated. The most obvious contributor to this was the assumed consumption by the USSR which has since been discounted. It is therefore not surprising that a decrease is observed in Table IV-1 when compared with the previous submission.

Since 1986, there has been a net increase in CFC consumption by approximately 80 to 90 percent. However growth in the phenolic foam market sector has been largely at the expense of CFC-containing PU- and PIR-based products. Therefore, to gain a true picture of phenolic foam's contribution to the foam plastic insulation industry's net reduction in CFC usage, evaluations must include a comparison of the respective progress being made with advancing product technologies.

Table IV-1. Estimated Global CFC Consumption for Phenolic Foams (1986 vs. 1990)

Region	Tonnes 1986*	Tonnes 1986 Revised	Tonnes 1990
North America	2,500-3,000	700	1,500
Western Europe	1,000	400	700
Japan	100	300	400
USSR/Eastern Europe	3,000	0	0
Rest of World	NA	NA	100
Total World	6,600-7,100	1,400	2,700

NA: Not Available.

* As reported in 1989 Foams Technical Options Report

Technical Options to Reduce CFCs in Phenolic Foams

The phenolic foam industry worldwide has been extremely active in seeking alternative blowing agents for its products, spending in excess of five million US dollars (estimated

to be 5 percent of annual turnover) on the issue to date. The industry has undoubtedly benefitted from having technology development teams already in place as a consequence of the relatively recent emergence of the "base" technologies.

Immediate

Hydrocarbons (open-celled foam)

Achieving high thermal efficiencies is important to the growth of phenolic foam use worldwide. The previous 30 years of relative inactivity bear testimony to the fact that the poorer thermal efficiencies of open-celled foams are not tolerable in most markets. This is likely to be an increasing trend in the future as concern switches more and more towards energy conservation.

Despite this general statement, some phenolic foam manufacturers have been able to sustain and further develop markets for open-celled hydrocarbon blown foams in the short term. The typical blowing agent used is pentane.

In their open-celled state, most products are approximately 60 percent less efficient than their CFC-containing counter-parts. Therefore, they can only be viewed as "fixes" for certain sectors of the market, even though in some cases penetration has reached upwards to 5 percent.

Short/Intermediate Term

HCFCs

Most manufacturers of closed-cell phenolic foam have expressed interest in and carried out development work with partially halogenated materials. Several technologies have emerged with at least one in each of the major production process categories achieving a 100 percent substitution level. Accordingly, the total phaseout of CFCs from phenolic foams is now technically achievable. However, the commercial introduction of such technologies remains dependent on the availability and cost-effectiveness of the appropriate materials.

There is a wide choice of HCFC/HFC blowing agent options for the continuous lamination processes, since these production practices tolerate wide-ranging boiling points. One British company has been able to produce a range of products based solely on a blend of HCFC-22 and HCFC-142b, while one North American manufacturer has been able to use HCFC-142b to replace part of the CFC blowing agent blend.

In view of the additional constraints placed on the process, the production of laminates with these low boiling substitute blowing agents requires substantially greater control and optimisation to be as cost-effective as the use of blowing

agents with boiling points of ambient or above. Current experience suggests that the accommodation of low boiling blowing agents can increase the overall production costs dramatically in some cases.

Whilst the continuously laminated products would benefit greatly from the availability of ambient boiling HCFCs such as HCFC-123 or HCFC-141b, as has already been shown in commercial trials, the discontinuous processes are totally reliant on such materials because they are unable to handle the lower boiling blowing agents.

Since the supply of HCFC-123 and HCFC-141b remains uncertain, significant block foam product commercialisation has not been possible yet, although one product range has recently been launched in the UK. The supply shortage is likely to persist until the end of 1991 or possibly later. The timing depends on the findings of the PAFT and AFEAS programs and the resulting investment climate.

At this time, the biggest single factor affecting the investment climate is the position of the Montreal Protocol signatories towards HCFCs. A quick resolution of HCFC acceptability will prevent delays in CFC conversion for the discontinuous process sector. Since this issue will not be resolved until June 1992, there will be an inevitable delay in the reduction of CFC usage in the discontinuous process sector.

Hydrocarbons (closed-cell foams)

More recently, attempts to manufacture closed-cell pentane blown foams with intermediate thermal efficiencies (12 to 25 percent less efficient than CFC based products) have shown promise. Several groups are pursuing this route; the most notable being a joint British and French initiative.

However, questions concerning the fire performance of these foams need to be addressed (particularly in bulk storage situations) before such materials can be commercialised.

The potential use of chlorinated hydrocarbons also has been considered by worldwide manufacturers. Efforts to date have included the large expenditure in time and resources associated with full scale evaluations. As with other hydrocarbons and some HCFCs and HFCs, the use of these materials would require significant capital expenditure to process such flammable blowing agents. It is not yet determined whether this approach will yield a long term, cost effective solution for phenolic foams.

This conclusion is supported by the work of a major European polyurethane manufacturer that studied the use of 2-chloropropane (LBL-2) as a thermally efficient blowing agent. Since the company also has a significant phenolic foam

interest in the continuous lamination sector, it conducted parallel evaluations of this product.

In a similar vein, the possible use of dichloroethane as a blowing agent reportedly is being evaluated by a Japanese company. As of November, 1991, detailed progress reports on this evaluation did not exist.

Long Term

HFCs

Within the range of HFCs currently identified as potential blowing agents, none exhibit ambient boiling points. Accordingly, HFCs are unlikely to fulfil the total phenolic foam industry's requirements in the foreseeable future. Despite this, HFCs are attracting interest in many continuous laminate processes where this specific research work is in its early stages.

Recovery/Recycle

Closed-cell phenolic foams undergo similar emission processes to other closed-cell, CFC-blown rigid foam boardstock: small amounts of CFCs are emitted during the production process, while the remaining CFCs, stored in the foam cells, are released very slowly over the life of the foam, due to extremely low gas permeability.

Consequently, emissions during manufacture could be collected by carbon adsorption techniques, in theory. But the actual process efficiencies would be extremely low.

In contrast, the significant cutting losses associated with the block process (refer to Production Processes) offer an ideal opportunity for recovery and recycling. In fact, one British industrial insulation manufacturer has recently installed a plant to crush and recover the CFCs from block process scrap by use of carbon adsorption technology.

Whilst at present this process is only 40 to 50 percent efficient, it is proving to be cost effective. Efforts are continuing to improve process performance and achieve a target efficiency rating of 80 percent. More importantly, it appears likely that this same technology will be useable for HCFCs as and when they are introduced into this sector.

In addition, there has been a parallel drive to improve cutting yields still further and recently developed programmes have been helpful in achieving this. However, the limits of efficiency seem now to have been virtually reached.

With continuous lamination processes, there is little opportunity to operate similar recovery activities due to low trimming losses. However, at least one North American producer has been able to use CFC-113 recovered from other non-related processes.

Product Substitutes

Phenolic foams are noted for their excellent thermal efficiencies and outstanding fire performance. Together with their cleanliness (no fibres), moisture resistance, space-saving, and integrity, these factors must all be reviewed when considering product substitution.

This wide range of product benefits also makes it difficult to generalise about possible product alternatives. If any substitutes exist at all, they are likely to be very market specific. Little actual substitution has taken place to date.

Conclusions

From a technical viewpoint, the phenolic foam industry has made substantial progress towards the phaseout of CFCs. In this regard, the industry has undoubtedly benefited from having technology development teams already in place as a consequence of the relatively recent emergence of the "base" technologies.

The only alternative blowing agent solutions applicable to both major processes remain HCFC-123 and HCFC-141b, as stated in the previous Technical Options Report.

Closed-cell hydrocarbon blown foam could also become more prominent, but certain concerns must be addressed regarding flammability of the finished products and the plant modification necessary for explosion resistance. Cost of modification could be high.

Some use of HCFC-22, HCFC-142b, and HFC-134a may also occur in continuous processes, but this will be primarily in incremental activities.

With the current state of technology, it is clear that the commercial future of HCFC-123 and HCFC-141b will be critical to the success of a full replacement programme by 1995. So far, the unit decrease in CFC usage has only been of the order of 20 percent. The majority of this reduction has come from limited use of hydrocarbons in non-critical areas and from in-process CFC recovery. (The use of CFCs recovered from other non-related processes is an additional contributor but is not included here because its impact is on the overall CFC "bank" rather than on the consumption figures of the industry per se).

This relatively small reduction in CFC use so far is particularly frustrating in view of the availability of potential solutions. Whilst the use of the low boiling HCFCs will help reduce CFC consumption further in the next 12 to 18 months, the added cost of such HCFC-blown end products will certainly limit market acceptance. The introduction of high boiling HCFCs should minimise this effect in due course.

In the longer term, the completion of the move to non-ozone depleting substances is likely to be as much dependent on developments within the process machinery field as on new "systems" technology. At that point, capital investment also may become a

significant factor, particularly where "base" investments have been made in the relatively recent past.

Chapter Five

EXTRUDED POLYSTYRENE

Extruded polystyrene foam is produced by melting polystyrene resin in an extruder and injecting a blowing agent into the resin under high pressure. Dispersed into the molten polystyrene, the blowing agent volatilises as the mixture leaves the extruder, causing the plastic to foam.

There are two distinct forms of extruded polystyrene:

- foam sheet (six mm or less in thickness and with a density of 20 to 40 kg/m³), which is typically used in disposable food service packaging and packing products; and
- foam boardstock (greater than six mm in thickness and with a density of 20 to 70 kg/m³), which is typically used as an insulation product.

EXTRUDED POLYSTYRENE SHEET

Products and Applications

Extruded polystyrene foam sheet is a thermoformable material used primarily to manufacture food service and food packaging products, such as hinged carry-out containers, single-service plates, cups, egg cartons and food trays. Other applications include dunnage, laminated sheets, and wrap-around labels.

Food Service and Packaging

Food service applications for extruded polystyrene foam sheet include the manufacture of cups, plates, bowls, and hinged-lid containers, while food packaging applications include the production of meat trays, egg cartons, and produce trays. In 1986, food service and packaging applications consumed about 83 percent of the CFCs used for rigid polystyrene foam packaging.

CFCs are attractive blowing agents for some foam food service products because they contributed to the products' ability to insulate food and beverages at the proper temperature and to provide appropriate moisture resistance. In food packaging, CFCs

also contribute to the products' moisture resistance; therefore, the end products eliminate the need for frequent in-store rew wrapping.

Dunnage

Dunnage is loose fill packaging materials such as foam "peanuts," pellets, and chips. This foam is used to protect products during transit and, thus, reduce the amount of breakage. Foam dunnage is reusable, sanitary, lightweight, and moisture resistant.

Laminated Foam Sheets

Laminated foam sheets are used as art board and in insulated packages. Providing aesthetic versatility when used as art board, laminated foam sheet is rigid yet lightweight, and readily accepts printing inks. In insulated packaging applications, laminated foam sheets are lightweight, rigid, and moisture resistant, in addition to providing thermal insulation.

Production Process

Extruded polystyrene foam sheet is produced by a process that mixes polystyrene resin with additives and melts the mixture to a low viscosity in a two-stage screw extruder. During the process, blowing agents are injected into the extruder under high pressure and dispersed into the polymer melt.

Then, this mixture is cooled and forced through a die under controlled pressure. As the molten polymer exits the die, the dissolved blowing agent vaporises and expands. This reaction causes the plastic to foam. An annular die is used to form a tube, which is subsequently slit to make foam sheets.

Final production stages involve cooling, shaping, cutting or winding the foam into the desired form. Extruded foam sheet is normally aged two to four days prior to thermoforming into the final product. Approximately 80 percent of the extruded polystyrene foam produced consists of foam sheet that is thermoformed into a variety of products.

The thermoforming step typically generates a substantial amount of foam scrap. In some cases, 30 to 40 percent of the extruder feed becomes scrap. Manufacturing processes commonly include grinding and repelletising steps after final cutting and thermoforming.

The pelletised foam scrap recovered from thermoforming is recycled back to the extruder feed. The typical extruder feed mixture is 65 percent virgin polystyrene and 35 percent recycled polystyrene.

Global Consumption of CFCs in Extruded Polystyrene Sheet

The 1986 global consumption of CFC-11 and CFC-12 in rigid extruded polystyrene foam manufacture for packaging was estimated at 20,000 tonnes. Since 1986, consumption has substantially declined as manufacturers have switched to alternative blowing agents.

By 1991, global consumption of fully-halogenated CFCs has been or is being phased out by foam packaging manufacturers in Australia, Asia, Canada, Europe, Hong Kong, Japan, the Far East, and South America.

The CFC most frequently used in food service and packaging in 1986 was CFC-12. In 1988, food service product manufacturers eliminated fully-halogenated CFCs from their manufacturing processes in Australia, Asia, Canada, Europe, Hong Kong, Japan, and South America.

In the United States, extruded polystyrene meat trays are no longer made with CFCs. In addition, approximately 99 percent of extruded polystyrene foam egg cartons are now made without CFCs. US manufacturers are meeting on a regular basis to overcome technical problems so that CFCs can be eliminated from the manufacture of all of these products as soon as possible. This effort has been put forward on a global basis to complete a phaseout of fully-halogenated CFCs in food packaging as soon as possible.

In the past, dunnage was manufactured using one of the following blowing agents: CFC-11; CFC-11 blended with CFC-12 and/or hydrocarbons (primarily pentane); or pentane alone. In Europe, almost all loose fill is now made with hydrocarbons; in the United States, manufacturers are in the process of eliminating the use of CFCs by converting to hydrocarbon blowing agents, particularly pentane.

In 1986, dunnage consumed about 12 percent of the CFCs used in rigid extruded polystyrene sheet packaging applications in the US. Today the consumption figure is much smaller for the US and the rest of the world.

Laminated foam sheet consumed about four percent of the CFCs used for rigid foam packaging in 1986. CFC-12 and blends of CFC-11 and CFC-12 were typically used in these products.

US manufacturers of laminated sheet products have converted to HCFC-22, HCFC-141b or hydrocarbons. Laminated polystyrene sheet is not made in significant quantities in Europe.

Since 1986, global consumption of CFCs in all extruded polystyrene sheet applications has been rapidly declining. A virtual phaseout has been achieved in developed countries, however, it is believed that small amounts of CFCs may still be used in some developing countries.

Technical Options to Reduce CFCs in Extruded Polystyrene Sheet

To be an effective blowing agent for extruded polystyrene sheet used for packaging, compounds must satisfy certain technical criteria:

- solubility -- there must be adequate solubility in the molten resin and low solubility in the extruded foam products;
- safety -- substitutes must be low in toxicity and their flammability characteristics must also be considered;
- stability -- high thermal and chemical stability is required in the manufacturing process;
- diffusivity -- low diffusivity is necessary for post-expansion; and
- environmental acceptability.

The solubility of the blowing agent in the molten polymer is a critical property. If the blowing agent separates from the polymer matrix, gas pockets will form.

Stringent requirements for food packaging also pose challenges as manufacturers seek new blowing agents. In many countries, the use of any compound used to manufacture a product for food applications requires regulatory clearance.

Immediate

Carbon Dioxide

While atmospheric gases such as CO₂, nitrogen, and water vapour have not demonstrated adequate solubility for existing commercial processes, a new process technology has been developed that allows 100 percent CO₂ to be used in polystyrene foam sheet production. With this new technology, CO₂ has become an immediately available, cost-effective option.

Still, many believe that CO₂ must be blended with another physical blowing agent, such as HFC-152a or a hydrocarbon, since CO₂ used alone may limit extrudability or product densities.

Hydrocarbons

Hydrocarbons are also an immediately available option. N-pentane, butane, isopentane and isobutane are readily available petroleum products. Several manufacturers are already using hydrocarbons alone or in combination with carbon dioxide or HCFC-22.

On a cost per pound basis, pentane and butane are the cheapest available blowing agents for foam sheet food service and packaging applications. They offer excellent solubility properties, better plasticizing properties, and the required diffusivity.

Polystyrene foam packaging products made with hydrocarbons offer a similar high quality as those made with CFCs. Many companies in Europe and the Far East currently use hydrocarbons or are converting from CFCs to hydrocarbons. The primary concerns associated with the use of hydrocarbons are VOC emissions and flammability.

Regarding emissions, hydrocarbons are photochemically reactive volatile organic compounds (VOCs) that contribute to ground level ozone pollution. Emissions may be reduced through the use of recovery and reuse technology, incinerators, or catalytic converters. In addition, manufacturers using hydrocarbons must obtain permits for their facilities and meet allowable local emission limits. In some countries, such as the United States, obtaining permits for facilities can be difficult or even impossible in high pollution areas.

In areas where hydrocarbon emissions are restricted, additional investments could be as high as US\$1 million to install equipment to comply with air pollution regulations. Either destruction of the blowing agents via incineration or recovery of the blowing agents via carbon adsorption is required.

Conversions to strictly hydrocarbons requires substantial capital investments to ensure worker safety and to comply with environmental regulations concerning hydrocarbon emissions. One-time capital conversion costs are estimated at US\$1 million per plant for modifying equipment to meet safety standards. Modifications required to ensure worker include anti-static guards, spark arresters, and ventilation equipment to diffuse heavy hydrocarbon vapours as well as employee retraining. Actual conversion costs will vary, however, depending upon plant size, plant locations and emission control requirements.

Operating costs for using hydrocarbons, however, are lower than those for CFCs. In fact, it is estimated that manufacturers can expect a payback in 12 to 18 months on the capital investment necessary to meet flammability and emissions criteria.

HCFC-22

In most applications, the quality of extruded polystyrene sheet products made with HCFC-22 is comparable to that of products made with CFC-12. Non-flammable, low in toxicity, HCFC-22 provides high chemical and thermal stability.

Substitution of HCFC-22 for CFC-12 in food packaging has been successfully demonstrated in North America. Egg carton manufacturers have reported minor technical hurdles which have been overcome. However in dunnage, HCFC-22 is too volatile to be used alone. It is more effective when blended with less volatile compounds, such as hydrocarbons, HCFC-123 or HCFC-141b.

Capital investment required for new equipment to handle HCFC-22 is under US\$50,000 per plant, and operating costs for HCFC-22 are similar to those for CFC-12.

According to the UNEP figures, HCFC-22 has an ozone depletion potential 95 percent less than CFC-12. In addition, smaller quantities of HCFC-22 are needed to manufacture polystyrene sheet in comparison to the amount of CFC-12 required. Consequently, these characteristics combine to make HCFC-22 a very appealing blowing agent that can help reduce further ozone depletion. Other atmospheric gases, such as carbon dioxide and nitrogen, also may be blended in small quantities with HCFC-22 to further reduce the amount of HCFC-22 used in polystyrene sheet production.

Because of the ozone depletion concerns associated with HCFC-22, it is considered by the industry to be a transitional substance only. In 1991, many of the manufacturers who initially switched to HCFC-22 are now switching away from this blowing agent.

Manufacturers are considering other non-ozone depleting, immediately available alternatives such as CO₂ and hydrocarbons. For example in the US, most manufacturers of extruded polystyrene food service and packaging products expect that they will not be using HCFC-22 after 1992.

Intermediate and Long Term

HFC-134a and HFC-152a

HFC-134a and HFC-152a are under serious consideration as intermediate and long term alternatives to CFCs in extruded polystyrene applications.

Easy to use and nonflammable, HFC-134a has no ozone depletion potential (ODP). Commercial scale production of HFC-134a is scheduled to begin in 1993, assuming favourable results in toxicity testing and process development.

Presently estimated to be more costly than HCFC-22, the future cost of HFC-134a can be expected to decline due to its planned worldwide use in automobile air conditioners. However, even at a reduced cost, HFC-134a may prove to be too expensive.

HFC-152a is commercially available and is presently used in aerosol applications. HFC-152a has already successfully completed regulatory inhalation studies, and is awaiting regulatory clearance for food packaging uses.

HFC-152a has no ODP. Its low molecular weight of 66 versus 121 for CFC-12 suggests that its blowing efficiency will be double that of CFC-12 (i.e., half as much will be required to foam a given amount of resin). This could translate into production cost savings.

Notwithstanding the anticipated higher cost per pound and the capital investment required to handle a flammable blowing agent, HFC-152a appears to be emerging as the most likely long-term alternative blowing agent for extruded polystyrene sheet. Plant trials in North America have successfully demonstrated its use in numerous polystyrene sheet applications.

The future use of HFCs appears to be dependent upon their acceptance in the environmental community, their cost-effectiveness, and the future status of hydrocarbons in light of environmental air quality regulations.

Other long-term alternatives include resin developments that may allow the use of atmospheric gases. These resins may be available by the mid-1990s.

Conclusions

Since 1986, manufacturers of rigid extruded polystyrene foam packaging products have moved rapidly to voluntarily adopt alternatives to fully-halogenated CFCs. The alternatives originally included HCFC-22, hydrocarbons, blends of these chemicals, and blends with carbon dioxide.

Substitution of CFC-11 and CFC-12 in food service and packaging and laminated sheets should be completed by using hydrocarbons, CO₂ and HCFC-22.

Today, manufacturers are working hard to eliminate the use of HCFC-22 where possible by substituting hydrocarbons, 100 percent CO₂, HFC-152a or blends. Complete phaseout of HCFC-22 by the food service and packaging industry by the end of 1992 may be premature for two reasons: the industry, at least in the United States, may not have regulatory approval for specific blowing agent/food applications before this date, and hydrocarbon permitting may not be an option for some manufacturers.

Most producers of dunnage outside the US use hydrocarbons as a blowing agent. US producers are now moving down the same path.

EXTRUDED POLYSTYRENE INSULATION BOARD

Products and Applications

Extruded polystyrene foam boardstock was invented in Sweden but was further developed in the United States in the early 1940s. It is a rigid foam with a fine closed-cell structure. The original blowing agent was methyl chloride, not CFCs. Extruded polystyrene foam insulation made with CFC-12 was introduced to the market in the early 1960s.

Globally, approximately 90 percent of extruded polystyrene rigid foam boards are used primarily for thermal insulation purposes. The cellular products consist almost entirely of polymer and blowing agent. The type of blowing agent used determines the character of the cellular structure formed during the manufacturing process. There are two main types of foam boards available:

- boards with a smooth skin covering the two principal heat transfer surfaces - the main application of the self-skinned material includes insulation for roofs, floors, and walls in dwellings and agricultural buildings. In some northern countries, another major application is the protection of roads and railways against frost-heave by laying the insulation boards in the earth below the road pavement and rail permanent way.
- boards with a planed or cut cell surface that provides grip for plaster, adhesive, and pour-in-concrete - the main application for this product includes wall insulation of concrete buildings, tile and plaster backing, core material for sandwich panel construction, and low temperature space. There are a number of small specialty applications in most geographical markets as well.

High moisture resistance combined with mechanical strength makes extruded polystyrene insulation both an economical and practical material for below-ground building applications, such as basements, foundations and earth-sheltered homes, and inverted roof applications, where the waterproofing membrane is below the insulation material.

Other properties of extruded polystyrene foam include:

- low thermal conductivity;
- resistance to freeze-thaw deterioration;

- excellent compressive strength and dimensional stability (low shrinkage); and
- good handling properties, including low toxicity and low blowing agent diffusion loss with time.

Production Process

The manufacturing of extruded polystyrene foam board for insulation purposes involves an extrusion process similar to that described for sheet. Polystyrene resin is mixed with additives, then continuously fed into an extruder where it is melted. Blowing agent, continuously injected under high pressure, is dispersed in the resin to form a foamable gel. The gel is then cooled and extruded through a square cross section die where the blowing agent volatises, causing the plastic to assume a foam structure.

After the foam has been formed, it is transported away by a continuous conveyer belt and cut into appropriate lengths and widths. This cutting section can also include equipment to remove the skin (i.e., make planed boards). Internally generated scrap is recycled within the plant. In order to be recycled the scrap has to be reground with consequential release of cell gases.

In closed-cell insulation foams, such as extruded polystyrene, the blowing agent performs two functions:

- (1) it reduces the foam density, and
- (2) it contributes insulation value to the foam.

The blowing agent which stays in the foam to provide insulation value, the primary blowing agent, is sometimes called the insulating gas. A second, or auxiliary, blowing agent is sometimes used for foaming; another proprietary technology uses vacuum foaming. In all processes the primary blowing agent must be present to provide characteristic high level insulation performance.

Extruded polystyrene foam insulation board production units operate in North America, Brazil, Japan, South Korea, Egypt, Israel, Saudi Arabia, Kuwait and all countries in Western Europe except Luxembourg, Ireland, Portugal, Denmark and Switzerland.

In 1991, a plant commenced production in Hungary using HCFC-142b as the blowing agent/insulating gas. The Brazilian unit will have converted to HCFC-142b by the end of 1991.

It is believed that no production currently exists in other countries of Eastern Europe, the Soviet Union, Central and South America and Central and South Asia. The unit in Australia operating in 1986 ceased production in 1988.

Blowing Agent Requirements

A blowing agent is usually a volatile, chemically stable compound, and by its introduction into the molten polymer, it reduces the density of the product by the formation of a myriad of closed cells within its structure.

Until the late 1980s, CFC-12 was the traditionally preferred blowing agent for extruded polystyrene insulation boards because of its attractive properties:

- low toxicity;
- non-flammability;
- high solubility in polystyrene;
- compatible boiling point (-30°C) and vapour pressure for extrusion process;
- very low diffusivity through polystyrene;
- low thermal conductivity;
- chemical inertness; and
- thermal stability at process conditions.

At the time of writing of the first UNEP Foams Technical Options report (June 1989), the worldwide extruded polystyrene boardstock industry established that by the end of 1993 CFC-12 use could, from a purely technical viewpoint, cease completely.

There were two substitute materials identified to successfully replace CFC-12, given sufficient time for thorough product research and development efforts for various applications and manufacturing processes. These replacement candidates were HCFC-142b and HCFC-22.

The availability of HCFC-22 did not present any problems, but that of HCFC-142b, the key insulating gas and blowing agent, did. Only now, in late-1991, is the supply situation for HCFC-142b easing, although it is still critical in some areas. HCFC-22, however, has a relatively high permeation rate out of polystyrene and does not provide the long-term insulation value required.

Conversion to HCFC-142b, either alone or in combination with other auxiliary blowing agents including HCFC-22, means not only considerable investment in manufacturing ancillary equipment, product reformulation, and performance evaluation, but also in cost.

In the United States, HCFC-142b is around 15 percent more expensive than CFC-12 (including the tax of US\$0.55/kg). In Japan the price of HCFC-142b is double that of CFC-12, and in Western Europe it is over three times the price of CFC-12 (November 1991 data).

For example, an extruded polystyrene producer operating in a European country which has not introduced local use regulations is at a clear competitive advantage by using CFC-12 as its blowing agent/insulating gas compared to another manufacturer who has converted to HCFC-142b, since blowing agents are a significant part of the total cost of the product.

There is no premium price to be obtained for more environmentally benign products.

Approximately 75 to 85 percent of the HCFC-142b (or CFC-12) used in the manufacture of extruded polystyrene insulation is retained in the foam after production. HCFC-142b (or CFC-12) is the blowing agent/insulating gas providing the product with its low overall thermal conductivity.

As the insulating gas, it performs two main functions:

- it promotes the physical processes necessary to make the foam; and
- it provides thermal properties that improve the insulation performance (especially long-term) in the boards.

The blowing agent function is quite often supplemented by auxiliary blowing agents such as methyl chloride, ethyl chloride and hydrocarbons (butane and pentane). These compounds, having relatively high permeability, do not provide long term insulation value and are used solely as blowing agents in order to achieve low product densities.

Global Consumption of CFCs in Extruded Polystyrene Insulation Board

Approximately 17,600 tonnes of CFC-12 were used worldwide in 1986 in the manufacture of extruded polystyrene foam insulation board. At that time, extruded polystyrene insulation boards consumed approximately seven percent of all CFCs used in foam applications.

In spite of market size increases ranging from 30 percent to over 80 percent in the three main producing areas of North America, Japan and Western Europe, CFC-12 consumption had decreased to 12,000 tonnes by 1990.

Thus CFC-12 consumption by the world's extruded polystyrene insulation industry has decreased by 32 percent from 1986 to 1990. Estimates suggest that this figure will be well over 70 percent by the end of 1991.

This consumption data is a combination of accurate input received on a confidential basis from all producers in North America, Japan and all but two of the producers in the European Community, and industry estimates for other producers.

Technical Options to Reduce CFCs in Extruded Polystyrene Insulation Board

Immediate/Short Term

Since quality and performance of extruded polystyrene foam insulation -- the two main reasons for its increased marketplace acceptance -- were based on products developed and optimised using CFC-12, alternative blowing agents need to provide equivalent performance to CFC-12 blown foams.

Extruded polystyrene insulation boards are noted for their thermal insulation, moisture resistance, strength, dimensional stability, and fire performance characteristics. Boards made using the blowing agent options available in the shorter term do not perform quite as well in every respect as CFC-12 blown foams.

The foam insulation manufacturer must make critical blowing agent and process modification choices to provide the best products for particular market applications. Different producers in the same or different markets may make different choices. In fact, not all alternatives may be usable in each process of a particular manufacturer.

In the June 1989 Technical Options Report, HCFC-22, HCFC-142b and hydrocarbons were cited as the promising short-term available substitutes and a list of the likely combination of these options was made. A comparison of the principal properties of these alternatives is shown in Table V-1.

In fact, all of the conversions so far executed have been based on HCFC-142b as the insulating gas with HCFC-22 as an auxiliary blowing agent in some processes.

It must also be mentioned that in places where HCFC-142b was not available or where the product development and plant conversion process was not yet complete, CFC-12 could be "diluted" with HCFC-22. This is very possible in those plants where CFC-12 had previously been the sole blowing agent. Thus a marked decrease in the ODP of the product was able to be achieved as an intermediate measure.

Table V-2 shows a cost comparison in the three major producing areas for 1991. The differentials between CFC-12 have narrowed in some areas whilst hardly changing in others from the 1989 estimates.

A short term option conversion experience is described in the addendum to Chapter V.

**Table V-1. Alternative Blowing Agents for Extruded Polystyrene Insulation Foam,
Available in Short-Term (Comparison to CFC-12)**

Property	CFC-12	HCFC-22	HCFC-142b	Hydrocarbons
Boiling Point, °C	-30	-41	-9	C ₄ -10 C ₅ +30
Thermal Conductivity (relative to CFC-12)	1.00	1.09	1.15	C ₄ 1.75 C ₅ 1.29
Permeability through Polystyrene (relative to CFC-12)	low 1	high 100	low 1	high 20
Flammable	no	no	yes	yes
Ozone Depletion Potential (relative to CFC-12)	1.00	0.05	0.06	0
Global Warming Potential (relative to CFC-12)	1.00	0.16	0.17	*

* negligible (short atmospheric life-time)

**Table V-2. Relative Price Comparison of Blowing Agents, 1991
(figures for 1989 in parentheses)**

Area	CFC-12	HCFC-22	HCFC-142b
United States	1	0.75 (2)	1.15 (3)
Japan	1	1.4 (2)	2.0 (4)
Western Europe	1	1.6 (2)	3.0 (4)

Note: Vertical comparisons are not valid.

Intermediate and Long Term

In the 1989 Flexible and Rigid Foams Technical Options Report, HFC-134a and HCFC-124 were named as two further alternative blowing agents, although they were only available in very limited quantities at that time. HFC-152a is a third blowing agent alternative now being considered. The status of each is:

HFC-134a

HFC-134a is part of PAFT I (Programme for Alternative Fluorocarbon Toxicity Testing) carried out by a consortium of producers. The results obtained so far are encouraging. The chronic two-year study is scheduled for completion by late 1991, with the final results available in the spring of 1992. Commercial production capacity is installed, but awaiting the final toxicity study results.

HFC-134a offers the following properties:

- thermal conductivity that is approximately 40 percent higher than CFC-12;
- a boiling point of -26°C;
- low permeability through polystyrene; it is believed to be similar to CFC-12;
- non-flammability; and
- a zero ozone depletion potential.

Although HFC-134a shows distinct advantages from the environmental viewpoint (zero ODP) and from the safety and handling viewpoint (non-flammable), its relatively high thermal conductivity does not make it an attractive option on paper as an insulant gas/blowing agent for extruded polystyrene foam insulations.

Another major drawback already identified is the poor solubility of HFC-134a in organic materials including polystyrene polymer.

Combined with its price, the above two factors virtually rule out any widespread use of HFC-134a in extruded polystyrene foam .

HCFC-124

HCFC-124 is part of PAFT III. The toxicity testing so far is, in the limited scope reported, encouraging. Conclusive results are not expected before 1993. HCFC-124 offers the following properties:

- thermal conductivity that is approximately 12 percent higher than CFC-12;
- a boiling point of -11°C;
- low permeability through polystyrene;
- non-flammability; and
- an ozone depletion potential of 0.02 (i.e., 1/50 of CFC-12).

On the basis of above characteristics, HCFC-124 would appear to be an attractive option. Only limited amounts of HCFC-124 have been available for basic technical appraisal. The first announcement of commitment to commercial production of HCFC-124 has just been made in the United States with a project start-up in 1993.

Given the time frame involved it is highly unlikely that extruded polystyrene manufacturers would be able to afford the economic price required by potential HCFC-124 producers were the global extruded polystyrene industry the sole market for the compound.

HFC-152a

HFC-152a is an existing compound whose toxicological properties are known. Supplementary studies are not excluded, however. Production processes exist on a commercial scale in North America.

HFC-152a has the following properties:

- thermal conductivity that is over 30 percent higher than that of CFC-12;
- a boiling point of -25°C;
- high permeability through polystyrene, similar to HCFC-22;
- a flammability range in air that is 3.7 to 18 percent whilst the minimum ignition energy has been reported to be almost identical to that of hydrocarbons. (The value for HCFC-142b is two orders of magnitude higher); and
- a zero ozone depletion potential, whilst global warming potential is only one percent of that of CFC-12.

Whilst the environmental properties are excellent, the technical (high thermal conductivity and high polystyrene permeability) and process (low polystyrene solubility) properties combined with the flammability risks do not make HFC-152a an attractive candidate for extruded polystyrene insulation board.

Hydrocarbons

Hydrocarbons, primarily butanes and pentanes, can be used to foam polystyrene. They have been used for many years in the manufacture of extruded sheet polystyrene foam packaging products in Europe, North America and Japan. Hydrocarbons are readily available and are relatively inexpensive compared with other blowing agent alternatives. When applied to the manufacture of extruded polystyrene insulation boards, hydrocarbons exhibit the following disadvantages:

- Hydrocarbons are flammable -- their safe handling and processing require that appropriate safety measures and significant capital investment be taken in the manufacturing plants, as well as in the distribution chain. The flammability limits in air are 1.8 to 8.4 percent for butanes and 1.4 to 7.8 percent for pentanes.
- Hydrocarbon use can be subject to local air pollution regulations -- these regulations limit the emissions of volatile organic compounds, which contribute to smog formation.
- Hydrocarbon blown extruded polystyrene insulation boards may not meet insulation standards in certain regions around the world -- in the US and in some European countries, extruded polystyrene insulation boards manufactured only with hydrocarbons would not meet insulation standards. In addition, the large thicknesses (>80 mm and up to 120 mm) used in some regions and applications cannot be made with hydrocarbons using today's state of the art technology.

Recovery/Recycle

At present, there are no recovery processes known to be in use in extruded polystyrene boardstock facilities. There are several reasons why this option has not been considered technically and economically feasible in the past.

An estimated 80 to 85 percent of the HCFC/CFC-blowing agents are trapped within the cells of the finished product. Thus, only 15 to 20 percent of the blowing agents consumed are available for capture. However, as the industry converts to the more expensive HCFCs, capture and recovery of these compounds during production will become more economically attractive, and will support the development of recovery technology.

Currently, it appears that carbon adsorption offers the best possible capture technology. Several technical problems will need to be overcome first to successfully recover HCFCs (or CFCs). These problems include:

- Collection -- blowing agent emissions occur at several points in the process. A large portion of the plant air must be collected in order to capture most of the HCFCs (or CFCs).
- Capture -- plant air streams are quite dilute, making efficient adsorption on carbon more difficult. The use of auxiliary blowing agents can interfere with the efficient capture of the HCFCs (or CFCs). Contaminants in the plant air stream can interfere with the adsorption capacity and lifetime of the carbon bed.
- Recovery -- HCFCs (or CFCs) used in the manufacture of extruded polystyrene foam boardstock have low boiling points and thus complicate the separation from water (ice formation) and other contaminants in the air stream.

Product Substitutes

Foam insulation provides high energy efficiency combined with other physical properties. These include excellent fire-test performance, waterproof characteristics, low density, thin profile, and ease of handling. Other insulating products, such as expandable polystyrene bead board, cellular glass board, perlite board, fibreboard and gypsum board, can provide some of these properties, but not all. Consequently, these substitute products may not be considered alternatives for all applications of extruded polystyrene insulation foam.

When a substitution is made, the alternative material will often have a higher thermal conductivity per unit thickness, and hence will not insulate as efficiently as the foam insulation of equal thickness blown with HCFC-142b (or CFC-12). It is necessary to increase the thickness of the alternatives to compensate for lower insulating values.

The main difficulties in using alternative insulating products are in applications where the waterproof characteristic of foam insulants is a major advantage. In these uses, which are typically applications of extruded polystyrene insulation foam, there is no obvious alternative without considerable changes in design and construction practice (Curwell, 1988).

Phaseout Schedule

Based on the available alternative blowing agents, the extruded polystyrene foam board industry estimates that a complete phaseout of CFCs worldwide is technically possible by the end of 1993.

This goal will certainly be realised in the following regions:

- the United States, where a punitive tax on CFC-12 for insulation foams will be increased to US\$5.83/kg in 1994;
- Canada, where a regulatory ban is effective 1994;
- Scandinavia, where bans already are in force;
- the European Community, where a voluntary agreement between the European Commission and Exiba (the trade association representing over 95 percent of installed capacity within the Community) calls for a phaseout by the end of 1993; and
- Japan, where the extruded polystyrene industry has in 1991 announced a complete phaseout of CFC-12 in insulation boards.

Much will depend on the government's attitude and policy in the other producing countries some of which are party neither to the Vienna Convention nor the Montreal Protocol. As the worldwide availability of HCFCs increases and the supply of CFC-12 dramatically tightens for those countries which are not Parties to the Protocol nor have indigenous CFC production, there will remain little choice but to convert.

For those developing countries who are Parties to the Protocol continued CFC-12 use would still be possible. Consequently implementation of the "state-of-the-art" HCFC technology will depend on national official encouragement and support.

For worldwide conversion of the extruded polystyrene insulation foam industry to become a reality by the end of 1993, producers still using CFC-12 must start making plans for investment in equipment immediately to convert to the only practical alternative, namely HCFC-142b.

Conclusions

HCFC-142b (alone or in combination with HCFC-22) represents the most practical option to CFC-12 in extruded polystyrene board insulation. HCFC-142b, however, is not a technical "drop-in" for any of the manufacturing process currently installed.

Although unproven, recapture and recovery technology is being actively investigated to solve several technical problems. About 20 percent of the initial HCFC or CFC charge is released during manufacturing process.

The extruded polystyrene foam board insulation industry believes that a complete phaseout of CFC-12 can technically be accomplished by the end of 1993 only if the use

of HCFC-142b and HCFC-22 is accepted and even encouraged by government authorities.

Decisions to convert plants need to be made immediately if the necessary investment and work is to be completed by the end of 1993. Government support and encouragement would seem essential in non-Party and developing countries.

Conversion to HCFCs will maintain the long-term insulation performance of extruded polystyrene boardstock, but some other product properties may be negatively affected. Using HCFCs will achieve at least a 90 percent reduction in ozone depletion potential and at least an 85 percent reduction in greenhouse potential from this industry segment. Successful conversion to alternatives requires considerable technology, which means that smaller manufacturers will have greater resource difficulties.

ADDENDUM TO CHAPTER V: Short Term Option Conversion Experience

It is useful to record the experience of two major producers in a European country where a combination of media-induced public pressure and national government legislation for specific use regulations in 1986/1987 resulted in the development of an intensive research programme to identify suitable alternatives for CFC-12 by the companies involved. Table V-3 summarises the identified options.

Table V-3. Alternative Blowing Agents for Extruded Polystyrene Insulation Foam, Available in Short-Term (Comparison to CFC-12)

Property	CFC-12	HCFC-22	HCFC-142b	Hydrocarbons
Boiling Point, °C	-30	-41	-9	C ₄ -10 C ₅ +30
Thermal Conductivity (relative to CFC-12)	1.00	1.09	1.15	C ₄ 1.75 C ₅ 1.29
Permeability through Polystyrene (relative to CFC-12)	low 1	high 100	low 1	high 20
Flammable	no	no	yes	yes
Ozone Depletion Potential (relative to CFC-12)	1.00	0.05	0.06	0
Global Warming Potential (relative to CFC-12)	1.00	0.16	0.17	*

* negligible (short atmospheric life-time)

By late 1988, the results of the research programme clearly indicated that HCFC-142b was the candidate to be selected. Sufficient commercial quantities were unavailable at that time.

It must be understood that the mere selection of a new blowing agent only marks the beginning of the determination of the suitability for the large-scale production of the whole product range.

Variation in the initial feed level of blowing agent and in processing conditions can and do change the final physical properties of the foam. Up to one year can be spent in ensuring that the blowing agent selected can be satisfactorily adopted.

Elimination of CFC-12 meant a major change in a blowing agent system optimised over many years for each individual product. By mid-1988, task forces in the manufacturing functions were created to identify safety measures to be taken as result of the flammability of HCFC-142b in the following areas:

- storage tanks;
- supply and feed lines and pumps;
- the extruder;
- the foaming zone; and
- finished product storage.

A thorough check of all plant procedures, such as start-up and shut-down of the complete plant, raw material unloading and handling, was carried out to determine:

- measures for avoiding spills and leaks; and
- measures for avoiding combustible gas mixtures when the blowing agent and molten polymer leave the extruder die.

The results of this work were presented several weeks after the basic decision to convert to HCFC-142b had been taken.

On the basis of the evaluation results and taking into consideration that only two HCFC-142b suppliers (Solvay Fluor & Derivates and Atochem) were available in Europe, the necessary plant/equipment modifications were designed and the capital investment was estimated.

After the capital had been authorised, which can sometimes take a long period of time, the detailed tenders were obtained from the suppliers. The organisation and installation of the equipment, including the necessary changes to the computer programme controlling the production process, took around one and a half years.

The necessary capital for the conversion (installation, equipment) was around US\$500,000. The additional labour costs amounted to a similar figure. Thus, depending on location and size of plant, conversion of the manufacturing facility can entail costs ranging from US\$400,000 to US\$1 million (or up to 20 percent of the initial plant investment in some cases) and take up to two years to complete due to hardware delivery times.

During this time period, regular production was interrupted at least twice for one or two weeks to modify the R&D programme to full scale production. During these 24 hr/day scale-up trials, equipment and instrumentation were temporarily installed which were intended to simulate the final version yet to be delivered.

These plant trials not only served to gather experience on handling the new system for the plant personnel but also to produce extruded polystyrene foam of good, reproducible quality which was critical for application testing. Costs incurred in the plant trials alone were around US\$250,000.

Application testing, using full-scale production, was an important consideration in the decision to convert to HCFC-142b and needed to be fully evaluated. Although the results of pilot plant trials from the R&D programme had been promising, the companies had to be sure that the insulation boards produced in the actual large scale manufacturing plant would exhibit the expected performance in the various application areas.

The critical properties included:

- compressive strength of relatively fresh material;
- long-term compressive strength;
- tensile strength;
- moisture absorption [submersion tests, water vapour diffusion; freeze-thaw behaviour for upside-down roofs and perimeter (cellar wall) insulation];
- compliance with national insulation standards;
- long-term thermal conductivity (λ value); and
- fire performance (small scale test).

At first glance, achieving these properties may appear simple, but properly characterising the critical properties required a large number of tests both internally at the company and externally at recognised testing laboratories. This was necessary to ensure that quality and performance characteristics were maintained using a different blowing agent. Tests included:

- several hundred compression tests for sales and product specifications;
- long-term compressibility tests (three months minimum) for foundation and soil insulation (roads/railways); and,
- tensile testing for the proper design and calculation of sandwich panels.

The boards produced during the plant trials were used in full-scale testing in upside-down roofs (insulation above the waterproof membrane), sandwich panels exposed to extremes of temperature in cold stores, refrigerated trucks, hot-wire cutting in the fabrication of pipe shells, et cetera.

This testing effort, solely attributed to the conversion to HCFC-142b, resulted in labour and direct costs totalling US\$400,000.

This is merely one example of what can be involved in one country where publicly set standards, on whose fulfilment extruded polystyrene users had come to rely and expect, had to be maintained. This case history is however valid only for one particular manufacturing process. The steps outlined showed clearly that HCFC-142b is not a 'drop-in' replacement for CFC-12. Some products could not be properly made to give the desired performance.

Manufacturers using different production technologies have experienced similar difficulties in reformulating to preserve established performance.

The conversion process described above took from the inception of the R&D programme to continuous production using HCFC-142b almost 3 years.

The ozone depletion potential was thus reduced by over 90 percent in one major step.

The increased costs which are not honoured in a highly competitive insulation market can attain up to US\$12 per cubic metre. This is especially true in Europe where the cost differential between CFC-12 and HCFC-142b is greatest (November 1991 data).

Chapter Six

POLYOLEFIN FOAMS

Products and Applications

Manufactured in a variety of product forms, polyolefin foams include products made from either polyethylene or polypropylene resins. The major product forms are:

- Extruded -- this includes sheet (up to 6 mm in thickness), and plank (greater than 12 mm in thickness); and
- Moulded.

Sometimes, these general foam types include other olefinic constituents, such as ethylene/vinyl acetate or ethylene/acrylic acid resins, as modifiers.

Both polyethylene and polypropylene resins are extruded into sheet products. These sheet products are commonly used as protective packaging for furniture, electronic devices, and other goods. Other applications include flotation devices (such as life vests), construction materials, and gaskets. Historically, CFC-11, CFC-12, and CFC-114 have been used for most of these sheet products.

In addition, polyethylene resins are used to manufacture extruded plank products for designed cushion packaging of electronic or other high-value goods. Some plank products are also used in military packaging, flotation, construction, aircraft seating and other applications. Generally, CFC-12 and CFC-114 were used in the manufacture of plank products.

Polyethylene and, more recently, polypropylene resins also are used in expandable bead products. These foam products are used primarily as moulded cushion packaging and automotive bumper systems. The most common blowing agent used for these product applications has been CFC-11, CFC-12 or hydrocarbons.

In most polyolefin foam applications, products are used because of their specific properties. The most important attribute is polyolefin foam's ability to insulate products from mechanical, vibrational, thermal or other environmental stresses. Typically,

polyolefin packaging consists of foam inserts in a cardboard box; alternatively a package may be made entirely of polyolefin foam with only straps to secure the device.

Packaging of military hardware is one important application of polyolefin foam. When items such as missiles, explosives and sophisticated computer hardware are shipped through the distribution network, the product packaging is specifically designed to insulate the device from a broad range of possible conditions. These include the mechanical and vibrational stresses from rough handling and rugged transit conditions, moisture and humidity, sand and dirt, and temperatures varying from arctic to equatorial extremes.

An additional benefit of polyolefin materials is their reusability. In many applications, the package may be reused several times to package new goods, thereby conserving packaging materials.

Production Processes

The two primary manufacturing processes used to produce polyolefin foams are extrusion and moulding.

Extrusion Process

In extrusion processes, the resin is melted and then passed through a die, where the product rapidly expands and then cools. For sheet products, an annular die is used to form a hollow cylinder of foam which is slit to produce a flat sheet that can then be rolled for storage or shipment. Plank products are typically made using a specific die to produce the particular cross-section desired. Each cross-section requires a different die. Occasionally, the planks are made in circular or other non-rectangular cross-sections. The extruded plank is then cut to length and edges trimmed, if necessary.

The thickness of sheet products range from 1 to 12 millimetres; plank products can be manufactured in thicknesses from 12 to over 100 millimetres and in widths up to 1,200 millimetres.

A special manufacturing process, which involves the cross-linking of extruded sheet and its subsequent expansion with a decomposable blowing agent, such as azodicarbonamide, will not be discussed because it does not involve CFC use. The resulting foam is not generally considered as a substitute for most non-crosslinked polyolefin products.

Moulding Process

For moulded products, the blowing agents are absorbed into the unexpanded resin particles in a closed vessel under elevated temperatures and pressures. The resin particles are then either partially or fully pre-expanded. Product is shipped to a moulder who completes the pre-expansion, if necessary, and then places the fully expanded

particles into a mould. Steam is introduced, which heats the particles, causing them to expand, fill the mould and fuse together.

All three foam types are closed cell products. Thus, most of their blowing agents are initially trapped within the foam. Some emissions of blowing agents do occur. Examples include:

- with very thin sheet products, a significant portion of the blowing agent may be lost at or near the die; and,
- for extruded plank and thicker sheet products, some blowing agents are lost in trimming operations, which open the cells.

CFC emissions are not a concern in moulded products since the beads are expanded prior to shipment using either carbon dioxide or hydrocarbons in a closed system which captures the gas.

Global Consumption of CFCs in Polyolefin Foams

In the previous report, the 1986 total global consumption of all CFCs in all polyolefin foams was estimated to be 13,000 tonnes. The 1986 consumption estimate has now been revised to 19,000 tonnes following identification of a larger number of manufacturers.

For 1990, projections estimate that the use of CFC blowing agents has been reduced to 12,350 tonnes, a 35 percent cut in overall consumption. This reduction has occurred despite a significant increase in polyolefin foam production.

Considerable progress has been made in eliminating the use of CFCs in all product types. Many extruded products have been converted to HCFC-22, HCFC-142b, hydrocarbons and/or carbon dioxide.

Some manufacturers of mouldable bead products have converted to hydrocarbons and/or carbon dioxide combined with pre-expansion. Other applications await the further development of enabling technology or the commercial availability of suitable alternatives.

To a large extent, CFC conversion has occurred in Japan and North America. Little conversion has happened in developing countries. In some countries, where substitution has yet to occur, the conversion has been delayed because a technically and commercially feasible option has yet to become available.

In many other cases, the uncertain future of HCFCs has caused some manufacturers to delay conversion from CFCs until a viable long term solution can be developed.

Technical Options to Reduce CFCs in Polyolefin Foams

Blowing Agent Alternatives

One of the primary criteria in blowing agent selection is the ability to match the diffusion rate of blowing agents out of the foam with the diffusion rate of air into it. This match is necessary because the polyolefin resins are resilient.

If the diffusion rates are not sufficiently matched, the foam will either shrink or grow while aging. This is unacceptable in all three product types.

Immediate

The compounds mentioned as short-term blowing agent substitutes in the 1986 report were HCFC-22, HCFC-142b, and hydrocarbons, primarily butanes and pentanes. At that time, it was estimated that between 1989 and 1993, most polyolefin foams then utilising CFCs could be converted to one of these agents or another alternative.

Much has happened since the 1986, including large-scale conversion to the alternatives mentioned in the earlier report. There has also been considerable discussion of the need for zero-ozone depletion potential alternatives for non-insulation foams. For example, the United States Clean Air Act Amendments of 1990 specifically ban HCFCs after January 1, 1994 in all foams except insulation and automotive safety cushioning products. Other nations have similar regulations under consideration.

A possible early elimination of HCFCs concerns some industry segments where no clear non-ozone-depleting alternatives exist. This possibility already may have retarded the conversion from CFCs to HCFCs, producing an overall negative environmental impact, because the potential financial costs associated with two rapid conversions is a heavy burden for manufacturers in highly competitive markets.

HCFC-22

HCFC-22 has a very low boiling point and a high vapour pressure. These characteristics limit its use to the manufacture of some thin sheet products. Thicker sheet and plank products would be extremely difficult if not impossible to make with HCFC-22.

Vapour pressure can be handled by increasing extrusion pressure; however, this option requires equipment modification. In addition, HCFC-22 has low molecular weight and permeates quickly, which results in foam shrinkage.

HCFC-142b

For thicker sheet and plank products, the preferred alternative has been HCFC-142b, even with its moderate flammability. The permeation rate through polyethylene is close enough to air to provide a dimensionally stable foam with the use of permeability-modifying additives.

Hydrocarbons

The hydrocarbons are quite flammable. For example, butane flammability limits are about 1.8 to 8.4 percent with an extremely low energy of ignition. Consequently, using these substitutes requires careful evaluation of equipment and procedures in manufacturing, storage, handling, and shipping, as well as a review of local regulations and the possible dangers for customers.

In some areas of the world, such as the United States, hydrocarbons are classified as volatile organic compounds -- contributors to smog formation. Therefore, these compounds are subject to regulations limiting plant emissions. For extruded foams, the release of hydrocarbons in very dilute concentrations from storage areas and the subsequent collection could be inefficient and prohibitively costly (see Recovery/Recycle section below).

In some instances, significant plant modifications will be required to handle these blowing agents. In others, the manufacturer may be unable to use flammable blowing agents because of safety and handling reasons or local air pollution regulations.

Some manufacturers, primarily foam sheet manufacturers, have converted or expect to convert from CFCs to hydrocarbons. This is particularly true in Europe.

Short/Intermediate Term

Carbon Dioxide and Other Inorganic Gases

Carbon dioxide, nitrogen and other inorganic gases have very low solubility in the resins and may be of only limited use in extruded foams of these types. In addition, use of these gases may create very high pressures that are beyond the capability of some processes without significant or prohibitive capital expenditure. These volatile gases are, however, being used in some mouldable bead products where the process pressure problem has been overcome.

Long Term

The 1989 Technical Report stated that some processes might be dependent upon the commercialisation of longer term alternatives, including HCFC-123, HCFC-124, HFC-134a, and/or HCFC-141b. Since that time, HFC-152a has also been identified as a possible long-term alternative.

While it appears that all polyolefin foam types can now convert from CFCs to one of the short term options, some of the identified long term alternatives actually may be preferred over the shorter term options. Unfortunately, sufficient quantities of these materials are not yet commercially available. In addition, issues involving toxicity, manufacturing processes, and costs remained unresolved.

Chemical manufacturers have announced capacity expansion for HFC-134a and HCFC-124, and test quantities are available for evaluation to determine technical feasibility.

The following summarises concerns about the long-term options currently under consideration:

HFC-134a

HFC-134a appears to be prohibitively expensive in polyolefin foams and is not expected to see major use.

HFC-152a

Although flammable and somewhat expensive, HFC-152a has a blowing efficiency that might offset these factors. Like all HFCs, it also has limited solubility in the resin formulations. This could limit its ability to make low density foams.

Additional concerns with dimensional stability, related to permeation rates from the foam relative to the entrance of air into the foam, must be satisfactorily answered through manipulation of the foam formulation.

HCFC-123, HCFC-124, and HCFC-141b

It now appears that HCFC-123, HCFC-124, and HCFC-141b will be not used in polyolefin foam products because they are less suitable than other options.

Cost of Conversion

Accurate estimates of one-time conversion costs cannot be made, since they will be quite specific to manufacturing location, process characteristics, and product mix. Cost

estimates per line range from several hundred thousand to more than one million US dollars.

Foam manufacturing cost is very sensitive to blowing agent cost. Thus, some technically workable blowing agent options may not be commercially feasible. This could be the case where blowing agent cost is high or where the gas is not available in a given area and would need to be shipped from a producing region.

Recovery/Recycle

Recovery feasibility is primarily a function of product thickness and type. Some mouldable product suppliers use hydrocarbons in a closed pre-expansion process which captures essentially all of the gas. In extruded foams, where the blowing agent is trapped in the foam cells, the diffusion rate is inversely proportional to the square of the product thickness.

For thicker sheet and all plank products, collection of the blowing agents to any significant extent is generally impractical. In these cases, the blowing agent entrapped within the foam cells diffuses slowly over the life of the foam.

In very thin products, a major portion of the blowing agent is emitted at or near the die and can be captured fairly easily. One producer of very thin polypropylene foam sheet products is currently capturing and recovering blowing agents at greater than 95 percent efficiency.

When air streams containing organic vapours are captured, the contaminant can be removed by carbon adsorption. The efficiency of such operations depends on the concentration of vapours in the air.

Except in the case of very thin foams that lose a large quantity of blowing agent near the die, these air streams are quite dilute. This characteristic dramatically increases the cost and difficulty of efficiently recovering organic blowing agents.

Additional concerns are posed by many HFCs and HCFCs, which form flammable compositions in air at greater than atmospheric pressure. (This includes HCFC-22 and HFC-134a.) The recovery of a low boiling point blowing agent (B.P. < 0°C) is further complicated by ice formation from moisture in foam plant ambient air.

Product Substitutes

In many applications of polyolefin foams, products are used because of their specific properties. Whilst materials such as paper, cardboard, and expanded polystyrene can be used in some packaging applications, they are not effective substitutes in most applications of polyolefin foams.

Conclusions

In 1986, an estimated 19,000 tonnes of CFC-11, CFC-12, and CFC-114 were used in the manufacture of various polyolefin products. By 1990, CFC use had been reduced by 35 percent, to 12,350 tonnes, in this industry segment.

Primary substitutes were hydrocarbons, carbon dioxide, HCFC-22 and/or HCFC-142b. Essentially all polyolefin foam products can be converted to these blowing agent systems by the end of 1993.

If available to a manufacturer prior to 1993, HCFC-123, HCFC-124, HCFC-141b, HFC-134a or HFC-152a may also be used, although technical and commercial feasibility has yet to be fully determined.

It is still too early to tell if any of these possible alternatives will prove feasible for some or all applications. Considerable effort is underway to evaluate these approaches since better alternatives to hydrocarbons and HCFCs are desirable and deadlines for conversion are imminent in some countries.

Due to the performance demands of end-use applications, the resulting foam properties of the CFC substitutes are not expected to differ greatly from those of the current products. However, it will probably be necessary for the manufacturer to adjust formulation and processing conditions to maintain similar foam properties. This may change operating costs and increase the difficulty of making a conversion. Possible interferences with additives used for anti-static, flame retardant, colouring or other purposes may be an additional barrier to use of some alternatives in specific products.

It also may take an extended period of time for a manufacturer to make an entire product line conversion, because these foam products are made in a variety of shapes and for different applications.

Some options, where the diffusion rate of the blowing agent out of the foam is not well matched to the diffusion rate of air into the foam, might be useful in foam sheet products alone. This is because the loss of blowing agents is strongly related to product thickness and so aging time (and associated foam swelling or shrinkage) for very thin products might be acceptably short.

Recovery is generally not a practical means of limiting emission of blowing agents, except for some very thin sheet products.

Since polyolefin foams are used for their specific performance characteristics, the economic viability of substituting other products that use non-ozone depleting blowing agents is very limited.

Appendix A

ADVANCED TECHNOLOGIES FOR APPLIANCES AND CONSTRUCTION

Introduction

Heat is transferred from a warm area to a cooler area by means of conduction, convection, and radiation. Thermal insulation reduces these heat transfer mechanisms. If the interior of the insulation contains a vacuum below 10 Pa (1×10^{-4} Torr), the material is one of the best insulators available since heat flow can only occur by radiation. A Dewar flask is a familiar example of this.

In the mid 1930s, Kistler (1) noted that low thermal conductivity (high thermal resistivity) was obtained at modest vacuums for aerogels and small diameter powders. Because of the availability of other insulating materials such as low cost, closed-cell, plastic foams, further development based on this concept did not occur until the 1980s.

Foam Panel Composites

Advanced insulation technologies for appliances and construction are being developed using composites of high thermal resistance panels or elements encased within lower thermal resistance foams. Both vacuum panels and gas-filled panels can achieve higher thermal resistance than existing homogenous foams, and may be employed in these composites.

Vacuum Panels

Many insulation designs call for flat plate geometries. Flat evacuated panels have been made containing fine powders, fibrous glass or ceramic spacers to support the parallel plates against the atmospheric pressure.

The first patent on a powder evacuated panel appears to be that of Gervais and Goumy (2), which described a panel consisting of a very small diameter fumed silica filler material in a metallized-plastic envelope. Two US patents (3,4) were issued to the Barito and Downs for panels evacuated to 133 Pa (1 Torr). These panels, containing a filler material of precipitated silica or fly-ash and precipitated silica, achieved effective thermal conductivity (k) values below $0.007 \text{ W/m} \cdot \text{K}$ ($0.05 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$ or r-values above 20/inch).

In the early 1980s, Japanese refrigerator manufacturers were the first to employ flat panels in a commercial product (5). The panels were foamed into refrigerators so that the insulation was a composite of the panels and the foam. The panels were constructed of perlite as the filler material and were contained in a metallized-plastic envelope. Manufacturing was discontinued in the mid 1980s.

Oak Ridge National Laboratory (ORNL) reported thermal conductivities on evacuated panels from France, the United States, and Japan that degraded with time from near 0.007 to 0.010 W/m·K or greater. In addition, ORNL reported thermal conductivities for a number of powder systems as a function of internal gas pressure (6-11).

A vacuum insulation product which consists of diatomaceous earth as the filler material and steel as the barrier material has also been patented (12). The thermal shunting, i.e. the heat transfer from the hot to the cold side around the steel circumference, is minimized in some applications of this concept, such as 7 m long hollow cylinders used to insulate steam pipes (12).

Powdered silica, which is pressed into panels and vacuum-sealed in a special film, has recently been announced as an alternative insulation material. According to the manufacturer, the panels have an insulation value about twice that of high-grade PU (polyurethane) foam (13).

Researchers at Lawrence Berkeley Laboratories (LBL) are also developing evacuated insulation panels containing monolithic silica aerogel tiles that achieve k-values of 0.007 W/m·K at 1×10^4 Pa (76 Torr).(14) The thermal properties of these panels are very sensitive to the thickness and the boundary temperatures and emittances, since these materials are transparent to thermal radiation at certain wavelengths. Fricke and co-workers at the Physikalisches Institut der Universität Würzburg have described efforts to opacify aerogels to reduce thermal radiation transport. (15,16) Organic aerogels with potentially higher thermal resistances are being developed by Lawrence Livermore Laboratories. (17)

Glicksman and co-workers at the Massachusetts Institute of Technology have worked on glass enclosed compacts of precipitated silica as a component to be distributed in foam boards. The thin glass envelopes may result in lower gas permeability rates without significant increases in thermal shunting, and use of numerous vacuum compacts avoids the problem of a single penetration destroying the low k of a panel/foam composite (18).

Compact Vacuum Insulation (CVI) is based on the hard vacuum with spacers concept.(19) Researchers at the Solar Energy Research Institute (SERI) are developing the concept for various applications. The thermal resistance (R-value) of this concept is independent of thickness, as it is essentially a classic radiation heat shield. Theoretical calculations indicate that R-values of $1.8 \text{ m}^2 \cdot \text{K/W}$ in 0.0025 m (10 h·ft² · °F/Btu in 0.1 inches) may be attained, if edge losses through the metallic containment material can be minimized. Similarly, edge effects will reduce the performance of stacked panels to far less than the sum of individual panels.

Fine (20) used published thermal conductivity data with the gas pressure ceiling to obtain k of $0.007 \text{ W/m} \cdot \text{K}$ to identify candidate filler materials with material costs of less than US\$1.00 per board foot ($12 \times 12 \times 1 \text{ in}$ or $0.3 \times 0.3 \times 0.0254 \text{ m}$). The most promising candidates are listed in Table A-1. Other recent reviews have also been done by Kollie, et al. (21), Fay (22) and Feldman (23).

Table A-1. Candidate Filler Materials, Pressure Ceilings, and Material Costs (20)

Material	Gas Pressure Ceiling (Pa)	Material Cost (US\$/board foot)
Beverley Silica Dust	130	0.10
Evacuated Foam	30	0.20
Perlite or a Mixture of Silica Dust and Fumed Silica	270	0.50
Fibrous Glass with CVD Al	70	0.50
Precipitated Silica or Precipitated Silica and Fly Ash	1,330	0.70 - 0.80
Kaowool Blanket	10	1.00

Envelope Materials

The envelope material surrounding the vacuum element or panel must prevent gas diffusion into the panel or limit the amount of gas diffusion over the panel's service life. The maximum allowable pressure is determined by the filler and the desired k -value of the panel. For the diffusion of gas into the panel, the increase in the partial pressure of each gas component -- primarily oxygen, nitrogen, and carbon dioxide -- is proportional to the external partial pressure, the envelope's permeability and surface area, and the time. It is inversely proportional to the interior volume of the panel. For example, with a 0.0127 m thick panel 0.308 m square, the gas permeability must be below $0.025 \text{ fmol/m}^2 \cdot \text{s} \cdot \text{Pa}$ ($5 \cdot 10^{-3} \text{ cc/m}^2 \cdot \text{atm} \cdot \text{d}$) to insure that the pressure inside the panel does not exceed one hundredth of the ambient partial pressure over $6.3 \cdot 10^8 \text{ s}$ (20 years). To insure the pressure does not exceed 10^{-3} of the ambient over $3.15 \cdot 10^9 \text{ s}$ (100 years), the permeability must be $5 \cdot 10^{-4}$.(21)

For most polymeric films, the oxygen diffusion rate is at least five times greater than nitrogen. The useful life can be determined by the rate of increase of oxygen within the

panel, noting that the ambient partial pressure is $2.1 \cdot 10^4$ Pa (0.21 atm). Carbon dioxide diffusion is greater than oxygen so that a panel exposed to a high concentration of CO_2 may lose its R-value much faster. Table A-2 presents representative values of the oxygen permeability of several candidate materials.

Table A-2. Oxygen Transmission Rate of Films at 0% Relative Humidity and 298°K.

Film	Thickness (μm)	O_2 Transmission Rate ($\text{fmol/m}^2 \cdot \text{s} \cdot \text{Pa}$)
PVA, Polyvinyl Alcohol (21)	13 - 25 125	0.5 - 1.5 0.70
EVOH, Copolymer of Ethylene and Vinyl Alcohol (21)	13 - 25 250	0.5 - 1.0 0.05
Vapour Deposited Quartz Film (27)	30	0.15 - 4.5
Aluminum Foil (21)	18	0
Silica Glass (27)	25	0

Claims of still lower values have been made for some EVOH films. The oxygen transmission of the PVA and EVOH materials substantially increases in the presence of water; the films are laminates using outer layers which are barriers to water vapour.

The properties of the polymeric films need to be experimentally substantiated over a range of conditions. Test procedures must be developed to rapidly simulate the long term behaviour and possible degradation of the films. Although long-term deterioration should not be a problem with glass or corrosion resistant metals, thin aluminum foils are subject to pinholes. Glass films, although flexible, must be protected from surface damage; a thin layer of foam has been found to provide this protection.

The envelope must have a combination of low thermal conductivity and low thickness to limit conductive heat transfer around the circumference, which may substantially increase the overall k-value of the panel. Heat will flow from the hot to the cold side of the panel around the edges of the envelope. To minimize diffusion, the envelope must be fused together; a low conductivity spacer cannot be used. To properly account for the circumferential heat flow, realistic thermal boundary conditions must be applied to the top and bottom surfaces.

Table A-3 summarizes the overall k-value as a function of the envelope thermal properties, the product of thermal conductivity and thickness of the envelope material, $k \cdot th$. For a $k \cdot th$ value of 3300 (W/m · K) · (μm), the overall k-value is substantially increased even for a 90 cm panel. This corresponds to the conditions for a stainless steel envelope 0.2 mm (7.5 mils) thick or an aluminum foil 0.02 mm (0.7 mils) thick.

Table A-3. Overall k-Values for Evacuated Panels -- Including Circumferential Conduction Around the Envelope*

Panel Diameter (cm)	Overall k-Value (W/m · K)		
	$k \cdot th$ (W · μm/m · K) Value		
	3,330	330	110
15	0.028	0.0091	0.0063
22.5	0.021	0.0075	0.0057
30	0.017	0.0067	0.0053
60	0.011	0.0055	0.0049
90	0.0084	0.0051	0.0048

* Calculated for a 2.154 cm thick cylindrical panel with a one-dimensional heat flow k-value of 0.0048 W/m · K, and top and bottom heat transfer coefficients of 5.7 W/m² · K.

Conduction through the glass bead spacers in hard vacuum panels will increase the overall k-value still further. Thus, the metallic envelopes are only feasible when a single very wide panel can be used. A 0.4 mm (15 mil) glass envelope will have a $k \cdot th$ value of 330, while a 0.6 mm (25 mil) polymeric envelope will have a $k \cdot th$ value of 110. For these materials, circumferential conduction has a more modest influence on the overall k-value and smaller panels can be used without substantial thermal penalty. The use of many smaller panels side by side limits the overall performance loss if one panel fails or is punctured.

Engineering Technology

Manufacture of advanced insulation panels to date has been done by hand. Automated panel production using form-fill-seal machine technology, which is available and currently used in the food packaging industry, is possible. A generic process would involve drying of the filler material and forming of the container in parallel streams. The container would then be filled, evacuated, sealed and installed.

The variable cost for automated production has been estimated at less than US\$0.55/m² (US\$0.05/ft²). (24) Fixed costs are difficult to estimate as different applications may require many panel sizes. For example, 15 or more panel sizes may be needed to completely insulate units on a refrigerator/freezer production line.

The best installation method and the impact of the resulting incremental costs are not yet known to the authors. In addition to the possible loss of production, warranty costs must be established. Reliability issues as discussed above must be resolved before these costs can be estimated.

Gas-Filled Panels

Panels similar to those described above but containing a low conductivity gas have been developed at Whirlpool (25) and at LBL (26). The main differences between the evacuated panels and the gas-filled panels are the presence of the low conductivity gas at atmospheric pressure and low emittance baffles which serve to eliminate convection and radiation heat transfer. Panels filled with argon and krypton have been made at LBL.

Measurements performed at ORNL yielded k-values of 0.02 W/m · K for argon-filled panels and 0.012 W/m · K for krypton-filled panels. These are 10 percent and 20 percent above the theoretical limit, i.e., the conductivity of the gas phase only.

The gas-filled panels will have similar container requirements as the evacuated panels. Air infiltration will be a problem as the driving force for permeation is the partial pressure difference and not the total pressure. In addition, gas-filled panels will require structural components and low emittance coatings, since powder or some other filler will not be present to give the panels compressive strength or radiation barriers.

Advanced Foam Technology

The overall heat transfer through foam is due to three contributions: conduction through the cell gas, infrared radiation, and conduction through the solid polymer. For a typical foam filled with CFC-11, the relative contributions of the above factors are about 50 percent, 30 percent and 20 percent, respectively.

As higher conductivity blowing agents are added to the foam, the effective conductivity will increase. To counteract this, other forms of heat transfer must be reduced.

The radiation heat transfer through the foam is inversely proportional to the cell diameter and square root of the foam density. By making smaller cell foams, the radiation can be reduced. If at the same time the foam density is reduced, conduction through the solid polymer is also decreased.

Radiation can also be reduced by adding opaque microparticles to the foam; these particles embedded in the cell walls reduce the transmissivity. However, an excess of

powder will increase the thermal conductivity of the solid. An ideal micropowder has a low conductivity core coated with several angstroms of opaque material.

Most foil-faced foam panels have an increased conductivity with age because the facer is permeable or because air and blowing agent can move laterally along faults at the foam-facer interface. Although it has not been possible to-date to produce impermeable foil facers that do not have faults, calculations show that a panel with such a facer and containing a higher conductivity blowing agent, such as CO₂, could have a lower average conductivity over its useful lifetime than a current panel blown with CFC-11.

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Appendix B

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