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Foams

Coordinating Lead Author
Paul Ashford (United Kingdom)

Lead Authors
Andrew Ambrose (Australia), Mike Jeffs (United Kingdom), Bob Johnson (USA), Suzie Kocchi (USA), Simon Lee (United Kingdom), Daniel Nott (USA), Paulo Vodianitskaia (Brazil), Jinhuang Wu (China)

Contributing Authors
Theresa Maine (USA), John Mutton (Canada), Bert Veenendaal (The Netherlands)

Review Editors
Jorge Leiva Valenzuela (Chile), Lalitha Singh (India)

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EXECUTIVE SUMMARY

Following the mainstream introduction of HFC use in 2002, the phase-out of the use of ozone-depleting substances in the foam sector in the majority of developed countries is only now progressing towards completion. Consequently, predicting HFC usage patterns has been notoriously difficult and the downsizing of HFC demand estimates has been a feature of the last 3–5 years, being driven significantly by the costs of HFC-based systems when compared with other options.

Nevertheless, HFCs are being used in those applications where investment cost, product liability, process safety, and thermal efficiency are particularly important elements in the decision process. Where HFCs are used, careful consideration has been given to the use of blowing-agent blends for both cost and environmental reasons. Co-blowing with CO_2 (water)[1] has emerged as an important way of limiting HFC consumption in key applications such as the US appliance industry and the global spray-foam market.

It is now estimated that global HFC consumption in the foam sector is unlikely to exceed 75,000 tonnes annually in the period to 2015. This represents around 20% of the consumption that would have been associated with CFCs in the absence of the Montreal Protocol and around 50% of the uptake anticipated when the situation was first reviewed at the IPCC/TEAP Petten Conference in 1999. Not-in-kind insulation materials, such as mineral fibre, have continued to be the predominant choice in most global markets, primarily because of cost. Accordingly, foams are only used where their properties add value.

Hydrocarbon technologies have been widely adopted in several foam sub-sectors, including domestic appliances, water heaters, polyurethane (PU) sandwich panels, PU boardstock and some PU integral skin applications, and are expected to represent >55% of overall blowing-agent usage globally in the period after 2005. Progress into other sub-sectors has been thwarted by specific investment cost, product and process safety and, to a lesser extent, thermal performance.

HCFCs will continue to be used in foam applications in developing countries throughout the period and consumption has been predicted to grow to just under 50,000 tonnes by 2015. This assessment concurs broadly with the estimate in the 2003 TEAP HCFC Task Force Report (UNEP-TEAP, 2003), despite the different method used. Table 7A summarizes the projected consumption and emission pattern as at 2015, together with an assessment of the remaining blowing agent bank. The fact that annual emissions are not equivalent to annual consumption figures reflects the fact that most applications for which HCFCs, HFCs and hydrocarbons are considered as closed cell foams with time-delayed emission profiles.

As shown in Table 7A, emissions of HCFCs are expected to plateau in the 20,000–25,000 tonnes per annum range in the period after 2005, with decreases in production emissions from phase-out in developed countries being offset by emissions from domestic refrigerators at end of life. In contrast, the trend for HFC emissions will continue to be gradually upwards through the period of assessment as the bank builds. However, the most significant bank remains that related to CFCs. This is partly associated with the long period of historic use, but the impact of emissions on climate change is accentuated by the high average global warming potential (GWP) of the CFCs emitted. On the basis of current projections, and if there is no effort to instigate further end-of-life emission reduction options, the impact of CFC emissions will remain predominant, at least until 2050.

There is significant potential for managing emissions of CFCs, HCFCs and HFCs through further substitution, reduction in emissions during foam production/installation and improvements in end-of-life management. Some of these options involve innovation in building construction, allowing for disassembly as part of end-of-life management (e.g. the wider use of pre-fabricated building elements), while others involve the improved engineering of foam processes. As highlighted by Table 7A, the delayed release of blowing agents from both new and existing foamed products generates significant banks of blowing agent and there is a particular opportunity to focus on end-of-life issues both for recovery of existing materials containing ozone-depleting substances and also for future HFCs. The technical and economic potential for recovery still has to be fully quantified, although a lot of work is on-going now to

Table 7A. Projected global consumption and emissions of blowing agent by type as at 2015 (based on 2001 consumption data cited in the 2002 UNEP Foams Technical Options Committee Report (UNEP-FTOC, 2003)).

Blowing Agent	CFCs	HCFCs	HFCs	Hydrocarbons
Consumption (metric tonnes) – 2002	11,300	128,000	11,200	79,250
Consumption (metric tonnes) – 2015	Nil	50,000	73,000	177,250
Emissions (metric tonnes)	16,100	20,650	18,050	33,600
Bank as at 2002 (metric tonnes)	1,860,000	1,125,000	11,650	316,800
Remaining bank as at 2015 (metric tonnes)	**1,305,000**	**1,502,000**	**566,100**	**1,232,000**

[1] The CO_2 (water) option refers to carbon dioxide generated by the reaction of water with excess isocyanate in the formulation for polisocyanurate and polyurethane processes.

Table 7B. Cumulative emission savings resulting from the emission reduction scenarios outlined.

Measure	Year	CFCs	HCFCs	HFCs	CO2-eq	Est. Costs
		(tonnes)	*(tonnes)*	*(tonnes)*	*(Mtonnes)*	*US$/tCO2-eq*
HFC consumption reduction (2010–2015)	2015	0	0	31,775	36	15-100
	2050	0	0	225,950	259	
	2100	0	0	352,350	411	
Production/installation improvements	2015	78	14,450	16,700	36	Varying
	2050	58	31,700	32,700	68	
	2100	47	24,350	26,500	55	
End-of-life management options	2015	8,545	16,375	105	52	10–50[1]
	2050	64,150	144,650	88,540	540	
	2100	137,700	358,300	194,800	1200	

[1] Cost range for recovery of blowing agents from appliances only.

do so. However, this potential is likely to differ widely between sectors and applications. Although some emission management measures can be implemented relatively quickly, implementation in most cases is expected to be after 2007. Recognizing that the precise mix of measures cannot be fully defined at this stage, this chapter assesses the comparative impact of three scenarios:

- a linear decrease in the use of HFCs between 2010 and 2015, leading to a 50% reduction by 2015;
- the adoption of strategies for the reduction of production emissions in the block foam sub-sector from 2005 and from 2008 onwards in other foam sub-sectors;
- the extension of existing end-of-life measures to all appliances and steel-faced panels by 2010, together with a 20% recovery rate from other building-based foams from 2010 onwards.

Table 7B indicates the cumulative emission savings resulting from these three scenarios and gives an early indication of the likely costs based on initial assessments documented in the literature.

It can be seen that focusing on the reduction of HFC consumption provides the most significant saving in the period to 2015 and that, if any such reduction is extrapolated to use patterns after 2015, it offers the greatest 'HFC-specific' benefit up to 2100 as well. In contrast, end-of-life measures deliver lower savings in the period to 2015, but have the potential to deliver more overall savings in the period to 2100 if all blowing-agent types are considered. The value is particularly significant for CFCs, where GWPs are substantive and there is an incremental effect on ozone depletion.

The future consumption patterns for HFCs in the foam sector beyond 2005 are heavily reliant on the wider role of foams in energy conservation and, in particular, building renovation. It is expected that spray foam techniques may have a particular role to play. The development of well-grounded responsible-use guidelines will be vital for both the foam industry and climate change policymakers in order to ensure the most appropriate use of HFCs and the control of emissions, where applicable. However, in all cases, it will be necessary to assess the overall incremental energy benefit, together with the non-preventable direct emissions, in a policy-level comparison.

To illustrate the significance of energy-related emission savings, Table 7C provides typical ratios of CO_2 emissions saved

Table 7C. Ratios of indirect savings to direct emissions in various building applications

Application Sector	Method applied	Ratio of indirect (energy-related) savings to direct (HFC) greenhouse emissions	Key assumptions
Polyurethane spray foam, industrial flat warm roof	Life- cycle assessment (LCA)	15 – with full recovery of HFC at disposal 8 – without recovery of HFC at disposal	4 cm thickness; HFC-365mfc Germany
Polyurethane boardstock in private building cavity wall	LCA	140 – with full recovery of HFC at disposal 21 – without recovery of HFC at disposal	5 cm thickness; HFC-365mfc; Germany
Polyurethane boardstock in private building, pitched warm roof	LCA	92 – with full recovery of HFC at disposal 14 – without recovery of HFC at disposal	10 cm thickness; HFC-365mfc; Germany

by HFC-based foam to direct emissions of the HFC blowing agent during the lifecycle. In this instance, three typical applications were evaluated (Solvay, 2000).

These ratios do not imply that it is always essential to use HFC-blown foams to achieve the best overall thermal performance, but do illustrate that small incremental changes in thermal efficiency from the use of HFCs can have substantial overall emission benefits, primarily as a result of the long lifetime of most buildings. The benefits can be particularly significant if HFCs are recovered at disposal.

HCFC consumption in developing countries will be frozen after 2015 under the Montreal Protocol and will be phased out by 2040. In the business-as-usual analysis in this chapter, it is assumed that the decline is linear between 2030 and 2040. There is less certainty about HFC use beyond 2015, but the degree of innovation that has marked the last 20 years would suggest that the foam industry is unlikely to be reliant on HFCs beyond 2030. Accordingly, the business-as-usual analysis proposes a freeze in consumption at 2015 levels and a linear decline in use between 2020 and 2030.

7.1 Foam markets

7.1.1 Foams by broad grouping and application

Foamed (or cellular) polymers have been used historically in a variety of applications, utilizing the potential for creating both flexible and rigid structures. Flexible foams continue to be used effectively for furniture cushioning, packaging and impact management (safety) foams. Rigid foams are used primarily for thermal insulation applications of the types required for appliances, transport and in buildings. Rigid foams are also used to provide structural integrity and buoyancy.

For thermal insulation applications (the majority of rigid foam use), mineral-fibre alternatives (e.g. glass fibre and rock wool) have been, and continue to be, major not-in-kind alternatives. Table 7.1 illustrates the major benefits and limitations of both approaches.

The implications of these relative benefits and limitations vary substantially, both between products, within a category and between applications. This makes a generic conclusion about preferences impossible. The current thermal insulation market supports a variety of solutions (at least 15 major product types) and this reflects the range of properties demanded for the applications served. Unfortunately, only limited data are available covering the thermal insulation market at the global and regional levels. One of the complexities of global-market analysis is that building practice around the world varies, often responding to material availability and climatic conditions.

In reviewing the not-in-kind options, it is important to acknowledge continuing development. It looks likely that the use of vacuum panels in domestic refrigerators and freezers will increase and already most Japanese units contain at least one such panel in strategic design positions. However, the price implications of such technology choices make them relevant only when they are required to meet legislation relating to energy efficiency or where the market is clearly willing to pay the necessary premium.

There are at least twenty sub-sectors to be considered in any assessment of the market for foams. These are broken down in the Tables 7.2 and 7.3 according to whether they relate primarily to thermal insulation applications or not. This means that there is a mix of flexible and rigid foams in the Table 7.3.

Table 7.2 gives an indication of how this segmentation works for insulating foams. There are also a number of applications for non-insulation foams. These are shown in Table 7.3.

7.1.2 Energy savings

One of the prime reasons for using thermally insulating materials is to save energy. This objective is particularly important when the materials are used in the fabric of buildings and their related services, and also when they are used in appliances and equipment in our homes, offices and factories. As indicated in Tables 7.2 and 7.3, various materials meet the requirements for both these application areas and the following sections illustrate the importance of their role in the two categories.

7.1.2.1 Buildings (including building services, renovations)
Global assessments of carbon dioxide emissions have consistently revealed that emissions from the use of buildings (including appliances used in buildings) represent 30–40% of the global total. (Price *et al*., 1998). In the industrialized countries of the northern hemisphere, this can rise as high as 40–50% (Ashford, 1998). The reduction of these emissions depends on two parallel strategies. The first consists of reducing the carbon intensity of the energy used by fuel by switching to alternatives with less carbon (e.g. natural gas) or by using more renewable energy. The second consists of improving the energy efficiency of the buildings themselves, including the appliances used within them. The evaluation of some strategies developed by governments in this area has made it increasingly clear that the scope for fuel switching and the rate of investment in renewable energy sources between now and 2050 will not be sufficient to achieve sustainable carbon dioxide emission levels by 2050 (e.g. Carbon Trust, 2002). This has led to the recognition of the central role of energy efficiency measures in any strategy and the introduction of such ground-breaking measures as the Energy Performance in Buildings Directive from the European Union (OJ, 2003).

The delivery of more energy efficient buildings and appliances is a complex issue. A recent cost-abatement analysis conducted by the Building Research Establishment in the UK (Pout *et al*., 2002) revealed that over 100 *bona fide* measures exist to improve the energy performance of buildings alone. The IPCC has made similar observations earlier (IPCC, 2001). Accordingly, solutions need to be tailored to the circumstances

Table 7.1. Comparing the respective benefits and limitations of different insulation types.

Mineral fibre		**Cellular polymers**	
Benefits	*Limitations*	*Benefits*	*Limitations*
Initial cost	Air-based thermal properties	Blowing-agent-based thermal properties	Fire performance (organic)
Availability	Moisture resistance*	Moisture resistance	Limited maximum temperature
High maximum temperature	Low structural integrity	Structural integrity	First cost (in some cases)
Fire performance		Lightweight	

* Potentially affecting long-term thermal performance

Table 7.2. Assessment of application areas by thermal insulation type.

Foam Type		**Application Area**							
		Refrigeration & Transport			**Buildings & Building Services**				
		Domestic Appliances	Other Appliances	Reefers & Transport	Wall Insulation	Roof Insulation	Floor Insulation	Pipe Insu-	Cold Stores
Polyurethane	Injected/ P-i-P	□□□	□□	□□□	□□□	□□□	□□□	□□□	□□□
	Boardstock				□□□	□□□	□		
	Cont. Panel			□□	□□□	□□□			□□□
	Disc. Panel			□□	□□□	□□□			□□□
	Cont. Block			□□					
	Disc. Block			□□				□□	□□
	Spray		□□		□□	□□□		□	
	One-Component				□□	□			□
Extruded Polystyrene	Board			□□	□□□	□□□	□□□	□	□□
Phenolic	Boardstock				□□□	□□□			
	Disc. Panel				□□	□			□□□
	Disc Block							□□□	□□
Polyethylene	Board						□		
	Pipe							□□□	
Mineral Fibre		□	□	□	□□□	□□□		□□□	□

□□□ = Major use of insulation type □□= Frequent use of insulation type □= Minor use of insulation type

Table 7.3. Assessment of the use of foams by type in non-insulation applications.

Foam Type		**Application Area**					
		Transport		**Comfort**		**Packaging**	**Buoyancy**
		Seating	Safety	Bedding	Furniture	Food & Other	Marine & Leisure
Polyurethane	Slabstock	□□		□□□	□□□	□□	
	Moulded	□□□			□□	□□	
	Integral Skin		□□□		□	□	
	Injected/ P-i-P						□□□
	Cont. Block						□
	Spray						□
Extruded Polystyrene	Sheet					□□□	
	Board						□□□
Polyethylene	Board					□□	□□

□□□ = Major use of insulation type □□= Frequent use of insulation type □= Minor use of insulation type and the requirements of individual buildings. This can include aspects involving building services (e.g. pipe insulation) as well as measures associated with the fabric of the building itself. The approach adopted is necessarily different for new buildings than for existing buildings and there always has to be a balance between 'passive', fabric-based measures such as double- or triple-glazed windows and 'active' measures such as improved controls for the internal climate.

There have been several studies of the potential role of thermal insulation in the achievement of these objectives. One recent study (Petersdorff *et al.*, 2002) has demonstrated that the technical saving potential through the more widespread use of thermal insulation in Europe alone is more than 350 Mtonnes CO_2-eq/yr. This contrasts with earlier estimates (Ashford, 1998) which took more account of other competing measures, but concluded that the annual savings potential for the same region was 150 Mtonnes CO_2-eq/yr. In any event, the role of thermal insulation in the future reduction of carbon dioxide emissions is undeniable.

One of the major challenges for governments is the identification of appropriate policies and measures for implementing and encouraging improved energy efficiency in buildings. The construction of new buildings is typically well-regulated and provides a natural opportunity for increased energy efficiency standards. However, targeting new building standards alone will not deliver the required emissions savings, since most new building activity is undertaken in response to overall economic growth and social changes such as ageing populations and population migration. The daunting prospect for many governments is that the demolition rates for existing building stock are less than 0.5% per year and in some cases less than 0.2% (UNECE (2002) Database). Accordingly, unless there is a major demolition and rebuilding programme, the focus of attention will need to shift to measures required to renovate existing buildings. This is not easy because governments cannot generally impose requirements on existing owners. The problem is compounded because many owners are not the occupiers (or the payers of the energy bills), and costs and benefits are therefore not linked. The assessment of cost-effectiveness criteria therefore becomes critical, with discussion focusing on matters such as investment costs, payback periods, discount rates and the like. In the end, the questions to be answered are 'who pays?', 'when?' and 'how much?'. Government intervention, particularly in the domestic household sector, is expected to be a major part of many national strategies and the costs need to be considered carefully in order to get best value for investments (Ashford and Vetter, 2004).

In summary, it is clear that building renovation requires specific innovative products, supported by equally innovative policies and measures to improve the overall energy efficiency of existing building stock. The role of thermal insulation has already been highlighted by several studies, but it is anticipated that insulating foams will have a particularly important part to play because of their space-saving qualities and ease of pre-fabrication and/or direct application (e.g. spray foams). One of the purposes of this chapter is to identify the strengths and weaknesses of HFC-based foams and their alternatives in order to assess their likely uptake and possibilities for sound management. This can only be done in the wider context of this over-arching role for energy efficient products and buildings.

Apart from specific insulation foams, one-component foams (OCF) are very widely used in the building industry as gap fillers around doors and windows, as well as in plumbing applications. They provide excellent seals against draughts, thereby reducing the heat loss or gain by the building through improved air-tightness. In addition, they have major economic benefits because of their speed of application compared to any alternative method. The blowing agent acts both as a frothing agent and as a propellant. Initially, CFC-12 was used, but this has been replaced by a variety of alternatives including HCFC-22, hydrocarbons such as butane, propane and dimethyl ether, or HFC-134a and HFC-152a. This application is emissive and a recent European Union Proposal for a Regulation (COM (2003) 492) will severely restrict the use of HFCs in this application (UNEP-FTOC, 2003).

Finally, insulating foam is increasingly being used in pre-insulated pipes used to transport hot water underground in district heating systems. The foam provides the combination of thermal performance, moisture resistance and heat resistance required for this demanding environment.

7.1.2.2 Domestic refrigerators

The appliance market is highly competitive in all regions of the world and subject to stringent energy regulations in some places. The cost and performance characteristics of the insulating material are therefore both important parameters. Furthermore, the best possible insulation value is required in appliances to reduce wall thickness and maximize internal space, while preventing the settlement which could occur with other non-foam insulation types. The use of polyurethane foam to insulate domestic appliances started in Europe in the late 1950s as an alternative to mineral fibre, thereby revolutionizing production and reducing energy consumption. The technology is now universally employed (although the transition was only completed in the 1990s in developing countries) and has been a key factor in achieving dramatic improvements in appliance efficiency.

In response to shortages of electricity and to limit power-plant emissions, several countries have implemented regulations that require the labelling of products to indicate their relative energy efficiency, and some have established limits on the energy consumption allowed for refrigerators and freezers. Mandatory standards were implemented nationwide in the US in 1990. Limits were tightened in 1993, and again in 2001. In Europe, mandatory standards were implemented in 1999 and they are complemented by a progressive labelling programme. Several other countries have also implemented mandatory standards and labels. These standards, along with other programmes that provide incentives for manufacturers to design and market high-efficiency products, have resulted in thicker walls, requiring more foam, and may influence the choice of foam-blowing agent. The Appliance Research Consortium sponsored studies to determine the relative performance of leading candidates for the replacement of CFC-11 and HCFC-141b as blowing agents for refrigerator and freezer insulating foam. The results of these studies indicated that the highest insulating value was achieved using HFC-245fa. (Wilkes *et al*., 2003). In Japan, particularly stringent energy regulations have forced the limited introduction of vacuum panels, although cost penalties are preventing more widespread use.

Apart from its energy contribution, the foam also provides strength as the core of sandwich elements, therefore reducing the consumption of other materials previously needed for structural purposes. An example is the use of plastic internal liners instead of enamelled steel, with the resulting weight reduction. Since the foam is important for the performance and durability of the product, it must maintain both its insulation effectiveness and structural properties throughout the design life of the appliance.

7.1.2.3 Others

There are several additional applications in which rigid insulation foams act both as an insulating medium and as a strength-giving core material. These foams are generally polyurethane-based, although extruded-polystyrene foams are also used. Such foams are universally used in refrigerated containers (reefers) and in truck bodies. The best possible insulation value is needed in these applications to reduce wall thickness and maximize internal space, while preventing the settlement that could occur with other non-foam insulation types.

Rigid polyurethane foam is used for the same efficiency reasons in commercial refrigerator and freezer units, drink vending units and in domestic/commercial water heaters. The latter in particular are again subject to energy consumption limits.

CFC-11 has been used historically in all of these polyurethane systems, while CFC-12 has been used in extruded-polystyrene applications. Their main replacements globally have been HCFC-141b and HCFC-142b respectively. Pentane and HFCs are now being increasingly used as HCFC-141b is phased out in developed countries while, in the case of extruded polystyrene, HFC-134a based systems have been used to replace HCFC-142b owing to the high thermal insulation requirements.

7.1.3 Safety/resilience

Integral skin polyurethane foams are widely used in the transportation/automotive industries for in-cabin applications such as steering wheels, arm rests and gear shift knobs. They combine aesthetics and durability with the degree of softness required to minimize impact damage in the event of an accident. The components are produced by a reaction injection moulding technique. A low percentage of blowing agent is added to give a solid skin and a lower density core. The mouldings are produced in both developed and developing countries. Initially, the blowing agent in use was CFC-11 but options include HCFCs, HFCs, pentane and CO_2 (water). The use of HCFCs has been phased out in developed countries (UNEP-FTOC, 2003).

Closed cell polyurethane rigid and semi-rigid foams are used for buoyancy aids and life jackets. The buoyancy aids for boats are usually foamed in place. The blowing agent was initially CFC-11. This has been replaced with a variety of alternatives including HCFC-141b, and the future use of HFCs is envisaged (UNEP-FTOC, 2003).

7.1.4 Comfort

The largest polyurethane foam sector by overall volume is flexible foam for furniture, mattresses and transportation components such as seats. This foam is used globally and a number of different blowing-agent technologies have been deployed to replace CFC-11, which was used initially as the auxiliary blowing agent. Neither HCFCs nor HFCs are used in this sector.

Integral skin polyurethane foams are also used for furniture components such as armrests, and for footwear, especially sports footwear. One of their key features is very high durability. The components are produced by a reaction injection moulding technique. A low percentage of blowing agent is added to give a solid skin and a lower density core. The mouldings are produced in both developed and developing countries. Initially, the blowing agent in use was CFC-11 but options include HCFCs, HFCs, pentane and CO_2 (water). The use of HCFCs has been phased out in developed countries (UNEP-FTOC, 2003).

7.1.5 Market growth factors

There are three distinct factors involved in projecting market changes in the insulating foam sector. These can be listed as follows:

(1) Overall economic activity based on GDP (as a default) or on the number of units being produced in a given year. Considering the major uses of foams, this would be the number of buildings built/refurbished or the number of appliances (e.g. domestic refrigerators or freezers) being manufactured.

(2) The amount of insulation used per unit. This has tended to increase as energy standards for appliances have been raised or as building regulations have called for more insulation in new buildings to meet energy efficiency requirements. The expression used for this measure is the 'foam-volume ratio'. Increasing energy costs can also encourage greater use of insulation, but the driver is relatively weak in most regions because energy costs have dropped in real terms over recent years.

(3) The third driver for market growth in the foams sector is the relative share of the insulation market accounted for by foams. Although the trend may be in either direction depending on product priorities (e.g. fire performance, thermal efficiency, moisture resistance), the general trend

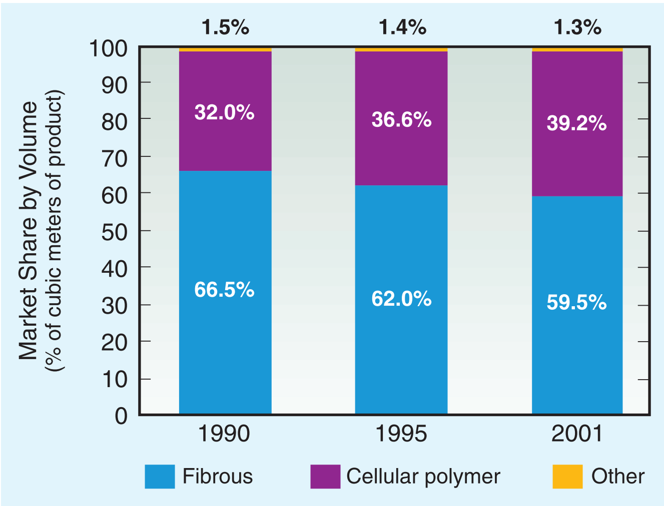


Figure 7.1. Variation of insulation by product type (1990–2001) in Europe

in Europe over the last ten years has been moving gradually towards foams (see Figure 7.1). Of course, this is unlikely to be consistent across all foam sub-sectors or regions.

These three factors have, in principle, constituted the overall market-growth drivers for the assessment of blowing-agent consumption from 1960 onwards. However, in practice, it has been more relevant to combine factors (2) and (3) into an overall 'foam-volume ratio' growth factor, since it is not normally possible to distinguish, at the regional level, overall insulation market growth 'per unit' from changes in market share of the types of insulation used.

For other types of non-insulating foams, the growth parameters are different and can be linked to indices such as global automobile production or fast-food sales. However, since these applications are unlikely ever to rely on HFCs, these parameters have not been considered quantitatively in this review.

7.2 Phase-out of ozone-depleting substances

The major classes of alternative blowing agents in use by sector are shown in Tables 7.4 and 7.5. In addition, there are a number of emerging blowing agents such as methyl formate and formic acid which are finding some acceptance. However, their use is not yet sufficiently widespread to justify inclusion in these tables.

7.2.1 Transitional use of HCFCs worldwide

The use of HCFCs in foam blowing in both developed and developing countries is generally limited to insulation and integral skin applications. Most foams for comfort and food applications use HCs (extruded-polystyrene sheet and polyethylene foams), liquid CO_2 (as a co-blowing agent) or methylene chloride (flexible, low-density PU foams).

7.2.1.1 Developing Countries

HCFC-141b is the most widely used CFC substitution technology for polyurethane foams in developing countries. The main reasons are the modest transition costs, easy implementation, similarity of end product performance (including energy) and wide availability. HCFC-142b and HCFC-22 are used for extruded polystyrene, although the uptake of this technology is limited to areas where the markets are sufficiently large to support the capital investment.

With limited further funding available to those who have already made the transition, HCFCs are likely to remain in widespread use in developing countries for a long time to come, possibly until 2040. This is particularly true of those who faced the challenge of CFC transition recently in stagnant economic conditions and favoured HCFCs as the most cost-effective option. Similar transition challenges face smaller enterprises in developed countries but, in this instance, the transition will be forced by regional regulation no later than 2015.

Other reasons for the continued use of HCFCs vary according to the application. The use of HCFC-141b as a blowing agent for the insulation of domestic refrigerators is associated with a potential lowering of energy consumption, which can assist in limiting energy demand in domestic markets where there are energy supply constraints. However, there may be constraints on trade for HCFC-containing articles in some regions (e.g. the European Union). Accordingly, HCFC-based technologies may simultaneously constitute an advantage and a disadvantage when multiple geographic markets are served. In summary, an appliance manufacturer's decision to use HCFCs, HFCs or hydrocarbons depends upon power supply and use, market forces, and existing regulations relating to energy and ozone-depleting substances in the targeted countries.

Similar considerations apply to sectors such as commercial refrigeration and other insulation applications. It is important to bear in mind that most industrial CFC conversions financed by the Multilateral Fund could use equipment that supports non-HCFC technologies such as CO_2 (water) and hydrocarbons. However, the degree of penetration of hydrocarbon technologies has been limited by the availability of hydrocarbons of an appropriate quality and by investment thresholds that set a cap on the funding available to save a kilogram of CFC.

HFCs, HCFCs, carbon dioxide (water) and HCs are currently used for automotive integral skin applications in developing countries in response to customer requirements, corporate policies or both.

In the case of extruded polystyrene, developing countries installing new capacity are likely to use HCFCs (HCFC-142b and/or HCFC-22) because HCFC equipment remains readily available and little equipment is available as yet for the installation of turnkey operations capable of using blowing agents with zero ozone-depleting potential.

In summary, as long as HCFCs remain available, HCs and HFCs will be used by developing countries only as widely as the additional costs associated with these technologies can be afforded or where corporate policy dictates. Some further ratio-

Table 7.4. Blowing-agent selection by product type and application area – thermal insulation.

<table>
<tr><th colspan="2" rowspan="3">Foam Type</th><th colspan="8">Application Area</th></tr>
<tr><th colspan="3">Refrigeration & Transport</th><th colspan="5">Buildings & Building Services</th></tr>
<tr><th>Domestic Appli-ances</th><th>Other Appli-ances</th><th>Reefers & Transport</th><th>Wall Insu-lation</th><th>Roof Insu-lation</th><th>Floor Insu-lation</th><th>Pipe Insu-</th><th>Cold Stores</th></tr>
<tr><td rowspan="8">Polyurethane</td><td>Injected/ P-i-P</td><td colspan="3">[HFC], HFC, HC, CO_2 (water)</td><td>HC, HFC</td><td></td><td></td><td>HC</td><td></td></tr>
<tr><td>Boardstock</td><td></td><td></td><td></td><td colspan="3">Hydrocarbon, HFC</td><td></td><td></td></tr>
<tr><td>Cont. Panel</td><td></td><td></td><td>HC</td><td colspan="2">HC, HFC</td><td></td><td></td><td></td></tr>
<tr><td>Disc. Panel</td><td></td><td></td><td>[HCFC] HC,HFC</td><td colspan="2">[HCFC], HC,HFC</td><td></td><td></td><td>[HCFC] HC,HFC</td></tr>
<tr><td>Cont. Block</td><td></td><td></td><td>HC, HFC</td><td></td><td></td><td></td><td colspan="2">HC, HFC</td></tr>
<tr><td>Disc. Block</td><td></td><td></td><td>[HCFC] HC,HFC</td><td></td><td></td><td></td><td colspan="2">[HCFC], HC,HFC</td></tr>
<tr><td>Spray</td><td></td><td>[HCFC] HC,HFC</td><td></td><td colspan="2">[HCFC], HC,HFC</td><td></td><td></td><td></td></tr>
<tr><td>One-Component</td><td></td><td></td><td></td><td colspan="2">HC, HFC</td><td></td><td></td><td></td></tr>
<tr><td>Extruded Polystyrene</td><td>Board</td><td></td><td></td><td>HC, HFC</td><td colspan="3">HCFC, CO_2, HFC, HC</td><td></td><td>HCFC, CO_2, HFC</td></tr>
<tr><td rowspan="3">Phenolic</td><td>Boardstock</td><td></td><td></td><td></td><td colspan="2"></td><td></td><td></td><td></td></tr>
<tr><td>Disc. Panel</td><td></td><td></td><td></td><td colspan="2">HFC</td><td></td><td></td><td>HFC</td></tr>
<tr><td>Disc Block</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">HC, HFC</td></tr>
<tr><td rowspan="2">Polyethylene</td><td>Board</td><td></td><td></td><td></td><td></td><td></td><td>HC</td><td></td><td></td></tr>
<tr><td>Pipe</td><td></td><td></td><td></td><td></td><td></td><td></td><td>HC</td><td></td></tr>
</table>

[ ] denotes mainly developing countries

nalization of HCFC usage patterns may be required post-2015 to comply with the anticipated freeze in consumption under the Montreal Protocol. The maturity of alternative technologies and conversion costs are likely to be decisive factors in prioritizing further substitution.

7.2.1.2 Developed Countries

In developed countries, ongoing HCFC use in polyurethane applications is limited to the smaller contractors (e.g. those applying spray foam). HCFCs also continue to be used for extruded polystyrene, particularly in North America. These uses are still in line with the Montreal Protocol. However, in some regions (e.g. the European Union), HCFCs have been phased out early and replaced by hydrocarbons, HFCs (HFC-134a, HFC-152a, HFC-245fa and HFC-365mfc/HFC-227ea blends) or CO_2-based blowing-agent systems, where these are appropriate. The approach adopted by different countries varies significantly, with some governments pursuing bans on use in specific foam sub-sectors, and others pursuing either a substance-based approach or relying on the Montreal Protocol timetable to ratchet down supply. There are often combinations of any two of these approaches and, sometimes, even all three. Although there have been regional difficulties, reductions in HCFC use are occurring in most developed countries. There is a slight complication, however, with the potential import of polyurethane systems containing HCFCs when developing countries are the source, since these are not discouraged by the Montreal Protocol itself.

Table 7.5. Blowing-agent selection by product type and application area – non-insulation.

Foam Type		**Application Area**					
		Transport		**Comfort**		**Packaging**	**Buoyancy**
		Seating	Safety	Bedding	Furniture	Food & Other	Marine & Leisure
Polyurethane	Slabstock	CO_2 (water LCD*) CH_2CL_2		CO_2 (water, LCD) CH_2CL_2		CO_2 (water, LCD) CH_2CL_2	
	Moulded	CO_2 (water LCD, GCD)			CO_2 (water LCD, GCD)	CO_2 (water LCD, GCD)	
	Integral Skin		HCFCs, HCs, HFCs, CO_2 water			HCFCs, HCs, HFCs, CO_2 water	
	Injected/ P-i-P						CO_2 (water)
Extruded Polystyrene	Sheet					HCs, CO_2, (water)	
	Board						HCFCs CO_2, HFCs
Polyethylene	Board					HCs	HCs

* liquid carbon dioxide technology

7.2.2 CO_2 (including CO_2 (water))

CO_2 and CO_2 (water) are widely used as blowing agents in many non-insulating polyurethane foam sectors. These include flexible slabstock, moulded foam for transportation, footwear and integral skin foams for transport and furniture applications. In many cases, this blowing-agent technology has been the direct replacement for CFC-11.

This technology is not widely used for insulating polyurethane foams since it gives a lower thermal performance. However, there is emerging work in Japan (Ohnuma and Mori, 2003) on the potential use of super-critical CO_2 for some polyurethane spray foam formulations. The commercialization of this technology is being monitored closely, but most recent reports suggest that some subsidy for equipment investment may be required to stimulate market acceptance.

As a sole blowing agent or in conjunction with co-blowing agents (ethanol, hydrocarbons, acetone, isopropanol, water), CO_2 is principally used in XPS (extruded polystyrene) in regions which have already chosen to phase out HCFCs, and where the market considers the loss in thermal efficiency to be offset by the other inherent properties of XPS boards (moisture resistance, mechanical strength, compressive strength, dimensional stability and resistance to freeze-thaw deterioration). Higher densities or lower conversion may partially or wholly offset the low cost of CO_2 itself in some XPS applications. Furthermore, the use of CO_2-based blowing-agent systems is technically challenging, and not suitable for many existing manufacturing lines, particularly where such lines require substantial investment. These considerations put the technology out of reach for many small and medium enterprises.

Nevertheless, the use of CO_2-based technology for XPS is likely to continue to grow as long as the cost of alternative HFC solutions remains high.

7.2.3 Hydrocarbons

In rigid polyurethane insulating foams, the use of cyclopentane and various isomers of pentane to replace fluorocarbons has very rapidly gained wide acceptance in all regions. For building applications, normal pentane is the most widely used isomer. Normal pentane and cyclopentane/isopentane blends are typically used in rigid polyisocyanurate insulating foams in North America. In domestic refrigerators and freezers, cyclopentane was introduced in Europe in 1993 and it has gained acceptance in all regions except the USA, where existing VOC-emission regulations and stringent fire safety codes make the conversion of existing facilities uneconomical. The technology has been refined and optimized for cost-effectiveness and a blend of cyclopentane/isopentane is gaining prominence. Despite the higher thermal conductivity compared to foams based on HCFC-141b or HFC-245fa, appliances based on the hydrocarbon option attain the highest A+ energy efficiency category under the EU's stringent requirements. The technology provides good processing and other foam characteristics. The safety precautions for processing this flammable blowing agent are also well established. However, the cost of the necessary safety measures and the management infrastructure required can be uneconomical for small enterprises.

For rigid XPS insulation foams, hydrocarbons can be used as co-blowing agents with either CO_2- or HFC-based systems. Typically based on isomers of butanes or pentanes, they provide processability and in some cases contribute to the insulation value of the foams. The use of these flammable blowing agents is, however, limited due to their adverse influence on fire performance. Nonetheless, there is considerable uptake in Japan, where specific fire test configurations support the blowing agent's use.

7.2.4 HFCs

HFCs have been under consideration as replacements for HCFCs since the early 1990s. However, the absence of materials with an appropriate boiling point initially limited the potential for their use to gaseous processes such as those processes used to manufacture XPS (HFC-134a, HFC-152a). More recently, the development and commercialization of HFC-245fa and HFC-365mfc has enabled a wider range of processes to be encompassed by HFC technologies. However, the price of HFCs (particularly the newer materials) has ensured that HFCs are only used where they are perceived to be absolutely necessary – most notably where product liability, process safety and/or thermal performance benefits are evident.

As a consequence, it is now estimated that global HFC consumption in the foam sector is unlikely to exceed 75,000 tonnes annually in the period to 2015. This represents around 20% of the consumption that would have been associated with CFCs in the absence of the Montreal Protocol and around 50% of the uptake anticipated when the situation was first reviewed at the Petten Conference in 1999.

However, cost is a complex component, since it can be applied at both bulk substance level and at system formulation level. Box 7.1 illustrates the point.

7.3 Foam sub-sector analysis

7.3.1 Selecting blowing agents in applications where HFCs are considered

7.3.1.1 Thermal insulation foam

Building (polyurethane, phenolic, extruded polystyrene)

The construction industry is very cost-competitive and the use of HFCs in polyurethane rigid foams will naturally be restricted to those applications and circumstances where other blowing agents are unsuitable because of safety or performance factors. It is likely that the largest sector using HFCs will be the spray foam industry, because of safety constraints on the use of pentane and the product performance limitations (thermal conductivity and density) when using CO_2 (water). Another major sector, and one where small and medium enterprises are heavily involved, is the production of discontinuous sandwich panels. Here again, HFCs are expected to be the major blowing agent because of the high costs of flame-proofing such equipment for the use of HCs. The adoption of HFCs will only occur in the larger boardstock or continuously-produced sandwich panel sectors, where the end product has to meet very stringent flammability specifications. Although foams based on HFCs typically display superior insulation properties per unit thickness, this is only likely to be a decisive factor where there are significant space limitations[2]. One such sector may be the strategically important renovation market.

Box 7.2 illustrates the significance of different approaches to comparing thermal insulation and, in particular, the effect on lifetime CO_2 emissions of selecting different insulation materials with a constant thickness.

For phenolic systems used in the continuous boardstock sector and the discontinuous block and panel sectors, the considerations are very similar. However, because of the intrinsic fire properties of the foam matrix, the use of hydrocarbons has been found to be more feasible (c.f. progress in Japan with isobutane) than had been originally anticipated for foams used typically in fire-sensitive applications. A further factor influencing the non-selection of HFCs as blowing agents is the fact that phenolic chemistry does not offer the co-blowing options available to polyurethane systems. Accordingly, the blowing-agent component of formulations can be in excess of 10% in some instances, with significant cost implications. Nonetheless, the use of HFCs (particularly HFC-365mfc/HFC-227ea blends) is expected continue in a significant proportion of the phenolic foam market for the foreseeable future, particularly if fire performance standards continue to become more stringent, as is currently the case in Europe.

As with rigid polyurethane foams, the use of HFCs in rigid extruded polystyrene foams tends to be restricted to circumstances where other blowing agents are unsuitable (because of safety, processability and/or performance), as their price makes them too costly for many market segments. Systems based principally on HFC-134a can match HCFC-142b thermal conductivity, and are used in applications where insulation value and/or space are at a premium. HFC-134a is also long lived in the foam and provides excellent insulation performance over time (Vo and Paquet, 2004), making it suitable for applications with long lifetimes. HFC-152a, on the other hand, leaves the foam fairly quickly, but has improved processability. This makes it easier to use for the creation of large cross-sections, where the use of CO_2- or HFC-134a-based systems are technically challenging and beyond the capabilities of many small and medium enterprises today.

Appliances

Because of the challenging insulation and structural characteristics required for refrigerator and freezer insulation, no proven not-in-kind technologies are available at present that can meet all the requirements. Vacuum insulation panels have been used (as a supplement to the insulating foam) in limited quantities and are increasingly being used in critical locations in cabinets in Japan. However, high costs continue to limit their use to applications where thermal performance is of paramount impor-

[2] To facilitate the use of HFCs, BING has carried out studies (FIW, 2002) to define the ageing characteristics of the foams as required by CEN standards.

Box 7.1. Relationship between blowing-agent cost and foam cost

The thermal insulation market is a complex competitive environment but, in common with most suppliers to the construction industry, cost pressures in the insulation sector are ever-present. These pressures apply to all insulation types and the major driver is often the cost per unit of thermal resistance provided.

The blowing agent for thermal insulating foams is usually a significant contributor to thermal performance (Vo and Paquet, 2004). A more expensive blowing agent can therefore be justified if the benefit in thermal resistance can offset the additional cost. This has often been the case in traditional uses of CFCs. While more expensive than hydrocarbons and other alternatives, they provided cost-effective insulation because thinner boards could be used. Although the thermal performance of HCFC blown foams was initially slightly worse than their CFC blown equivalents (UNEP-FTOC, 1995) system improvements soon restored parity after the transition from CFCs (UNEP-FTOC, 1999). However, this was in a situation where HCFCs were trading at prices similar to traditional CFC levels.

For blowing agents with significantly higher prices, such as HFCs, there is no obvious way to provide a competitive insulation product in highly cost-sensitive markets other than reducing the amount of expensive blowing agent used (e.g. by using a blend with hydrocarbon) or reducing overall foam density without affecting the product properties (e.g. compressive strength). In practice, there is no easy route to lower-density products with the same performance levels. However, co-blowing with CO_2 (water) has been an option for several HFC-based technologies, albeit with some upper limits imposed by the performance requirements of the product.

In a traditional foam formulation (e.g. with HCFC-141b), blowing-agent levels of between 6% and 12% by weight are the norm. In the case of polyurethane foam blown with 8% blowing agent, the following scenario could be envisaged:

Polyurethane chemical costs	€1500 /tonne
Blowing-agent (1) cost	€1000 /tonne
Blowing-agent (2) cost	€4000/tonne

With an 8% loading and 32 kg/m^3 density, the change in blowing agent from (1) to (2) would push up the cost of foam by 15%. However, if it were possible to reduce the expensive blowing-agent loading to 4% by co-blowing with CO_2 (water), the impact on cost would drop below 10%. These apparently small adjustments have been demonstrated to be critical in the competitive market place and the prudent use of expensive blowing agents has resulted in a reduction in the predicted uptake of HFCs worldwide.

Of course, there are insulation foam applications where the market is less sensitive to blowing-agent cost. This is particularly the case when a specific blowing-agent choice makes it possible to adopt a more economic building solution. This can be the case in some renovation markets as well as for exposed foam products such as pipe insulation.

tance. Polyurethane foam therefore continues to be used for the bulk of this application.

Although hydrocarbons are being successfully used as the blowing agent for refrigerator and freezer production in most regions of the world, there are some situations, most notably in North America, where manufacturers have chosen HFCs as the preferred replacement for ozone-depleting substances in this application. Their reasoning is that HFCs can provide the superior insulation performance needed to meet existing, stringent, energy standards while meeting customer demand for storage capacity, product dimensions and cost. Using HFCs as blowing agents also precludes the need for the prohibitively large investments needed to meet stringent safety codes and VOC-emission regulations in existing facilities. These considerations can outweigh the advantage of lower material costs and lower direct GWP associated with the hydrocarbon alternatives. The use of HFCs as blowing agents for refrigerator foam was minor prior to 2003. However, it has since increased significantly in North America as HCFC-141b has been replaced, and may also increase in some other regions as HCFCs are ultimately phased out (UNEP-FTOC, 2003). The primary HFC used in North America is HFC-245fa.

With respect to the global warming implications of this choice, analyses of total equivalent warming impact (TEWI) and life cycle climate performance (LCCP) have indicated that, because of the superior insulating and ageing characteristics

Box 7.2. Choosing insulation for new building projects

The choice of insulation type can be impacted by many factors, including long-term thermal performance, efficient utilisation of space, cost and ease of installation. For most new buildings, a minimum energy performance is required for the building fabric (usually stated in terms of U-value or R-value). All insulation types can normally meet this minimum standard, but different thicknesses will often be required. Where space is constrained (constant thickness), this can pose a problem and energy penalties can be paid as shown below.

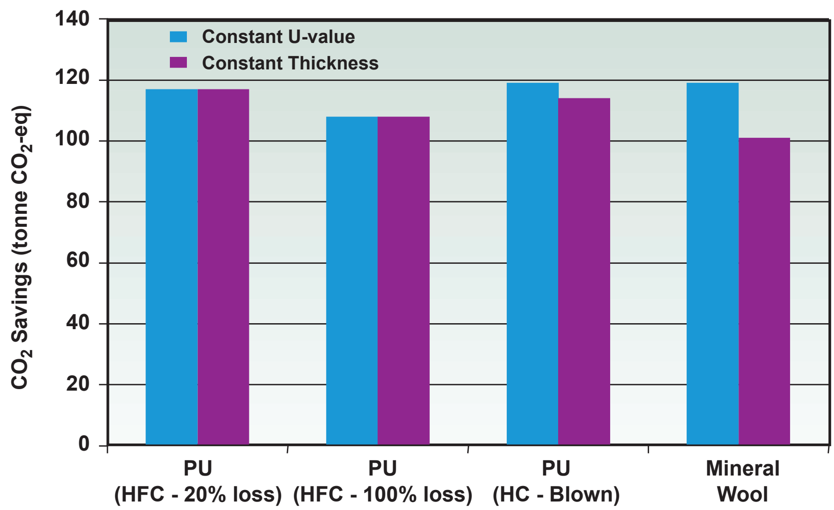


Figure Box 7.2. Lifetime CO_2 savings for a typical building fabric insulation measure (domestic - Netherlands)

However, where constant U-value can be maintained, blowing-agent choice is often the decisive factor. The graph illustrates the impact on total CO_2-equivalent savings of different loss assumptions for an HFC blowing agent. The impact of this direct emission is usually greater than any embodied energy consideration if any significant blowing-agent losses occur during the production, use or decommissioning of the foam.

Since the given parameters (e.g. thickness constraint) vary according to the application, it is vitally important that such an analysis is carried out on an application-by-application basis rather than at product level in order to make the most appropriate decision. Where the level of insulation permitted is generally low, the differences in overall lifetime CO2 savings can be substantial between different insulation materials.

when using HFC-245fa, the use of an HFC blowing agent can be at least neutral in most markets, or even beneficial when compared to the use of a hydrocarbon blowing agent (Johnson, 2004).

Some other appliances also rely on the insulation and structural benefits of insulating foam. Water heaters and commercial refrigerators and freezers (including display units), along with insulated picnic boxes (or coolers) and various flasks and thermoware, are substantial markets in this sector. The requirements and options are generally similar to those for domestic refrigerators and freezers. However, in some cases, the space requirements are not as stringent. The average operating temperature for water heaters is higher than for refrigerators and freezers and, at these temperatures, the energy disadvantage of hydrocarbon blowing agents is not significant. Most manufacturers are therefore using hydrocarbons or CO_2 (from water) in such applications as substitutes with zero ozone-depleting potential.

7.3.1.2 Product and process safety

Process Safety Issues: Toxicity and Flammability

The production and use of foams involve important safety considerations. These often play a role at the manufacturing stage and include worker exposure and flammability issues.

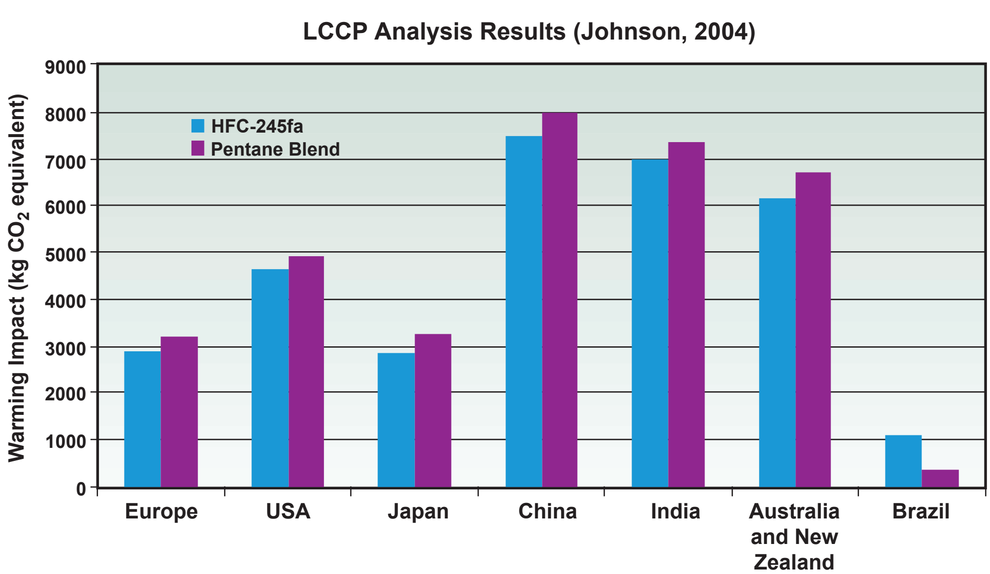
In flexible polyurethane foams, a technically suitable alternative to CFC-11 as an auxiliary blowing agent is methylene chloride (dichloromethane). However, it is classified as Carcinogen category 3 in the EU and OSHA has established exposure standards in the USA. Nevertheless, HFCs are not

Box 7.3. LCCP analysis results for a refrigerator

A summary of the results of an LCCP analysis conducted on a European refrigerator is shown here. The two products compared were identical in all respects, except for the blowing agent (BA), which was HFC-245fa in one product and a cyclo/iso-pentane blend in the other product. This analysis assumed that 90% of the blowing agent would be recovered or destroyed at end of life by processing refrigerators in appropriate facilities as required by EU directives. In the table below, a second column was added, extending the analysis to include a case where only 50% of the remaining blowing agent was recovered or destroyed at end of life. Note the dominance of the CO_2 emissions due to energy consumption of the product in both cases. Emissions are in kg CO_2 equivalent.

	HFC-245fa (90% recycled)	HFC-245fa (50% recycled)	Pentane Mixture
BA Production Energy	4.5	4.5	1.2
BA Production Emissions	2.8	2.8	0
BA Transport Energy	0.17	0.17	0.05
Refrigerator Production: BA Emissions	18.7	18.7	0.1
Refrigerator Production Energy	5.0	5.0	5.0
Refrigerator Transport Energy	8.0	8.0	8.0
Refrigerator Use Energy	2697	2697	3198
Refrigerator Life BA Emissions	68.8	68.8	0.1
Refrigerator Shredding Emissions	17.0	85	0.1
Long-Term Emissions	67.9	339.5	0.2
Total Impact	2882	3230	3212

The analysis was extended to cases in which it was assumed that the product was used in several different regions of the world. Note that the net global warming impact is lower for the HFC-245fa product in all regions considered, except Brazil (where most of the power is from hydroelectric sources). In this analysis, it was assumed that 90% of decommissioned refrigerators in Europe would be recycled, with recovery or destruction of the blowing agent. The levels of recycling or destruction assumed for other countries were 50% for Australia, New Zealand, and the US; 95% for Japan; and 20% for China, India, and Brazil.



considered to be alternatives to methylene chloride in this application (UNEP-FTOC, 2003).

The use of hydrocarbons in foam manufacture can be a major issue. The use of pentane for rigid polyurethane and polyisocyanurate foams has required significant re-engineering of production sites, as well as worker training to prevent explosive mixtures occurring. Although these investments can be amortized quickly over a large production volume in the larger enterprises, the conversion cost can be prohibitive for small and medium enterprises in both developed and developing countries. The safety record for the use of pentane has been good for over ten years and there have been very few incidents. By contrast, the use of highly flammable blowing agents in the extruded-polystyrene sheet sector to replace CFC-12 has resulted in several incidents, especially in developing countries. In the extruded-polystyrene-foam board sector, handling improvements in, for example, Japan and Europe have resulted in the use of such flammable mixtures without incident (UNEP-FTOC, 2003). Significant concern exists in Europe and other areas about the safety of hydrocarbons in applications involving the use of polyurethane spray foam (Box 7.4).

Small and medium enterprises (SMEs) in both developed and developing countries can have particular difficulty with handling hydrocarbons. Whilst the unit costs and operating costs associated with hydrocarbons are low, the capital costs involved in converting manufacturing plants to comply with national regulations for the handling of flammable blowing agents may be prohibitive, particularly for SMEs in developed countries where no financial support is available. Even in developing countries, the Multilateral Fund limits the grant available for conversion by the adoption of a funding threshold, often leav-

Box 7.4. Process safety and renovation: The example of polyurethane spray foam in Spain

Although work continues on the safe use of hydrocarbon systems in polyurethane (PU) spray foams, the current commercial reality in Spain is that the only viable alternatives to HCFC-based systems for closed cell insulating foams are HFC-based. This has resulted in the need for well-coordinated transition programmes, not all of which have proceeded smoothly. Spray foam systems provide unique opportunities for the renovation of buildings, particularly roofs in both the residential and commercial/industrial sectors. The building style in Spain and other Southern European countries lends itself to the use of PU spray foam for upgrading the insulation of flat roofs. The key advantage is that there is no need to 'tear off' the existing roof material prior to the application of spray foam. This has a critical impact in the installed cost of a re-insulated roof, as shown in the table below:

Insulation option	Cost/m²
PU spray foam	€ 21.24
Mineral wool	€ 49.20
Extruded polystyrene (CO_2 blown)	€ 48.24
Expanded polystyrene	€ 47.16

In Spain, very few houses built prior to 1979 have any significant insulation in them. The estimated number of houses in this category is around 7.3 million. The policy objective of the Spanish government is understood as the renovation of at least 5% of this total between 2005 and 2012 (Energy Efficiency & Economy Strategy 2004–2012 – Buildings Sector E4 Working Document, July 2003). If the rate of renovation is constant, this will equate to just over 45,000 houses per year.

The budget set aside for the improvement of the building fabric (both residential and commercial/industrial) is € 2,780 million, although this will include the installation of new glazing and other fabric measures. This represents an average investment allocation of just over € 30 per m2. If the roofs of 45,000 houses per year were re-insulated with PU spray foam, the overall cost of the work, assuming an average roof size of 100m2, would be € 776 million (i.e. 28% of the total budget). This seems a reasonable proportion of funds to be allocated for this purpose bearing in mind the resulting CO_2 saving. However, if other insulation technologies were used as an alternative to PU spray foam, either the percentage of the total budget allocated to roof renovation would need to be increased to more than 50% of the total budget, thereby forfeiting other options, or the roofing area insulated per year would be less. The figure in this box illustrates the impact, given a constant budget allocation (28%), on CO_2 savings in lifecycle terms of the application of the different technologies. The lifetime of any roof renovation measure is assumed to be 15 years, given the durability of the waterproof membranes used, and it is the same for all options.

Box 7.4. Continued

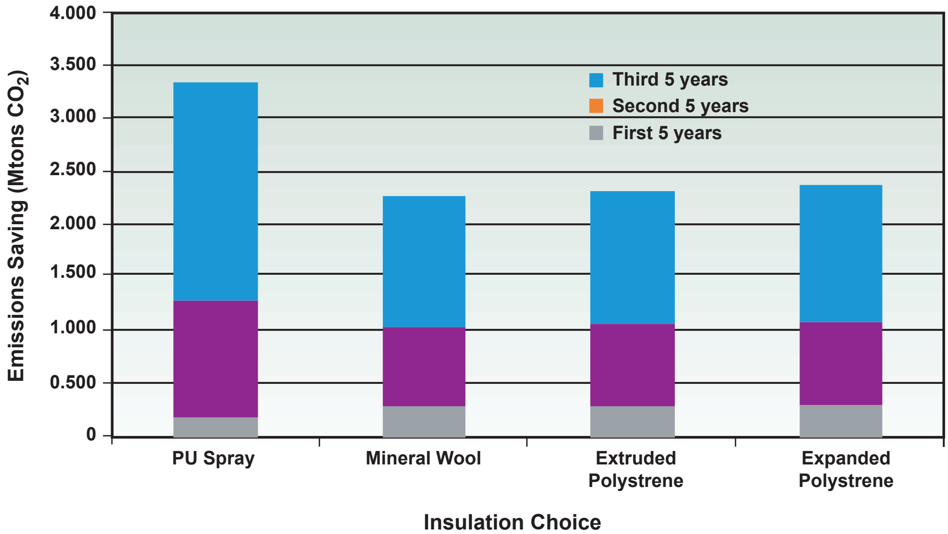


Figure Box 7.4. Cumulative renovation programme savings – five-year intervals [Insert from o/leaf]

The use of PU Spray foam involves the direct emission of HFCs (15%) during application, with the result that the CO_2 savings during the eight-year implementation period of the programme are offset, making them lower than for the other options. However, in the subsequent seven-year period, the increased market penetration of PU spray foam in the constant budget scenario makes the delivery of overall savings much more efficient. In the Spanish case, the prediction is that more than an additional 1 Mtonnes of CO_2 would be saved during the lifetime of the measures. These are important additional savings for a government faced with significant greenhouse-gas emission challenges and they explain why the Spanish are keen to see the retention of the HFC-based PU spray technology option.

(Source: Ashford and Vetter, 2004)

ing the enterprise significantly short of funding for a hydrocarbon route. Within the MLF system, hydrocarbons only become viable when the CFC-11 consumption reaches about 50 tonnes per annum. Smaller enterprises may therefore be obliged to use HFCs (or more likely HCFCs) despite their negative impact on operating costs and, potentially, the environment (UNEP-FTOC, 2003). In addition, the rigorous operating procedures required to store, handle and process flammable blowing agents safely may prove too much of a challenge for many SMEs, particularly in developing countries.

<u>Product safety issues: End-product Fire Performance and Integral Skin Quality</u>

The use of a flammable blowing agent can also have an effect on the fire properties of the end product. This is particularly important in the building/construction sector. Some of the most stringent fire product safety standards are not yet being met by hydrocarbon technology and the use of HFCs is envisaged for these applications (UNEP-FTOC, 2003).

There are other safety reasons why blowing-agent choice can be important. For example, in integral skin foams for the automotive sector, the combination of skin quality and impact absorbency is critical for steering wheel and facia applications. The use of in-mould coatings has been one approach used to combat the poorer quality skins created by some alternatives. However, there are drawbacks to this approach in terms of costs and processing. In some applications, HFCs are being used to produce skin quality more comparable with that once attained with CFCs and HCFCs.

7.3.2 *Introduction to tables*

Table 7.6 and 7.7 are intended to provide a reliable overview of the issues affecting the selection of insulation materials and, in particular, blowing agents. The tables are believed to be sufficiently comprehensive to provide sound guidance. However, the format does not lend itself to detailed reasoning in all cases. Accordingly, the reader is encouraged to refer to relevant text elsewhere in the chapter or to seek advice from sector experts if the information available requires further clarification or qualification.

Table 7.6. Sub-sector analysis – selection criteria.

Foam type	Not-in-kind options	Non-HFC zero-ODP options	HFC use criteria
Domestic appliances (domestic refrigerator and freezer).	Mineral fibre was widely used in this application until the mid-1970s but was replaced by polyurethane technology because of improved thermal performance and strength. Vacuum panels are emerging but are not used in isolation.	Hydrocarbons (HCs) (especially cyclopentane/ iso-pentane blends)	HFCs are used where space savings and energy savings are paramount or where there are VOC and /or capital investment issues for hydrocarbons (e.g. USA). Benefits provided by (some) HFCs include: • higher insulating value (lower thermal conductivity) at operating temperature than other options, resulting in energy savings; • good thermal conductivity ageing characteristics; • fire safety in manufacturing, often non-flammable atmospheres; • no local pollution effect (classified as non-VOC in some regions); • relatively low investment costs because of the benefits mentioned above. HFCs used are mostly HFC-245fa and some HFC-134a
Other appliances (water heaters, ice makers, display cases, vending machines…)	Again, mineral fibre was used historically, but was replaced by polyurethane technology in the mid-1970s. Mineral fibre is still used in some water heaters where moisture can be driven out routinely.	HCs (pentanes and cyclopentane) are more difficult to use because plants are sometimes set up for more customized manufacture. CO_2 (water) can also be used where foam plays a limited role. In limited applications methyl formate and formic acid in blends with HFC-134a.	
Boardstock: polyurethane, polyisocyanurate, and phenolic	Mineral (glass) fibres, extruded- and expanded-polystyrene boards. Extruded-polystyrene and mineral (glass) fibres are widely used alternatives but are not suited to all building methods.	HCs (n-pentane and cyclopentane) are the predominant choice for cost reasons.	HFCs are used only when warranted by end-product fire performance or specific thermal performance. Benefits provided by some HFCs include: • higher insulating value (lower thermal conductivity) than other options; • fire safety in manufacturing and fire resistance of insulating boardstock. HFCs used include HFC-245fa and HFC-365mfc (and its blend with HFC-227ea).
Continuous and discontinuous panels	Mineral fibres compete as either built-up systems or as steel-faced panels. High densities (>150kg/m^3) are required to achieve strength as panels.	HCs (n-pentanes and cyclopentane) are the predominant choice for cost reasons. In limited applications, CO_2 (water), methyl formate and formic acid in blends with HFC-134a.	HFCs are used where end-product fire performance is an issue with insurers (e.g. LPC full-scale flammability test in UK) or where investment costs for HCs are prohibitive for small and medium enterprises (disc. panels). Benefits provided by some HFCs also include higher insulating value than other options at operating temperatures for applications such as walk-in coolers/cold storage. HFCs used include HFC-134a, HFC-245fa and HFC-365mfc (and its blend with HFC-227ea).

Table 7.6. continued (2)

Foam type	Not-in-kind options	Non-HFC zero-ODP options	HFC use criteria
Spray	No direct alternative	Attempts to commercialize HC technology in the USA but safety concerns remain among SMEs. CO_2 (water) can be used with equipment modification, but leads to the need for higher thickness (cost) to offset insulation and higher density (cost) to improve dimensional stability.	HFCs are currently the predominant option in this sector, providing safety for operators, insulation value and product performance (dimensional stability). HFCs used include HFC-365mfc-based blends, HFC-245fa and HFC-134a.
Blocks	No direct alternative. Mineral fibre is widely used in pipe insulation, although it requires greater space because of its higher thermal conductivity.	HCs (pentanes and cyclopentane) are used successfully for cost reasons. Plant safety can be an issue when making blocks discontinuously.	HFCs may be used where end-product fire performance is an issue. Blends of HFCs and blends of HFCs with pentanes can be a relevant compromise. HFCs used include HFC-245fa and HFC-365mfc-based blends.
Pipe (pipe-in-pipe)	Traditional insulation materials unsuitable for the environment – particularly in district heating (underground) applications.	Cyclopentane	Only rationale for HFC use is safety and/or investment constraints for small and medium enterprises. HFCs used include HFC-365mfc-based blends, HFC-245fa and HFC-134a.
Extruded-polystyrene board	Glass and mineral fibres, wood, cellular glass and other polymeric (urethane and phenolic) foams.	CO_2 or CO_2 with co-blowing agents such as ethanol, HCs, acetone and isopropanol. Most technologies are currently limited in product thickness.	HFCs are used because of more versatile processing. Fire and thermal performance can also have a bearing. HFCs used include HFC-134a and HFC-152a.
XPS panel	Mineral fibres compete as either built-up systems or as steel-faced panels. High densities (>150kg/m^3) are required to achieve strength as panels.	CO_2 or CO_2 with co-blowing agents such as ethanol, HCs, acetone and isopropanol. Most technologies are currently limited in product thickness.	HFCs are used because of more versatile processing. Fire and thermal performance can also have a bearing. HFCs used include HFC-134a and HFC-152a.
XPS pipe	Glass and mineral fibres. Silica, rock wool, slag wool and alumina silica fibres. Polymeric foams. Granular insulation.	None (CO_2-based systems have not been developed).	HFCs offer necessary process versatility together with dimensional stability and thermal benefits. HFCs used include HFC-134a and HFC-152a.

Table 7.6. continued (3)

Foam type	Not-in-kind options	Non-HFC zero-ODP options	HFC use criteria
Transportation (PU and XPS)	No viable alternatives owing to stringent requirements for insulation, structural strength and durability (resistance to vibration)	Hydrocarbons (pentanes and cyclopentane) for polyurethane. No non-HFC alternative for extruded polystyrene.	The thermal benefits can play a role where space is limited. Fire safety in manufacturing can also play a role in some operations. For extruded polystyrene, production versatility is the key. HFCs used include HFC-134a and HFC-152a (for extruded polystyrene). HFCs used include HFC-365mfc-based blend, HFC-245fa and HFC-134a for polyurethane.
Non-insulating foam one-component	Caulk	Hydrocarbons	No ongoing role for HFCs where HC technologies can be managed safely.
Extruded-polystyrene sheet	No real alternative	Hydrocarbons (butane and propane) in conjunction with CO_2.	Very limited use for safety applications HFCs used include HFC-152a.
Automotive integral skin	PVC or leather skin over other substrates. Difficult to achieve same impact performance	CO_2 (water) with and without in-mould coating. Hydrocarbons for high volume and heavy duty productions	Only where safety and investment issues exist for small and medium enterprises. HFCs used include HFC-245fa, HFC-365mfc-based blend and HFC-134a.
Other integral skin	Flexibility and durability difficult to match with other substrates (e.g., EVA shoe soles have low resilience and durability)	CO_2 (water) is a viable option with in-mould coating.	Only where safety and investment issues exist for small and medium enterprises. HFCs used include HFC-245fa, HFC-365mfc-based blend and HFC-134a.
Buoyancy	PVC foams and inflatable buoyancy aids for life jacket	Hydrocarbons are technically feasible but not economically viable due to low production volume.	Only where safety and investment issues exist for small and medium enterprises.

Table 7.7. Sub-sector analysis – emission characteristics.

Foam type	Emissions functions		
	Production/ 1st Year (%)	**Use (%/yr)**	**End of life**
Domestic appliances (domestic refrigerator and freezer).	4 %	< 0.5% per year	Most HFCs will be present. The emission depends on the means of end-of-life management. HFCs may be incinerated (minimum emission) or shredded and sent to a landfill (maximum emission).
Other a ppliances	5 %	< 0.5%	Most HFCs will be present. The emission depends on the means of end-of-life management. HFCs may be incinerated (minimum emission); or shredded and sent to a landfill (maximum emission).
Polyurethane/polyisocyanurate/ phenolic boardstock	6 %	0.5%	Significant portion of HFCs will be present at end of life. Separation for HFC recovery could be difficult and destruction will only be achieved if all combustible materials are treated together in a suitable incinerator.
Panels	5–6 %	< 0.5 %	Most HFC content will be present. Can be reused, reprocessed through a recovery plant or incinerated.
Spray	15 %	0.75%	Significant portion of HFCs will be present. Separation for HFC recovery will be difficult and destruction will only be achieved if all combustible materials are treated together in a suitable incinerator.
Blocks	45% for pipe and 15% for slab.	0.75 % (with impermeable facing materials).	Significant portion of HFCs will be present. Separation for HFC recovery could be difficult in some slab applications (but not for pipe sections). Destruction may only be achieved if all combustible materials are treated together in a suitable incinerator.
Pipe (pipe-in-pipe)	6 %	< 0.25 %	Most of HFCs will be present at end of life. It is feasible to recover the pipe and recover the steel from the pipe section and treat the foam and other plastic components in a suitable incinerator.
Extruded-polystyrene board	15–25% for HFC-134a based XPS. 15–25% for HFC-152a based XPS.	0.75 % +/- 0.25 for HFC-134a based XPS. 15% for 152a based XPS	Significant portion of HFC-134a will be present at end of life. The insulation boards can be re-used if not adhered to substrates. The boards with HFCs can be destroyed in a suitable incinerator.
Extruded-polystyrene panel	25%	0.75% for permeable facer. Negligible for impermeable facer.	Most of HFC-134a will be present at end of life. The insulation panels can be re-used. The panels with HFCs can be destroyed in a suitable incinerator.
Extruded-polystyrene pipe	25 %	0.66%	Significant portion of HFC-134a will be present at end of life. The insulation shells can be re-used. The shells with HFCs can be destroyed in a suitable incinerator.
Transportation (PU and XPS)	5–6 % for PU 25% for extruded polystyrene	0.5 % or negligible due to impermeable facers.	Most of HFCs will be present at the end of life. It is feasible to separate foam with its HFCs and destroy in a suitable incinerator.
Non-insulating foam one-component	100%	N/A	N/A
Extruded-polystyrene sheet	100%	N/A	N/A
Automotive integral skin	100%	N/A	N/A
Other integral skin	100%	N/A	N/A
Buoyancy	10%	2%	Significant portion of HFCs will be present in the foam at end of life. Separation and recovery of foam and HFCs will be difficult because foam is part of composite.

7.3.3 Summary of key themes

(1) The reasons given for the use of HFCs in Section 7.3.1 are replicated by sub-sector in the table.

They can be summarized as follows:
- better thermal performance, leading to enhanced capabilities in space-constrained environments;
- compliance with product fire classifications in applications and regions sensitive to 'reaction-to-fire' issues;
- minimization of risks in processing, particularly when risks cannot be specifically addressed by engineered solutions or when costs are prohibitive (e.g. SMEs);
- cost-effective application options, particularly important in the building renovation sector where costs may determine whether insulation is applied at all.

(2) Drawbacks to using HFCs remain:
- concerns about the ability to demonstrate objectively the environmental neutrality or benefit of using an HFC option, particularly for building applications;
- stakeholder concern about the growth of HFC use;
- cost implications of using HFCs in highly competitive markets where there is little, if any, return on the investment.

(3) Once an HFC technology has been selected, there are several strategies for minimizing emissions:
- optimization of the formulation to minimize HFC use (e.g. by using co-blowing agents);
- design of the product for low blowing-agent losses during the long use phase;
- design of the product for ease of processing at end of life (e.g. through greater use of pre-fabricated elements).

7.4 Blowing agents: use patterns and emissions

7.4.1 Quantifying consumption and establishing business as usual (BAU)

The anticipated growth drivers for foam use were discussed in Section 7.1.5. The three main growth factors driving foam use can be summarized as:
1. overall economic activity;
2. insulation usage per unit of activity (i.e. energy standards or costs);
3. changes in the respective market shares of foams and fibrous insulation.

Blowing-agent selection can have an influence on at least the two latter factors listed, as described explicitly in the sub-sector analysis. The summary of 'key themes' specifically explain the reasons why HFCs might be used. These include thermal performance, product/process safety and cost. It is important to note that cost appears as both a positive and a negative driver in terms of HFC selection, reflecting the fact that, *in defined applications*, HFC use can have specific cost and environmental benefits, even though the basic cost of the HFC and its global warming potential would intuitively indicate otherwise. An additional factor with a potentially significant effect on use patterns is local regulation. However, one of the challenging aspects of determining the impact of such regulation is that most potential legislation is still in the future and the full implications on HCFC substitution are still to emerge. Accordingly, in the absence of detailed information, future regulatory impacts cannot therefore be considered to be part of the BAU scenario.

One-component foams have been a particularly high-profile use of HFCs (indeed, the primary use) in foams over recent years. Since OCFs are totally emissive in their application, the impact on short-term HFC emission assessments has been profound. However, alternative technologies do exist and have only been limited in their market penetration by initial safety concerns. It seems fairly certain that HFC use in this sector will be phased out within the next ten years, and the current draft EU regulation on fluorinated gases reflects this reality. Accordingly, this eventuality is included in the BAU case. Nonetheless, it is worth noting in passing that the role of one-component foams in improving the air tightness of buildings is possibly one of the largest single potential contributors to overall energy efficiency improvement.

For insulating foams themselves, the situation with respect to HFC usage for the European Polyurethane Foam industry is covered by Jeffs *et al*. (2004). Similar tables have been generated for the ten other regions of the world on the basis of the assessment carried out by the Foams Technical Options Committee (UNEP-FTOC, 2003). These have been further developed to account for all fourteen identified blowing-agent types in the insulated foam sector (Ashford *et al*., 2004ab). These are shown in Table 7.8.

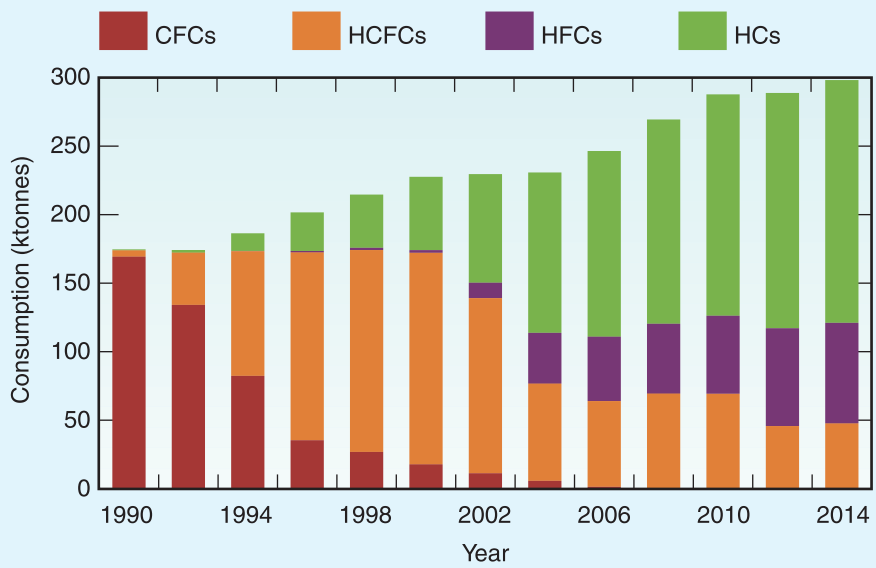
The resulting assessment of the global consumption of blowing agent is shown in the Figure 7.2, which illustrates the overall growth in consumption for the period to 2015 and how the newer blowing-agent options (HCs and HFCs) are replacing the ozone-depleting substances used previously (CFCs and HCFCs).

To generate substance-specific assessments, assumptions about the split between HFC-245fa usage and HFC-365mfc usage in competing markets are required. They have been made possible, at least in part, by the patent situation in North

Table 7.8. Identified blowing agents in the insulated foam sector.

CFCs	*HCFCs*	*HFCs*	*Hydrocarbons*
CFC-11	HCFC-141b	HFC-245fa	n-pentane
CFC-12	HCFC-142b	HFC-365mfc	isopentane
	HCFC-22	HFC-134a	cyclopentane
		HFC-152a	isobutane/LPG
		HFC-227ea	

Figure 7.2. Total blowing-agent consumption by type (1990–2015) - (aggregated)



America, where the use of HFC-365mfc has been *de facto* prevented by the decision of the sole licence holder to focus entirely on HFC-245fa. This has further implications for the use of HFC-227ea in foam applications since it is used exclusively in blends with HFC-365mfc within the foam sector.

An additional element of uncertainty is the split between n-pentane, iso-pentane and cyclo-pentane usage in the hydrocarbon-based sector of the market. Where specific regional information is available, this has been included in the models. However, for the most part, assumptions have been made based on practices in other regions or similar usage sectors. In any event, the total hydrocarbon emissions and banks are unaffected by this approach and the uncertainty has little impact on greenhouse-gas emission assessments.

7.4.2 Discussion of business-as-usual scenarios

Overall HFC usage

At the Petten Conference (Ashford, 1999), it was estimated that the global uptake of HFCs in foams would be around 75,000 tonnes by 2004, with further growth to 115,000 tonnes in 2010. This was also reflected in emissions estimates for Europe at that time of 13 Mtonnes CO_2-eq (March, 1998). Since then, however, it has become increasingly apparent that the cost of the relevant HFCs has driven a high level of innovation for alternatives and, in particular, blends which make best use of HFC properties without being totally reliant upon them (e.g. co-blowing with CO_2 (water) for spray foam applications in the United States). The resulting estimate for 2010 is now approximately 57,000 tonnes, rising to just under **73,000 tonnes by 2015**, and the re-appraisal of European emissions to below 10 Mtonnes CO_2-eq (Preamble to draft EU F-Gas Regulation, European Commission (2003)) is a further reflection of this realignment.

Ongoing HCFC usage in developed and developing countries

As a result of Montreal Protocol controls, the use of CFCs has dropped from more than 75,000 ODP tonnes in 1995 to around 10,000 ODP tonnes in 2002. The use of CFC blowing agents in developing countries is declining, but is likely to continue until 2005–2008. According to the TEAP HCFC Task Force Report (UNEP-TEAP, 2003), HCFCs are likely to play a continued role as 'transitional substances' in insulating and in integral skin foams. HCFC-141b is the most widely used blowing agent in the foam sector, with global demand at approximately 110,000 tonnes in 2001. Because it is banned for use in foams or scheduled for imminent phase-out in most developed countries, HCFC-141b consumption will drop significantly to approximately 28,000 tonnes in 2003–2004. However, HCFC-141b will still be considered a viable replacement for CFCs in developing countries and demand is expected to increase steadily to approximately 40,000 tonnes by 2015.

In the foam sector, demand for HCFC-142b and HCFC-22 is significantly lower than demand for HCFC-141b. Global demand for HCFC-142b was approximately 24,000 tonnes in 2001. That same year, global demand for HCFC-22 was approximately 9,000 tonnes. The demand for HCFC-142b is primarily based on the production of extruded-polystyrene foam in North America and Japan. HCFC-22 is also used, to a lesser degree, in polystyrene- and polyurethane-foam applications in North America. With the exception of HCFC-22 in Latin America, HCFC-142b and HCFC-22 consumption in developing countries is very low, although some use of HCFC-22 is occurring as a blend with HCFC-141b in integral skin foams. Once these chemicals are phased out in the foam sector in North America

(2010), their combined consumption in foams is expected to be less than 1,000 tonnes and to remain close to or below that level until 2015.

One of the key factors in defining the business-as-usual scenario related to the percentage of the phase-out of extruded polystyrene in the US foam sector in 2010 that would be dependent on the uptake of HFCs. This remains an extraordinarily difficult parameter to predict and a reasonably conservative estimate of 65% has therefore been adopted.

Finally, the business-as-usual scenario needs to address HFC demand assumptions beyond 2015 in order to establish a complete picture of the likely emissions scenario over the full lifecycle (up to 50 years) of foam products manufactured and installed in the period through to 2015. Beyond 2015, it is known that HCFC consumption in developing countries will be frozen under the Montreal Protocol and will be phased out by 2040. Accordingly, it is assumed that the decline is linear between 2030 and 2040. For HFC use beyond 2015, there is less certainty, but the degree of innovation that has marked the last 20 years would suggest that the foam industry is unlikely to be reliant on HFCs beyond 2030. Accordingly, the business-as-usual analysis proposes a freeze in consumption at 2015 levels and a linear decline in use between 2020 and 2030.

7.4.3 Business-as-usual emission projections and existing uncertainties

The development of interest in blowing-agent emissions from the foam sector was initially driven from within the Montreal Protocol process. Although this protocol operates in legal terms on a 'production/consumption' basis, the parties have never lost sight of the fact that three of the central clauses of the preamble to the protocol refer explicitly to controlling emissions (UNEP, 2003). Given this background, the parties have tended to encourage the technical and economic review of methods for reducing emissions from end uses involving ozone-depleting substances. In two key areas – refrigeration and foams – these opportunities are particularly significant because of the encapsulation and delayed release of the respective refrigerants and blowing agents. In promoting the consideration of these options, the protocol has been very careful not to mandate such emission reduction strategies, recognizing that these decisions are for individual parties or groups of parties.

The UNEP Foams Technical Options Committee (UNEP-FTOC, 1999) and, more latterly, the Task Force on Collection, Recovery and Long-term Storage (UNEP-TEAP, 2002ab) have addressed the issue of release profiles from foams. These have formed the basis for more recent modelling work (Ashford *et al*., 2004ab). However, efforts continue to be made to update specific emission functions where new evidence supports such revision (see Table 7.7 for the latest emission functions). The recent work of the extruded-polystyrene industry has been particularly noteworthy in this respect (Vo and Paquet, 2004; Lee and Mutton, 2004). This assessment has re-evaluated emission losses during the use phase of extruded polystyrene at 0.75% per annum against a previous estimate of 2.5% per annum.

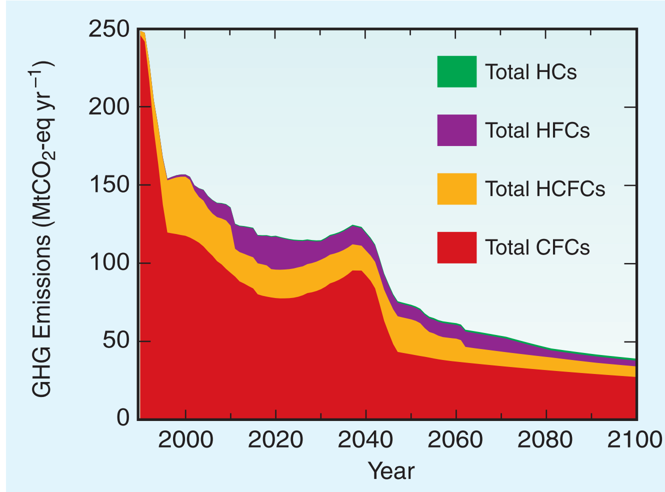


Figure 7.3. Business-as-usual emissions by blowing-agent type for the period 1990–2100

Figure 7.3 emerges from the adoption of these emission functions for the business-as-usual scenario and the most recent scientific values for GWPs presented in Chapter 2.

Some significant trends emerge. The increased CFC emissions peak in the period between 2030 and 2050 reflects the impact of decommissioning CFC-containing products from buildings. The business-as-usual scenario does not envisage any recovery of the blowing agent from these sources. However, the continuation of CFC emissions beyond 2050 illustrates that considerable levels of CFCs are expected to be re-banked in landfill sites (other end-of-life options include re-use, shredding without blowing agent recovery and shredding with blowing agent recovery). The assumption in the case of landfill is that the initial losses from foams are not excessive. Work carried out by the Danish Technical University on losses from refrigerator foam during shredding and landfill suggests overall losses in the range of 20% (Scheutz and Kjeldsen, 2001). At first sight, this seems low. However, if one takes into consideration the fine-celled structure of these foams and the fact that some blowing agent is often dissolved in the matrix, it becomes more reasonable to assume losses of this order for most landfill processes. In cases where car shredders are used, there is a third potential factor, since the foam particles generated through such shredders tend to be 'fist-sized' and do not represent a substantial increase in surface area to volume. This contrasts with European and Japanese shredders, which are designed to maximize surface area and encourage the release of blowing agent under controlled conditions. The 'fist-sized' pieces are more likely to mirror the type of debris obtained from building demolition processes and it is for this reason that the parallel is drawn for modeling purposes. The assumption, however, involves a high level of sensitivity. Figure 7.4 illustrates this sensitivity by considering what the emissions forecast would look like if, in a worst-case scenario, 100% of blowing agent was emitted at the

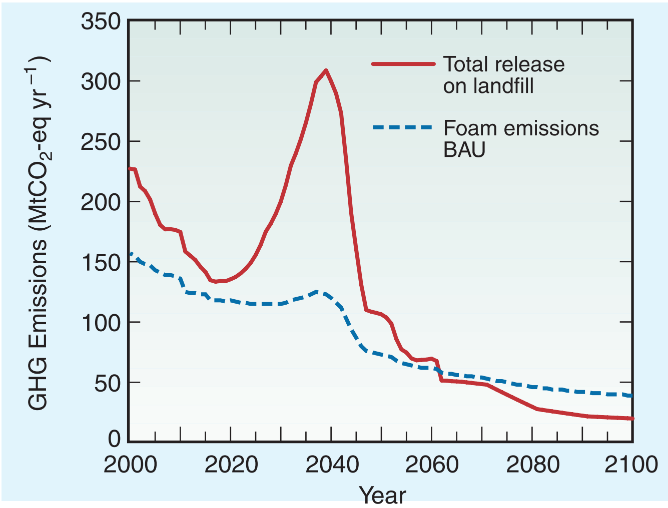


Figure 7.4. The impact of differing initial land-fill release assumptions on overall emission patterns

time of landfill.

This scenario, of course, means that the impact of blowing-agent emissions would be more concentrated and more severe during the period from 2030 to 2050. The uncertainty also indicates the need for further work in this area. What the adoption of a relatively conservative loss rate for landfill does ensure, however, is that any predicted savings from end-of-life measures are also conservative. The reality is probably somewhere in between.

Assuming the CFCs get there, consideration must be given to the potential for anaerobic degradation in the accumulated CFC banks in landfills. The work of Scheutz, Fredenslund and Kjeldsen (2003) revealed the potential for both CFC-11 and CFC-12 breakdown in managed landfill environments. The believed need for 'management' places this potential emission reduction factor somewhere between a business-as-usual uncertainty and a potential emission reduction measure. However, since this approach generates breakdown products, including HFCs (notably HFC-41), further work still remains to be done in characterizing the potential consequential effects of the by-products before the approach can be classified as a genuine emission reduction option. Nevertheless, the overall global warming impact of the emissions would be reduced if such a process were to occur in practice.

It remains difficult to evaluate the impact of such a measure in quantitative terms. It would reduce the impact of blowing agents landfilled in the past or in the future. Since reliance on landfill is falling in many parts of the world, this reduction could be limited. While the current emission models used for this report allow, for the first time, the quantification of the banks that have already been landfilled (but not included in the bank estimates quoted in this report), the degree of mitigation that can be achieved will be dependent on the prevalence of appropriately designed and managed landfill sites. An assessment of this potential goes beyond the scope of this report.

In summary, the emissions projections are highly sensitive to emission function estimates because of the slow release rates involved and the size of the remaining banks. This is an important caveat when viewing detailed emission assessments. Table 7.9 illustrates the estimated uncertainties for key blowing-agent types. It should be noted that the uncertainties are more pronounced for annual estimates than they are for cumulative emis-

Table 7.9. Sources of uncertainty in emission estimates for commonly used blowing agents.

Blowing agent	Annual emission uncertainty (2002) (tonnes / % of bank)		Key sources in 2002	Uncertainty level
	Upper boundary	Lower boundary		
CFC-11	+10,000/0.6%	-10,000/-0.6%	• Domestic appliance (end of life) • Polyurethane boardstock (in-use) • Polyurethane spray (in-use)	High (for specific year) Low Low
HCFC-141b	+10,000/1.2%	-5,000/-0.6%	• Polyurethane boardstock (production/use) • Polyurethane spray (prod/use) • Domestic appliance (production/use)	Medium (transition year) High (transition plus production losses) Low
HCFC-142b	+5,000/2.2%	-0/0.0%	• Extruded polystyrene (production/use) • Polyethylene rigid (production/use)	Medium (production losses) High (activity)
HFCs	+2,500/21%	-2,500/-21%	• Extruded polystyrene (production/use)	High (HFC-152a emission rate)

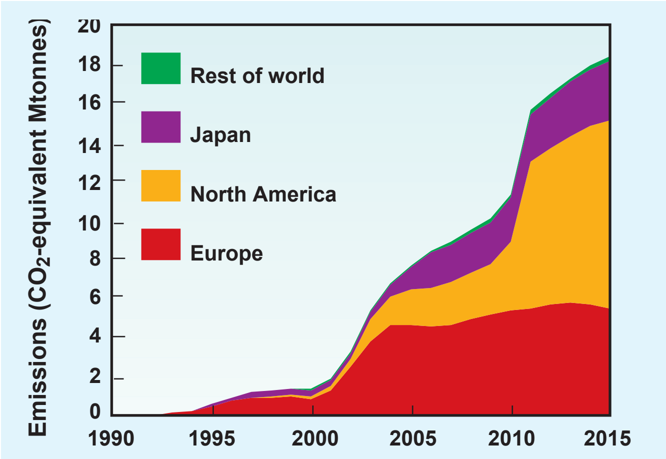


Figure 7.5. GWP-weighted global HFC emissions by region (1990–2015)

sions over longer periods. This reflects particular difficulties in predicting end-of-life activities (e.g. refrigerator disposal) on an annualized basis. It remains much easier to predict cumulative disposal over a ten-year period when the year-to-year variations offset one another.

The significant uncertainties in HFC emissions in 2002 as a proportion of bank size arise from the fact that this was a transition period (particularly in Europe) and the fact that HFC-152a emission rates were less certain. HFC uncertainties will continue to stabilize as the breadth of use develops and blowing-agent banks become established.

Focusing further on HFC emissions, it is clear that the vast majority will occur in the developed countries in the period to 2015, reflecting the fact that HCFCs will continue to be used during the period to 2040 in most developing countries. Figure 7.5 illustrates this fact.

This is important for the potential control of HFC emissions, since both Europe and Japan are already well advanced in end-of-life management options. The next section deals with these options as a sub-set of a review of emission reduction options in the foam sector.

7.5 Emission reduction options and their effects

As has already been noted elsewhere in the text, there are four areas of the product life cycle where emissions can be reduced. These are:

- selection of alternative technologies using non-GWP or lower GWP blowing-agents;
- production and first year (including installation losses);
- use phase;
- decommissioning and end of life.

The current 'best practice' and further options for improvement are discussed in the following text. 'Best practice' is not always easy to extrapolate from region to region because of significant differences in product types and processing methods.

7.5.1 *Production, first-year and use-phase options*

<u>Current status and best practice</u>

HFC selection, formulation and potential substitution

The selection of specific HFCs can have some bearing on the ultimate global warming impact of blowing-agent emissions. However, in practice, the two competing HFC technologies in most polyurethane applications are HFC-245fa (GWP 1020)[3] and HFC-365mfc/HFC-227ea blends (with GWPs of 950–1100 depending on blend composition). Accordingly, the distinction is minimal unless the formulations have significantly different loadings of HFC. This can be the case for HFC-245fa, which does have a higher blowing efficiency than HFC-365mfc/HFC-227ea. However, the difference in boiling points and flammability may offset this. In practice, therefore, there is little to be gained from switching HFCs to minimize impacts in the polyurethane sector.

For gaseous HFCs such as HFC-134a (GWP 1410) and HFC-152a (GWP 122), there would appear to be much more to gain by switching from HFC-134a to HFC-152a. However, this is far from being the case for two reasons. Both are related to the fact that the rate of diffusion of HFC-152a from foam cells is several times faster than that of HFC-134a. The implication is that the emission of HFC-152a is faster and less controllable than HFC-134a. This has the added implication that, where the foam is being used as thermal insulation, there is less blowing agent available to maintain that performance. Since long-term thermal performance is a critical characteristic of all insulation, the early loss of HFC-152a is a major drawback. As a result, HFC-134a is preferred in most insulation foam formulations. In practice (particularly in the case of extruded polystyrene), blends of HFC-134a and HFC-152a are used to obtain the best balance of properties.

With the possibility of HFC selection having only a superficial effect, and the formulation loadings being minimized in all cases because of cost, attention should rightly turn to potential substitution with non-GWP blowing-agent replacements. This subject was already covered in Sections 7.3.1 and 7.3.2 and it can be seen that, in most if not all cases, HFC selection is currently based on a well-grounded rationale. However, past experience shows that circumstances can change substantially with time, and technology breakthroughs in the areas of polyurethane spray foam, extruded-polystyrene foams or domestic appliances could have marked impacts on HFC consumption.

To reflect the fact that further technological development will be required and that experience with HFCs has only just started to be acquired in most instances, the emission reduction scenario considered in this analysis assumes that substitution can only realistically begin to take place after 2010. It is assumed

[3] The GWPs referred to in this section are the latest figures provided in Table 2.6 (from WMO (2003) and elsewhere). However, in the emission calculations carried out in this chapter, the appropriate SAR and TAR values have been used.

that up to 50% of the HFC use at that time could be replaced by alternative technologies but that this would occur progressively between 2010 and 2015, leaving a rump of foam types reliant on HFC-based technologies in 2015 which would, at best, freeze consumption until 2020, when further technological developments might be expected. The impact of such a scenario has been assessed under the heading of the '50% HFC reduction' option in the analysis that follows.

Production and first-year losses

Process management measures include the improved encapsulation of processing areas, particularly where unreacted chemical/blowing-agent mixtures are exposed at elevated ambient temperatures. The ability to capture the volatile blowing agent from the atmosphere will often depend on the amount of ventilation being used in the area (for safety and occupational health reasons, this is often significant) and the size of the processing area. The practicality and cost of such measures will vary significantly from process to process. For instance, in spray foams, there are few practical ways of recapturing blowing agent, although careful design of spray heads can limit over-spray and resulting blowing-agent loss.

In the extruded-polystyrene sector, process losses have also been under scrutiny within the industry and there is some evidence to suggest that losses in North America could already be lower than in Europe because of the product mix and process design. These differences have been documented earlier in a US EPA Notice of Data Availability (US EPA, 2001). The implication is that production losses could be as low as 10% in some scenarios. With current ranges being 15–25% for Europe and 10–25% for North America, the figure of 17.5% for North America and 20% for the rest of the world could justifiably be adopted in future as an alternative to the current default of 25% (Lee and Mutton, 2004). Nevertheless, a technical breakthrough is needed to handle the high-volume air flows and the very dilute blowing-agent concentrations generated from trim reprocessing (Cheminfo Services Inc., 2001) if major savings are going to be made in process emissions.

Another example of process management is the minimization of process waste. In the case of both phenolic and polyurethane block foams, there is an opportunity to recapture blowing agent from off-cuts. These can be significant in the case of fabricated pipe sections where block utilization rarely exceeds 55%. Similar waste minimization practices can also be encouraged during the installation phase of insulation products in buildings.

Taking these as examples of potential opportunities, this analysis has assumed that block-foam measures could be introduced as soon as 2005 and that efforts to improve processing and first-year losses could be implemented across other foam sectors from 2008. Given the technical and economic challenges, broader measures of this kind will not be expected to achieve a saving better than 20% on average.

Use-phase assessments

With respect to use-phase emissions, the main opportunities are provided through product design. They include the use of less permeable facings on boardstock products. However, care needs to be taken to avoid the misapplication of facing types, since breathable facings are critical to the satisfactory operation of some products.

The implementation of Article 16 of Regulation 2037/2000 in the European Union has increased the flow of information about the effectiveness of recovery of blowing agents from refrigerators (OJ, 2000). This information had already been established in several Member States and built into relevant standards (RAL GZ728, 2001; Draft DIN-8975-12, 2002). However, these standards were based on *minimum* recovery rates of approximately 70% of initial charge, implying considerably greater loss in the use phase than the assumptions used in the emissions models developed by the TEAP and others. This potentially higher loss rate has been supported by subsequent work by the Centre for Energy Studies in Paris (Zoughaib *et al*., 2003). There is a case, therefore, for increasing the annual loss assumptions in the use phase from the 0.25% used in the TFCRS study (UNEP-TEAP, 2002ab) to 0.5% or 0.75%. The difference with use-phase losses for commercial refrigeration or other insulated panels could be rationally ascribed to the presence of a thermoplastic liner. However, it has been decided to wait for further investigation of aged refrigerators before adopting this change.

Conversely, as discussed earlier, measurements of effective blowing-agent-diffusion coefficients for laboratory and field-aged XPS samples by Vo and Paquet, and work by Lee and Mutton on the average thickness and installed use temperature of XPS boards, have given a better understanding of loss mechanisms and support a reduction of annual use-phase losses to 0.75% from the original TFCRS study value of 2.5% (UNEP-TEAP, 2002ab).

Since considerable uncertainties about emission rates in use exist and bearig in mind that general thicknesses of insulation are likely to increase (lower surface to volume ratio), leading to reductions in emission rates, it is naturally difficult, and perhaps inappropriate, to postulate a fully defined emission reduction scenario in this phase of the lifecycle. The reality is that the losses in use (i.e. after the first year) are low as a proportion of the total blowing-agent loading, and that changes in technology are unlikely to have any major impact.

7.5.2 Decommissioning and end-of-life options

Some foam sub-sectors (e.g. steel-faced panels, domestic and commercial appliances and some types of boardstock) have significant potential for the recovery of the blowing agent at end of life. To quantify this potential, it has been necessary to evaluate the condition of foam at the time of decommissioning to ensure that enough blowing agent is still available for recovery. Considerable work has been gone into the verification of these levels since the development and publication of the

TFCRS Report in 2001/2002 (UNEP-TEAP, 2002ab). This has included work by the Insulation Technical Advisory Committee of AHAM[4], the Danish Technical University (Scheutz and Kjeldsen, 2001), the Japan Technical Centre for Construction Materials (JTCCM) (Mizuno, 2003) and others. The work of the JTCCM in particular has involved the sampling of foams of varying ages from over 500 buildings and the conclusions have broadly endorsed the emission functions included in the TFCRS Report (UNEP-TEAP, 2002ab). Use-phase emission rates for extruded polystyrene are the exception here and these have been re-evaluated in the light of the recent work by Vo and Paquet (Vo and Paquet, 2004).

Much of the aforementioned work, as well as Fabian *et al.* (2004), has highlighted the need for a robust method of assessing blowing-agent content in foams and this has led to the development by JTCCM of a draft Japanese standard on the subject and a draft ASTM standard.

A second element of importance has been the establishment of possible end-of-life treatment methods for foams. The latest models used for this analysis (Ashford *et al*., 2004ab) have incorporated four end-of-life scenarios:

1. re-use;
2. landfill;
3. shredding without recovery of blowing agent;
4. shredding with recovery of blowing agent.

It has been assumed that direct incineration of the foam results in the same loss profile as 'shredding with recovery of blowing agent' because of the similar front-end handling requirements. Both techniques have been used in Europe for refrigerators, although problems with incineration residue have curtailed the widespread commercialization of the incineration approach in this instance.

Technical options

The development of end-of-life management techniques for foams continues and further refinements to the mechanical recapture/recycle plants are emerging. One of the issues requiring improved management is the handling of hydrocarbon blown foams in refrigerators. At least two incidents have occurred in Europe in recent months and it has emerged that there is a need for increased awareness and risk management procedures, particularly in older plants.

As noted previously, the potential for the anaerobic degradation of ozone-depleting substances in landfill soils has also been investigated (Scheutz *et al*., 2003) but at present it looks as though the 'fluorine-carbon' bond might be too strong to be broken down by this route, even though CFCs and HCFCs have been successfully degraded to HFCs. It may be that the microbial organisms responsible need further acclimatization and this will be evaluated further over time.

[4] AHAM – Alliance of Home Appliance Manufacturers – a US-based industry association

The direct incineration of foam continues to be a focus of attention. The MSWI co-combustion study (APME/ISOPA/EXIBA, 1996) paved the way for the incineration of building insulation. However, as noted above, problems have continued in Europe with the direct incineration of complete refrigerators. In other parts of the world, where foam and metals can be separated without controls, the incineration of the removed foam would be an option. In the UK, a study has been conducted on the partial dismantling of refrigerators prior to transporting (Butler, 2002) with the aim of minimizing cost and environmental impact. However, at present, refrigerators continue to be sent to mechanical recapture/recycle plants rather than municipal solid-waste incinerators.

There has been little progress in techniques for recovering blowing agent from insulation products used in buildings, although the ongoing trend towards the increased use of prefabricated building elements in Europe and elsewhere is assisting in making currently installed foams more accessible at end of life. The ongoing JTCCM project is spending its third year investigating the technical potential for recovering blowing agents from previously installed foams and the results should be reported internationally by mid-2005.

Economic considerations

The JTCCM study also involves the evaluation of the cost-effectiveness of recovering blowing agents from foams in buildings. This will be the subject of the fourth and final year of the project. Preliminary indications from previous work carried out in the field (Swedish EPA, 1996) show that recovery from traditional buildings may be uneconomical. However, the fact that steel-faced panels could be processed through recapture/recycle mechanical refrigerator plants may have an impact on future achievements.

All of these approaches have been stimulated under the Montreal Protocol framework, which does not mandate recovery. Under the Multilateral Fund, the finance made available for phase-out is typically capped at $15/kg (Jeffs *et al*., 2004). At previous levels of activity, the mechanical recapture/recycling processes were handling refrigerators at a net cost of $15–20/unit (UNEP-TEAP, 2002ab), although more recent information from the market suggests that this may have even fallen as low as $10/unit. With typical recovery levels of 250–325 g per unit, the cost of recapture and destruction is $30–60 per kg of blowing agent.

The mathematics for HFC recovery will be based more specifically on climate change economics and the developing concept of the social cost of carbon (Clarkson and Deyes, 2002). These aspects are covered in more detail in Section 3.3.4.1. The cost of abatement calculations for HFC recovery are still in their infancy, but there is an expectation that if sufficient foam can reach such disposal facilities intact, the economics under a climate change scenario will be more favourable, even for foam from buildings. This would be particularly true if investments were to take into account the real value to the climate of the incremental destruction of ozone-depleting substances, the GWPs of which are even higher than those of the HFCs replacing them. These issues will be addressed further in the forthcoming UNEP Task Force on end-of-life management for foam.

Expanded 'best practice'
The domestic refrigeration sector remains the major focus for end-of-life management in the short term. If the European approach to such management were to be extrapolated for use elsewhere in the world, the implications for HCFC emissions would be significant. This would be potentially achievable in developed countries from 2007, but would take longer to establish in developing countries. Under the end-of-life scenario developed under this analysis, it is assumed that all decommissioned refrigerators could be managed worldwide from 2010.

The situation is less clear with respect to the recovery of blowing agent from building insulation. However, it is apparent that some building elements (e.g. steel-faced panels) could be managed technically and economically. Work is continuing in the UK to confirm the economics of panel recovery and a report is expected in 2005. The specific advantage associated with panels is that they could be managed using the plants already established for refrigerators. This means that full recovery could commence as early as 2007.

For other types of building insulation, the situation is less clear. Even with favourable technology and economics, the development of an appropriate infrastructure would take time. The JTCCM project is expected to provide further information on this issue when it reports finally in 2005. For the sake of this assessment, however, it is assumed that no more than 20% of the remaining blowing agent will be technically and economically recoverable and, even then, this will not be possible before 2010.

7.5.3 *Further analysis of cost elements*

There have been few systematic reviews of abatement costs for the foam sector. The March Consulting Group (1998) reviewed potential emissions and abatement options for HFCs in the European Union. However, this review only included the costs of the options identified at that time for the reduction of potential extruded-polystyrene emissions. Ecofys picked up the agenda in the EU Sectoral Objectives Report (Harnisch and Hendriks, 2000) and conducted a more systematic review of abatement costs for both the extruded-polystyrene and polyurethane sectors. However, there were several drawbacks to this study. First of all, it was written before the transition to HFC blowing agents had taken place in Europe and before many of the technology choices had been finalized. As a consequence, it considerably over-estimated the uptake and consequent emissions of HFCs in the region. Secondly, it was only tasked to look at emission-abatement options that would be effective by 2010. This immediately ruled out the costing of end-of-life management options and forced the focus onto HFC-substitution technologies.

For the major polyurethane foam technologies, abatement costs in the range of \$25–85 per tonne of CO_2-eq (1999 cost base) were estimated where replacement technologies were believed to exist (based approximately on a 50% emission reduction potential on average). If anything, it is anticipated that these costs are now on the low side, since many polyurethane-foam sectors have minimized the amount of HFCs used per unit of foam by the adoption of blends and other similar techniques, making abatement investments less effective.

Both March (1998) and Ecofys (Harnisch and Hendriks (2000)) gave particularly low estimates of abatement costs for measures for extruded polystyrene; both were in the range of \$6–12 per tonne of CO_2-eq on the basis of transitions to CO_2 blowing options with investment amortization over a fifteen-year period. However, it should be noted that a transition to CO_2-based technologies is not currently possible for smaller producers and other regional markets (e.g. North America). The more recent IMAC Report (US EPA, 2004) has reassessed this option on a global basis and states an even lower estimate for the cost of transition. However, industry sources have been quick to point out that all of the emissions models used for these costing exercises have:
- overstated in-life emissions (Vo and Paquet, 2004);
- under-estimated the magnitude and costs of density increases;
- under-estimated the significance of thickness constraints;
- used investment cost information that is too low.

Estimates of polyurethane-foam technology abatement costs from the IMAC have also been lower than those from earlier European studies, but this may be due to the adoption of a 25-year amortization period for investments, which most commentators consider to be excessive for this industry.

The IMAC Report is the only study so far to provide a systematic appraisal of the costs of recovering blowing agents from appliances at end of life. The estimates, described by the authors as 'illustrative, rather than definitive', suggest costs in the order of \$18–20 per tonne of CO_2-eq for automated processes and \$48 per tonne of CO_2-eq for manually dismantled units with foam incineration. Anecdotal information from Europe suggests that ozone-depleting substances are currently being recovered at a price of around \$40/kg. If transferred to HFC blowing agents, this would equate to an emission abatement cost of somewhere below \$40 per tonne of CO_2-eq, depending on the profit margins applied. This would be considerably lower again for CFCs where GWPs are higher.

There is no data at present about blowing agents recovered from building elements and this is a subject for review in the UNEP TEAP Task Force Report scheduled for publication in mid-2005.

7.5.4 *Revised emission projections*

Figure 7.6 illustrates the effects of the three scenarios developed in this review. These are:

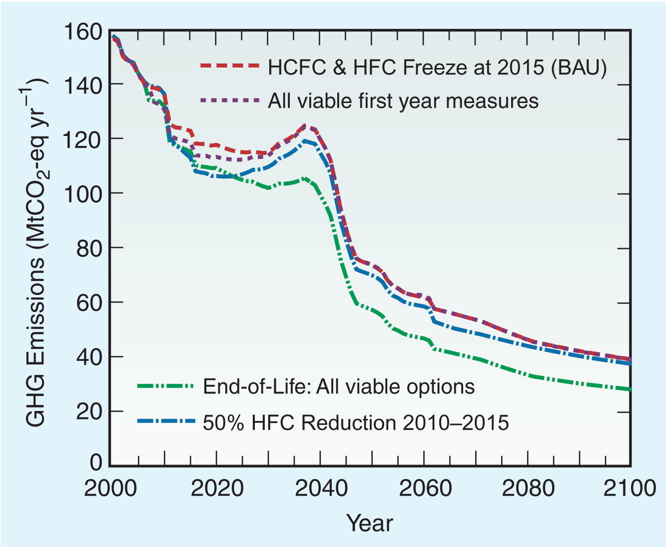


Figure 7.6. Summary of emission reduction scenarios for foams

1. a 50% reduction in HFC consumption between 2010 and 2015;
2. the implementation of production and first-year emission reductions in the block-foam sector from 2005 and in other sectors from 2008;
3. the geographic extension of end-of-life management for domestic refrigerators, together with a further extension to cover steel-faced panels and, where practicable, other building foams.

It can be seen that focusing on reducing HFC consumption provides the most significant saving in the period to 2015 and, if any such reduction is extrapolated to include use patterns beyond 2015, it offers the greatest 'HFC-specific' benefit to 2100 as well (see Table 7.10). In contrast, end-of-life measures deliver lower savings in the period to 2015, but have the potential to deliver more overall savings in the period to 2100 if all blowing agent types are considered. The value is particularly significant for CFCs, where GWPs are significant and where there is an incremental effect of ozone depletion.

Table 7.10 sets out the cumulative savings as at 2015, 2050 and 2100 by blowing-agent type, with the aim of providing a clearer picture of the analysis conducted. However, it must be recalled that these savings (particularly in the end-of-life scenarios) could be conservative depending on the assumptions adopted for the business-as-usual losses for landfill.

Of course, in reality, any set of measures is likely to encompass elements from all three scenarios rather than to follow one exclusively at the expense of the others. The purpose of this assessment is only to indicate the relative significance of various options in order to provide a basis for prioritization.

Table 7.10. Summary of impacts of individual packages of measures by blowing agent type: cumulative emission reductions resulting under each scenario assessed.

Measure	***Year***	**Cumulative Emission Reductions**			
		CFCs (tonnes)	**HCFCs** (tonnes)	**HFCs** (tonnes)	**CO_2-equivalents** ($MtCO_2$-eq)
HFC consumption reduction (2010–2015)	2015	0	0	31,775	36
	2050	0	0	225,950	259
	2100	0	0	352,350	411
Production/installation improvements	2015	78	14,450	16,700	36
	2050	58	31,700	32,700	68
	2100	47	24,350	26,500	55
End-of-life management options	2015	8545	16,375	105	52
	2050	64,150	144,650	88,540	540
	2100	137,700	358,300	194,800	1200

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