

Montreal Protocol on Substances that Deplete the Ozone Layer

"Celebrating 20 years of progress in 2007"



2006 Report of the Rigid and Flexible Foams Technical Options Committee (FTOC) 2006 Assessment

United Nations Environment Programme

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**MONTREAL PROTOCOL
ON SUBSTANCES THAT DEplete
THE OZONE LAYER**



UNEP

**2006 REPORT OF THE
RIGID AND FLEXIBLE FOAMS TECHNICAL OPTIONS
COMMITTEE**

2006 ASSESSMENT



**Montreal Protocol
On Substances that Deplete the Ozone Layer**

**United Nations Environment Programme (UNEP)
2006 Assessment Report of the
Rigid and Flexible Foams Technical Options Committee**

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2006 RIGID AND FLEXIBLE FOAMS REPORT

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2006 RIGID AND FLEXIBLE FOAMS REPORT

EXECUTIVE SUMMARY

INTRODUCTION

Historically, the blowing agent selection made by the foam plastics manufacturing industry was based heavily on CFCs. This was particularly the case in closed cell insulating foams, where the low thermal conductivity of the gases was advantageous. An assortment of CFCs and other ozone depleting substances (ODSs), including CFC-11, CFC-12, CFC-113, CFC-114 and methyl chloroform were used in various foam plastic product applications. However, the effect of the phase-out process has been to create further diversification.

The first technology transition in non-Article 5(1) countries took place in the early 1990s and led to the introduction of transitional substances such as HCFCs as well as the increasing use of hydrocarbons and other non-ODSs. A similar transition is now also reaching completion in Article 5(1) countries. Meanwhile, in non-Article 5(1) countries, attention has been firmly focused on a second technology transition out of HCFCs. This has resulted in further switches to both hydrocarbon and CO₂ technologies¹ and these technologies have gained market share in several sectors. Nonetheless, there are a number of sectors where safety and performance requirements have necessitated the use of HFC-based technologies – most notably in polyurethane spray foam and steel-faced panels. Secondary transition is still awaited in some key markets, such as the extruded polystyrene (XPS) market in North America and blowing agent selection for this sector is still not finalised.

As before, this report details, for each foam type, the technically viable options available to eliminate the use of ODSs as of 2006. It concentrates primarily on the transition status by product group and region and on likely future scenarios. In this edition, the management of banks and emissions is promoted from an Appendix to a chapter in the core report, reflecting the subject's increasing importance to legislators. Coverage of technical options per se continues to be located for information purposes within the appendices only.

TRANSITION STATUS

General

- In 2005 the consumption of CFCs dropped below 1% of total blowing agent usage for the first time.

¹ Carbon dioxide or CO₂ as a blowing agent in polyurethane foam can be chemically generated from the reaction between water and isocyanate but also added in both polyurethane and other foams as an auxiliary blowing agent in liquid or gas form. The different options are hereafter referred to as CO₂ (water), CO₂ (LCD) or CO₂ (GCD).

- The very strong growth in the demand for insulation foams, particularly to support energy efficiency improvements in buildings and appliances continues to be a major factor in the demand for CFC alternatives.
- Controls on end-of-life emissions of fluorinated blowing agents are being applied within the appliance sector in several developed countries, while additional voluntary actions are being actively encouraged for blowing agent recovery in the building sector in Japan.
- In addition, consideration is being given to bank management projects in Latin America although foam recovery may be logistically difficult, particularly in remote regions.

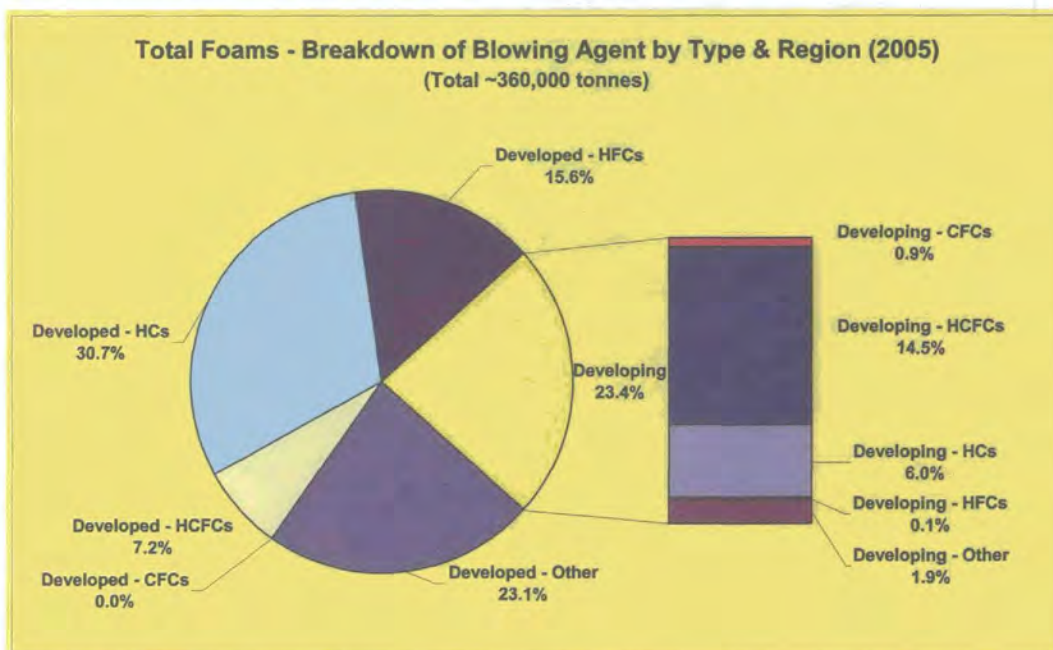
Developing Countries

- Virtually all transition projects phasing out CFCs are materially complete in non-insulation areas and are nearing completion in insulation applications. However, many projects are still awaiting formal closure.
- HCFCs continue to be the dominant blowing agent in virtually all insulation applications with the exception of appliance insulation where the use of hydrocarbon-blown foam continues to gain some ground, particularly in the larger countries of Asia and Latin America.
- Some use of HFC-blown foam is emerging in Latin America for appliances (mainly for export markets) as well as in OCF, integral skin polyurethane and shoe sole applications.
- Strong development of the insulation market in China, and to a lesser extent in MENA and Latin America, is driving the rapid introduction of XPS facilities using HCFC-based technologies. This sector alone has contributed a further 20,000 tonnes per annum of blowing agent consumption since previously assessed in 2001.
- The rate of growth of consumption of HCFCs in foam applications indicates that there could be a significant shortfall in the period immediately after the introduction of the freeze in consumption in 2015, as foam producers seek alternative technologies to maintain growth.

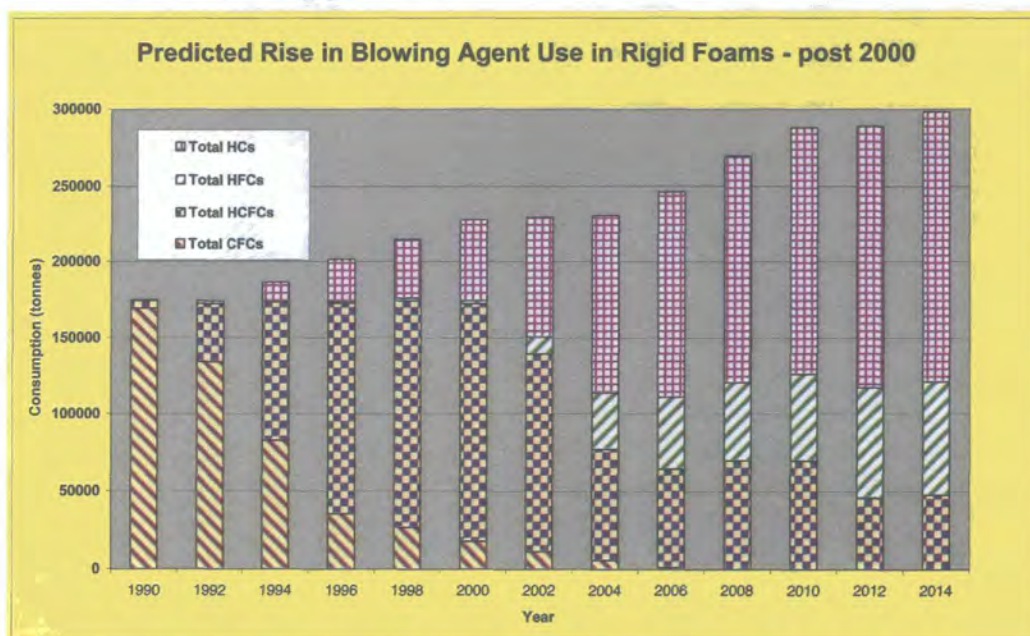
Developed Countries

- The use of HCFC-141b in insulation foams is now limited to relatively small amounts in Australia and Canada but significant usage of HCFC-142b and HCFC-22 is likely to continue in both Canada and the USA until at least 2008 and, in the case of XPS, until 2010.
- In the European Union and Japan the actual uptake of HFCs following HCFC phase-out has been lower than previously predicted, partially because of increased use of other alternatives (e.g. hydrocarbons) driven by the regulatory and market pressures to limit HFC uptake and partially through more efficient formulation in recognition of the economic realities of HFC use.
- Super-critical CO₂ technologies have now been commercially introduced for spray foam in Japan, although spray foam continues to be a challenging technology area in other regions

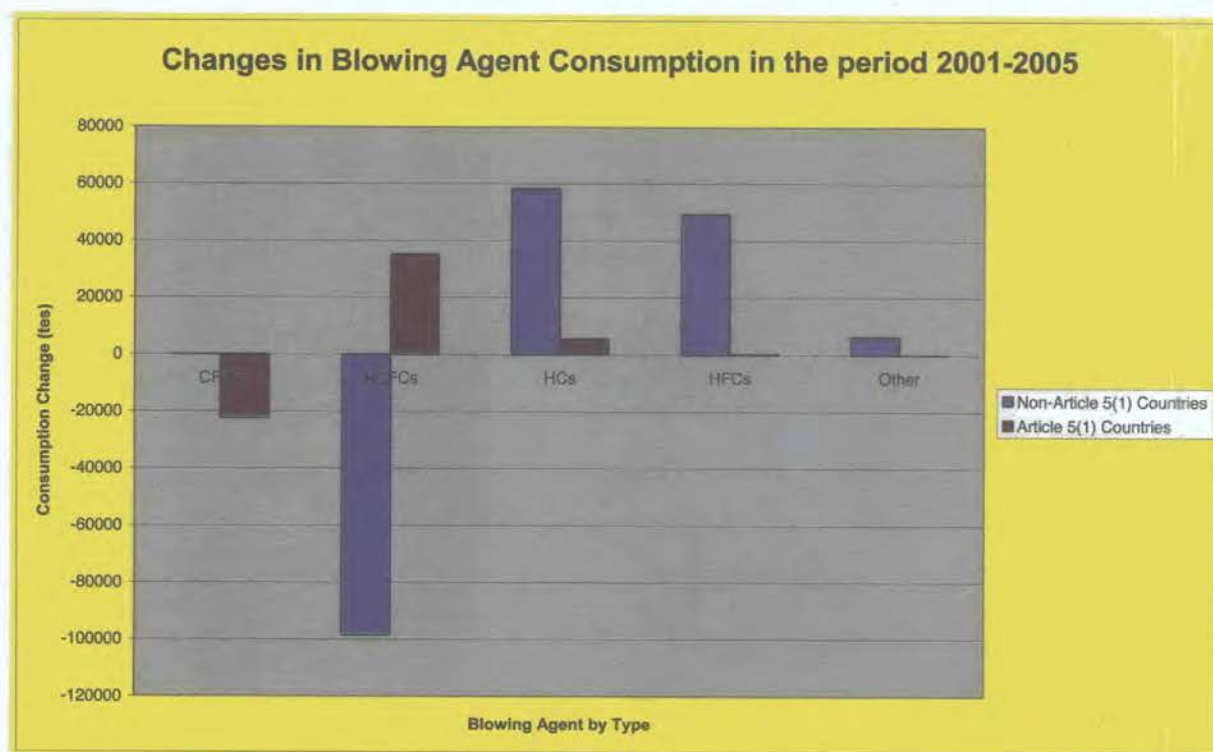
The chart below illustrates the overall status of transition for Article 5(1) and non-Article 5(1) countries in the combined rigid & flexible foam sectors as at 2005.



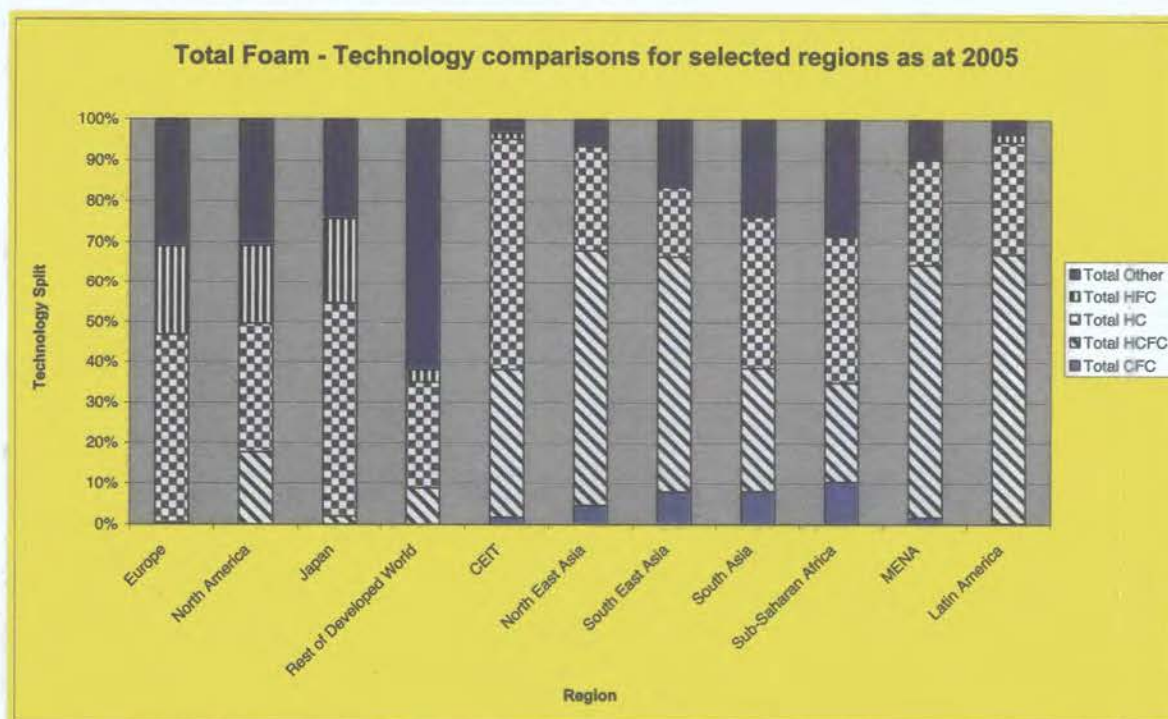
There has been a stabilisation or perhaps even a slight overall drop in the demand for blowing agents since 2001 which illustrates the ability of the industry to develop more efficient processes with more limited losses. However, as signalled in the IPCC/TEAP Special Report on Ozone and Climate (SROC-2005), the trend in blowing agent usage within rigid foams is expected to be upwards until 2015 driven largely by the requirement for better building insulation standards and product switches from less thermally efficient materials. The following graph shows the trend by blowing agent type:



The following graph illustrates the changes in blowing agent type by region since 2001...



...and the following graph provides further analysis of some of the regional variations in phase-out progress and in preferred technology options:



The lack of major increase in hydrocarbon use in Article 5(1) since 2001 is illustrative of the fact that most of the larger projects suited to hydrocarbon had already been tackled in the pre-2001 period. Transitions from CFCs have therefore been primarily to HCFCs and there is little evidence yet of any transition away from HCFCs in developing countries. The only circumstances where this has seriously occurred is where products exported to non-Article 5(1) countries (e.g. appliances) have been required to be ODS-free.

Although many of the transitions have now already occurred, there are a number of steps remaining. These include:

- Transition out of HCFC-142b/22 in the North American XPS industry
- Transition of the remaining minor CFC use in Article 5(1) countries
- Avoidance of, or progressive transition from, HCFC technologies in Article 5(1) countries
- Transition out of remaining minor use of HCFCs in other non-Article 5 countries such as HCFC-141b in Canada

In addition there are a number of actions which are being considered at regional level to minimise future emissions of ODSs. These include:

- Recovery of ODS blowing agents contained in domestic refrigerators and other appliances (see Banks and Emissions)
- Recovery of ODS blowing agents from building insulation where technically possible and economically viable (see Banks and Emissions)
- Further development of processes to reduce emissions of all types of blowing agent during foam manufacture and use

Whilst some transitions continue to take place and processes continue to be optimised, the technology choices are expected to vary with time and country status as shown in the following tables:

Foam Type	CFC Alternatives		
	Currently in Use	Anticipated in 2007-2015 period	
		Developed Countries	Developing Countries
Polyurethane: Rigid			
Domestic Refrigerators and Freezers	HCFC-141b, HCFC 141b/22, HCFC-142b/22 blends, HFC-134a, hydrocarbons, HFC-245fa	HFC-245fa, HFC-134a, hydrocarbons	HCFC-141b, hydrocarbons, HCFC-141b/22
Other Appliances	HCFC-141b, HCFC-22, HCFC-22/HCFC-142b, HFC -245fa; HFC-365mfc	CO ₂ (water), HFC-134a, HFC-245fa, hydrocarbons, HFC-365mfc/HFC-227ea, methyl formate	HCFC-141b, CO ₂ (water), hydrocarbons
Reefers & Transport	HCFC-141b, HCFC-141b/-22, HCs, HFC-245fa	HFC-245fa, HFC-365mfc/227ea	HCFC-141b
Boardstock	HCFC-141b, HCFC-141b/-22, HCs	Hydrocarbons, HFC-245fa, HFC-365/HFC-227ea	N/A
Panels – Continuous	HCFC-141b, HCFC-22, HCFC-22/HCFC-142b, HCs, HFC-245fa, HFC-365mfc	HFC-134a, hydrocarbons, HFC-365mfc/HFC-227ea, HFC-245fa	HCFC-141b
Panels – Discontinuous	HCFC-141b, HCs, HFC-365mfc, HFC-245fa	HFC-134a, hydrocarbons, HFC-365mfc/HFC-227ea, HFC-245fa	HCFC-141b
Spray	HCFC-141b, HFC-245fa, HFC-365mfc, Super-critical CO ₂	CO ₂ (water), HFC-245fa, HFC-365mfc/HFC-227ea, Super-critical CO ₂	HCFC-141b
Blocks	HCFC-141b; HCs, HFC-365mfc	Hydrocarbons, HFC-365mfc/HFC-227ea, HFC-245fa	HCFC-141b
Pipe	HCFC-141b, HFC-365mfc/227ea, HCs	CO ₂ (water), cyclopentane	HCFC-141b
One Component Foam	HCFC-22, HFC-134a, HFC-152a, propane, butane	HFC-134a or HFC-152a/Dimethylether/propane/butane	HFC-134a or HFC-152a/Dimethylether/propane/butane
Polyurethane: Flexible			
Slabstock and Boxfoam	HCFCs are not technically necessary for this end use	CO ₂ (water, LCD), methylene chloride, variable pressure, LCD, special additives	CO ₂ (water), methylene chloride, variable pressure, LCD, special additives
Moulded	HCFCs are not technically necessary for this end use	Extended range polyols, CO ₂ (water, LCD, GCD)	CO ₂ (water, LCD, GCD)
PU Integral Skin	HCFC-141b, HCFC-142b/-22	CO ₂ (water), HFC-134a, -245fa, -365mfc/227ea, hydrocarbons, methyl formate	CO ₂ (water), HFC-134a, hydrocarbons
PU Miscellaneous	HCFC-141b, HCFC-22/CO ₂	CO ₂ (water)	CO ₂ (water)

Table ES1 – Alternatives for Polyurethane Foams

Foam Type	CFC Alternatives		
	Currently in Use (2005/2006)	Anticipated in 2007-2015 period	
		Developed Countries	Developing Countries
Phenolic	Hydrocarbons, 2-chloropropane, HFC-365mfc/227ea	Hydrocarbons, 2-chloropropane, HFC-365mfc/227ea, HFC-245fa	HCFC-141b, hydrocarbons
Extruded Polystyrene			
Sheet	Primarily hydrocarbons, HCFCs are not technically required for this end use	CO ₂ (LCD), hydrocarbons, inert gases, HFC-134a, -152a	Hydrocarbons, CO ₂ (LCD)
Boardstock	CO ₂ (LCD) or with HC blends, hydrocarbons (Japan only), HFC-134a, HFC-152a HCFC-22, HCFC-142b	CO ₂ (LCD) or with HC blends, hydrocarbons (Japan only), HFC-134a, HFC-152a and HC blends	HCFC-142b, HCFC-22
Polyolefin	Hydrocarbons plus some HCFC-22, HCFC-142b	CO ₂ (LCD), hydrocarbons, inert gases, HFC-134a, -152a	Hydrocarbons, CO ₂ (LCD)

Table ES2 – Alternatives for Other Foams

LIKELY FUTURE SCENARIOS (INCLUDING BARRIERS TO TRANSITION)

Likely future scenarios and issues affecting transition are reviewed in detail within Chapter 2 of this Report. They encompass factors in both Article 5(1) and non-Article 5(1) environments. There are several common elements and these often focus on SMEs. Key points to highlight at this stage are:

- The financial constraints of SMEs remain key factors in many transition strategies, both in developing and developed countries. This has a particular impact on on-going uptake of hydrocarbon technologies.
- Both product and process safety issues remain upper-most within some sectors (e.g. spray foam) that would otherwise consider hydrocarbons
- There remains concern among some Article 5(1) users about the possibility of future supply/demand imbalances for critical HCFCs, particularly in environments where phase-out might be accelerated. This extends to the maintenance of adequate geographic supply chains.

- The future of HFC regulation in non-Article 5(1) countries continues to be an unknown. However, definition of longer-term use and emission patterns is being established in many cases so that evidence-based decisions can be reached.

BANKS AND EMISSIONS

The long historic use of CFCs in rigid foams, the long product lifetimes and the slow release rates of blowing agents continue to point to the existence of a significant bank of future CFC and HCFC emissions. These were well-documented in the foams chapter of the IPCC/TEAP Special Report (SROC) which was finally published in 2005. This report confirmed earlier estimates that suggested banks in excess of 1.8 million tonnes of CFCs and over 1.1 million tonnes of HCFCs. However, there has since been some debate about the precise size of these banks and particularly the reliability of the bottom-up emissions function approach in predicting overall emissions. A recent Task Force Report on Emission Discrepancies (TFED) has brought the subject into sharp relief and proposed three main explanations for possible discrepancies:

1. The under-estimation of use and emissions in the foam sector (affecting CFC-11, HCFC-141b and HCFC-142b projections in particular)
2. The under-reporting and misallocation of consumption of these chemicals in other applications resulting in the omission of consumption in emissive activities
3. The under-estimation of the lifetime of these chemicals (particularly CFC-11) in the atmosphere, resulting in an over-estimation of annual emissions by ‘inverse modelling’ from atmospheric concentrations

The conclusion of the TFED Report was that there was sufficient uncertainty in all of these areas to allow for the potential reconciliation of emissions estimated from bottom-up assessments and those derived by inverse modelling from atmospheric concentrations. Further work is required to evaluate the sources of uncertainty in more detail, and reduce them in some cases. This will involve further commitment from the foam sector in providing adequate information on consumption and use patterns, as well as improved information on emissions functions.

Meanwhile, in the light of this conclusion, the respective protocol communities are able to move forward with increased confidence when considering future projections of emissions from the foam sector and the value of bank management as an emissions reduction option. With respect to bank management itself, there is increasing interest in the potential for flexible mechanisms such as those found in the voluntary carbon market. Although these will trade fundamentally on the carbon value of ODS recovery, there are clearly mutually environmental benefits to be had under both protocols – particularly where recovery and destruction would otherwise be unaffordable.

CHAPTER 1: TRANSITIONAL STATUS

POLYURETHANE FOAMS

RIGID POLYURETHANE FOAM

NON-CONSTRUCTION APPLICATIONS

This sector includes domestic refrigerators and freezers, commercial refrigeration units, water heaters and refrigerated transport applications. It does not include miscellaneous non-insulating applications.

DOMESTIC REFRIGERATORS AND FREEZERS

Current Technology

In developing countries there is now very limited use (well below 1,000 tonnes) of CFC 11, mostly with the smaller producers. Transitions have been to both HCFC-141b and hydrocarbons, with economy of scale and date of conversion being important factors in the choice of technology.

Nevertheless, hydrocarbons (typically blends containing cyclopentane) remain the most widely applied technology globally. Hydrocarbons are used in all regions except for Sub-Saharan Africa, where the blowing agent itself is not available, and in North America where HCFC-245fa has become the dominant blowing agent. Hydrocarbon technology has evolved from the initial 100% cyclo-pentane to blends with other hydrocarbons. Blends of cyclo-pentane with iso-pentane have emerged as the favoured blowing agent in the market because of better cost effectiveness. The initially observed density increase with cyclo-pentane has been reduced by the blend because it offers greater cell pressure, improved flow and a more uniform and lower average density distribution. As of 2005, more than 60% of European production was based on this blend. Its use has been long established in Australia and is also increasing in the Chinese market. Blends of cyclo-pentane with iso-butane had initially grown in use for similar reasons to the cyclo-pentane/iso-pentane blend but the difficulty of using a liquid/gas blend sent its use into decline more recently. It now represents less than 20%. Energy standards are met by use of thicker foam and cooling system improvements.

Apart from the widespread use of HFC-245fa in North America, one producer continues the use of HFC-134a as the blowing agent for some models.

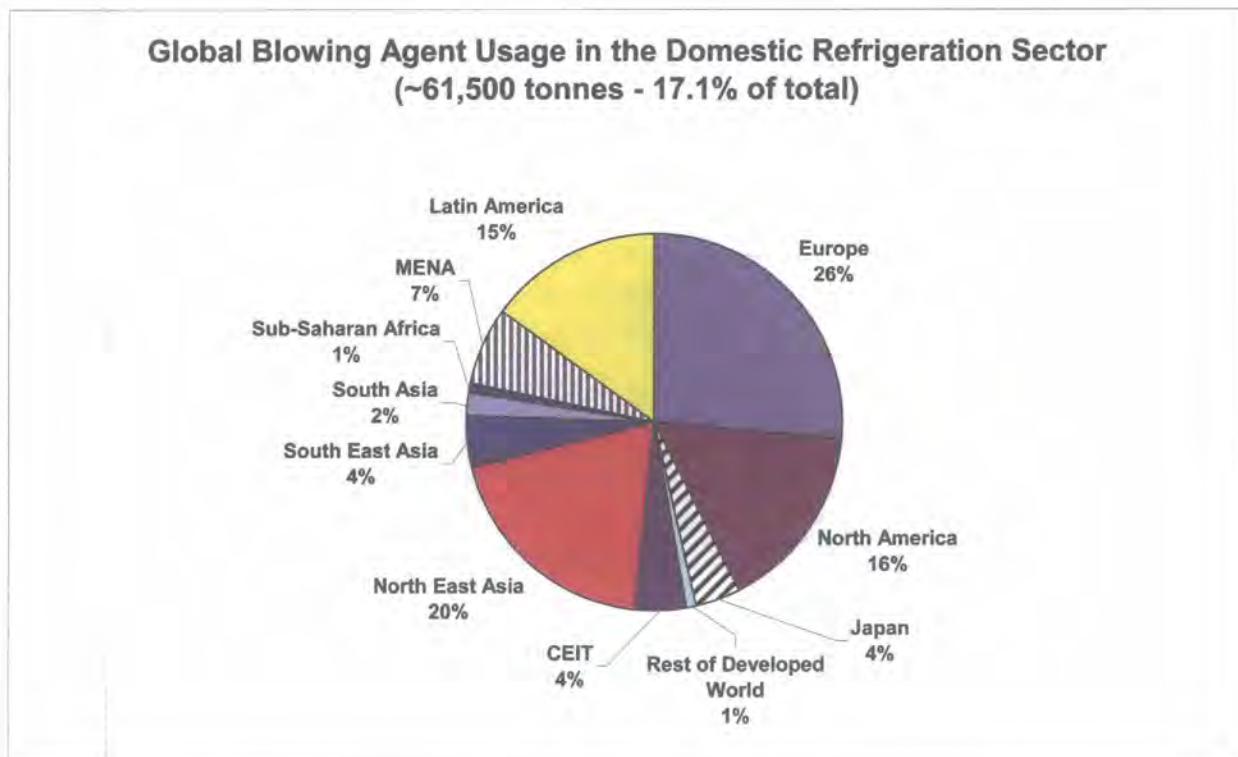
Latest Technology Trends

In developing countries the remaining conversion from CFC 11 will occur within the next 1-2 years. The most likely replacement continues to be HCFC-141b because of investment constraints.

Where local producers in developing countries are supplying international markets with constraints on products-containing ozone depleting substances, there is likely to be an earlier switch from HCFC-141b to non-ODS solutions. This has already occurred in some Latin American countries where limited HFC-245fa is already in use for exports to the United States.

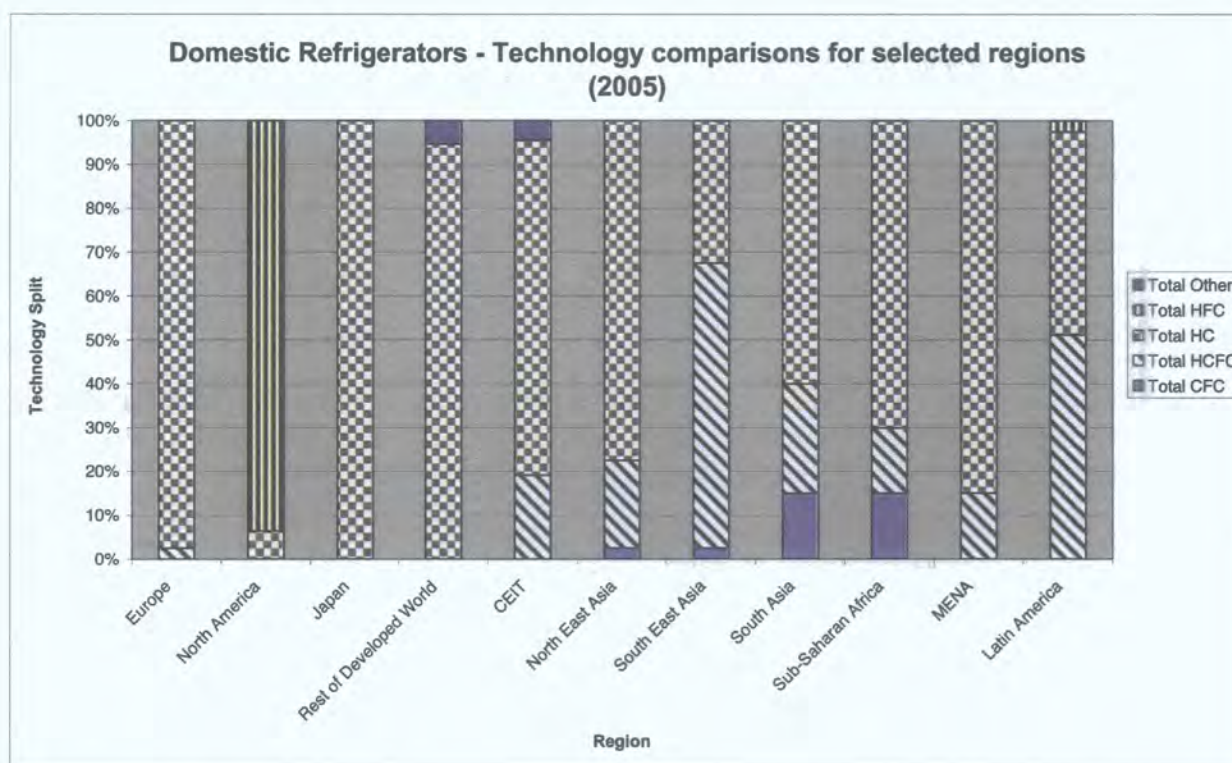
Data Summary

The current global distribution of blowing agent use in the domestic refrigerator and freezer sector is shown below:



It can be seen that the majority of production of domestic refrigerators is now in either Article 5(1) or CEIT countries. This contrasts with 2001 when the balance was in favour of non-Article 5(1) countries. The trend reflects the tendency to move the production facilities to regions with lower labour costs (e.g. Latin America and CEIT) and the fact that production in China is growing extremely rapidly and this is likely to become the single biggest market within the next five years. Production elsewhere in the world is fairly widely spread in contrast to many of the construction applications where climatic factors have more influence.

The transitional status for each of these regions and choice of technologies is shown in the following graph:



Additional Regional Observations

Except for earlier conversions (1993-1996), those regions supported under the Multilateral Fund have benefited from access to hydrocarbon technologies and the larger plants have already been converted as a priority. However, slower conversion in regions such as South Asia and Sub-Saharan Africa is indicative of the smaller-scale of many of the plants in the region. Nonetheless, where funding is available, the remainder are still targeted to switch to cyclo-pentane with the balance transitioning to HCFC-141b.

OTHER APPLIANCES

Current Technology

There has been considerable additional transition from CFC-11 in developing countries since 2001 and remaining use is very limited.

The main option, in both developed and developing countries, to replace CFC-11 in these sectors has been HCFC-141b. This is because of the low capital investment required by the manufacturers - many of these are small enterprises with limited production capacity.

Cyclo-pentane is used for commercial refrigerators and freezers in those areas where the market (in some cases driven by Government policy) demands a zero ODP, low GWP option. Some vending machines and water heaters are produced with CO₂ (water). For both appliances

the comparatively poor thermal insulation properties of the foam can be compensated by increased thickness in a number of cases.

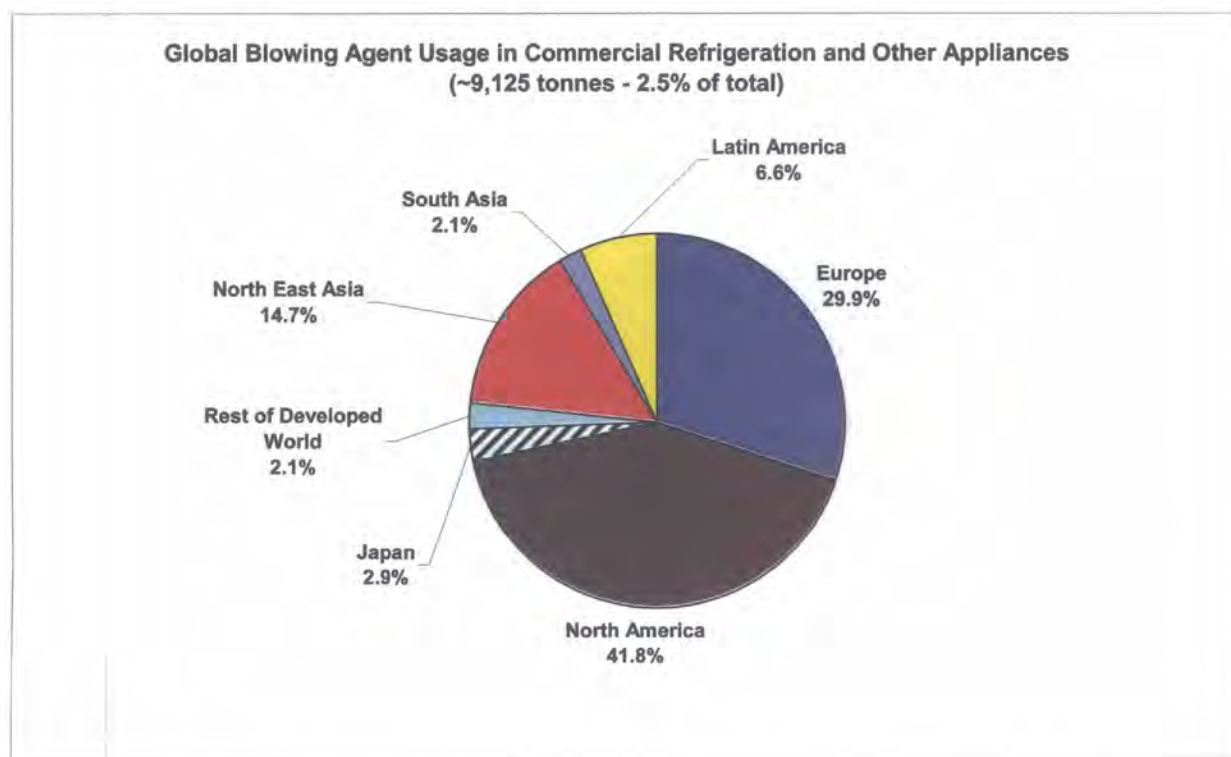
In a number of developed countries, a further transition from HCFCs has either already happened or will happen shortly. In Europe, water heaters have tended to switch to CO₂ (water). However, in North America, there is more widespread use of HCFC-22 and the phase-out of these blowing agents is not expected before 2008.

Latest Technology Trends

For the replacement of HCFCs the blowing agents being used are HFC-245fa and HFC-365mfc. The various forms of pentane are also technically suitable, but the cost of appropriate safety measures and the difficulty in supplying pre-blended formulations have tended to rule out wide scale use.

Data Summary

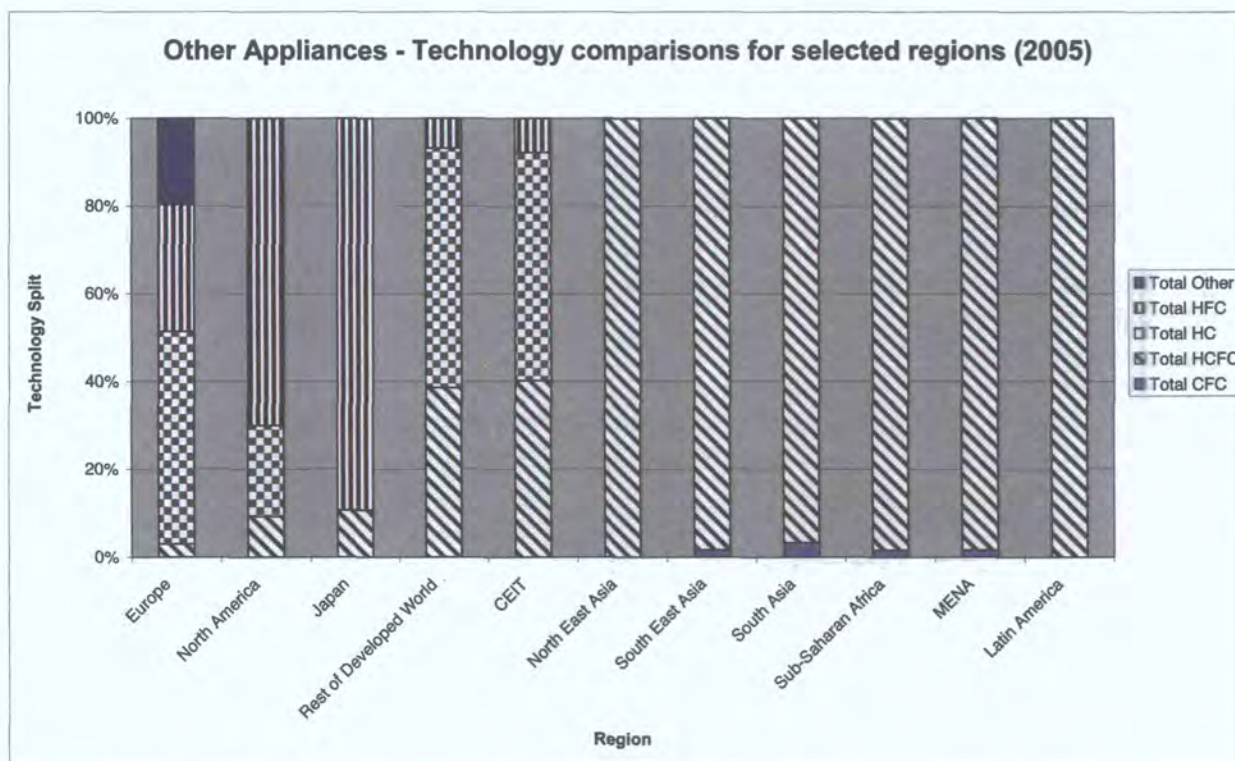
The current global distribution of blowing agent use in the commercial refrigeration and other appliances sector is shown below:



The North American demand for commercial refrigeration represents the largest single element of the blowing agent market, partly based on population, but also because of the propensity for drinking dispensers in public places and the size of the cabinets involved. It can

also be seen that the regional manufacture of commercial refrigeration units and other appliances is fairly widely spread.

The transitional status for each of these regions and choice of technologies is shown in the following graph:



Additional Regional Observations

As noted earlier, the 'Other' blowing agent used in Europe is CO₂ (H₂O). In general though, transitions from HCFCs in developed countries have favoured HFCs and, to a lesser extent, hydrocarbons. This is partly because of the smaller size of commercial refrigeration companies and the more widely varying product range being manufactured. The residual HCFC use in Europe relates to some Eastern European states not constrained by EU Regulation.

REEFERS & REFRIGERATED TRANSPORT

Current Technology

For reefers, the most widely used technology is HCFC-141b and, with the transfer of much of the global manufacture to Article 5(1) countries such as China, the use of HCFC-141b is likely to be maintained for a considerable time to come. However, some further conversion has

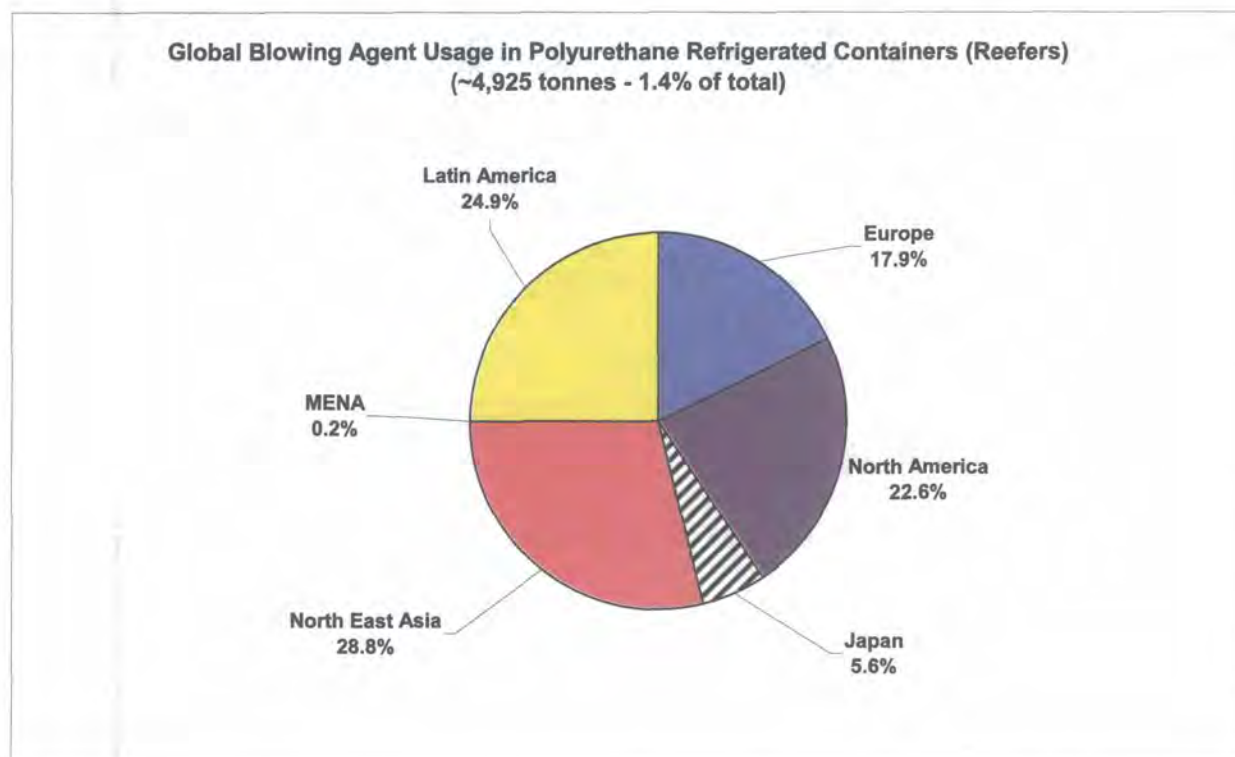
occurred in this and other refrigerated transport applications in developed countries since 2001 with both hydrocarbons and HFCs being selected as alternatives.

Latest Technology Trends

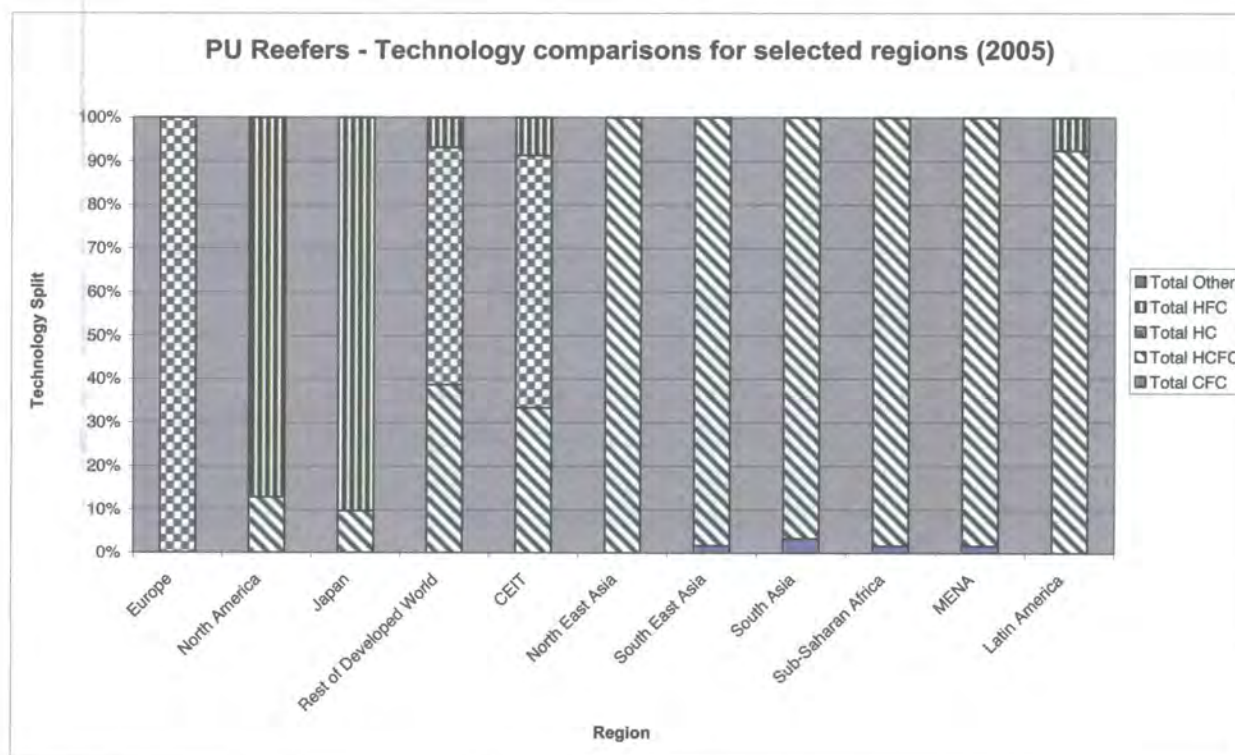
Where hydrocarbons are the preferred technology, linear pentanes are the usual choice. HFC-245fa and HFC-365mfc are the HFCs usually selected except in Latin America where HFC-134a has been used in some applications..

Data Summary

The current global distribution of blowing agent use for reefers and other PU transport applications is shown below:



The transitional status for each of these regions and choice of technologies is shown in the following graph:



Additional Regional Observations

The growth of China as a producer of reefers is well illustrated in the graphs and this is expected to continue. The development of hydrocarbon technology for other transport applications in Europe and for HFCs in North America and Japan is well illustrated, although HCFCs are likely to continue to predominate in most developing country regions.

CONSTRUCTION APPLICATIONS

This sector covers all applications of rigid polyurethane foams in building and construction, including the use of foamed panels in large-scale walk-in cold storage facilities, which are typically considered as temporary buildings.

BOARDSTOCK

Current Technology

At this point in time, boardstock manufacture is predominantly a developed country activity. Both HCFC-141b and n-pentane (or iso-pentane) were used in Europe from 1992 until the phase-out of HCFCs in 2003. Most remaining HCFC-141b use transferred to hydrocarbon on or around that date, although smaller niche applications converted to HFCs where the best foam fire performance has been required. Technology based on n-pentane has now therefore achieved greater than 95% of the market. In North America, the boardstock industry held to the use of

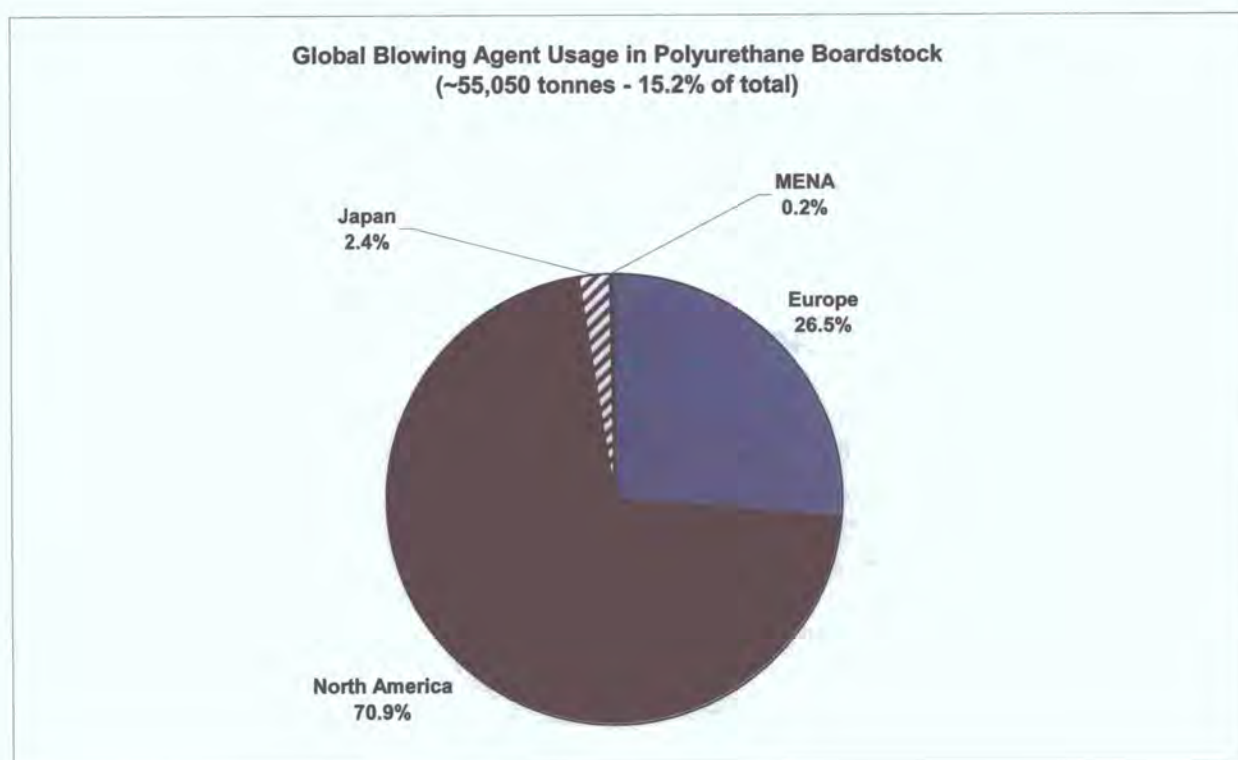
HCFCs until 2004, when the phase-out in use of HCFC-141b was mandated. For some time there was a question as to whether HFCs or hydrocarbons would be the predominant replacement technology. However, the industry virtually decided *en masse* to switch to hydrocarbons, with n-pentane being a substantial component of most blends in use. In Japan, HCFC-141b was the primary blowing agent in use until approximately 2003 when transition to both HFCs and hydrocarbons took place. Since then there has been additional pressure to switch out of HFCs and the PU boardstock market in Japan is now virtually completely hydrocarbon-based.

Latest Technology Trends

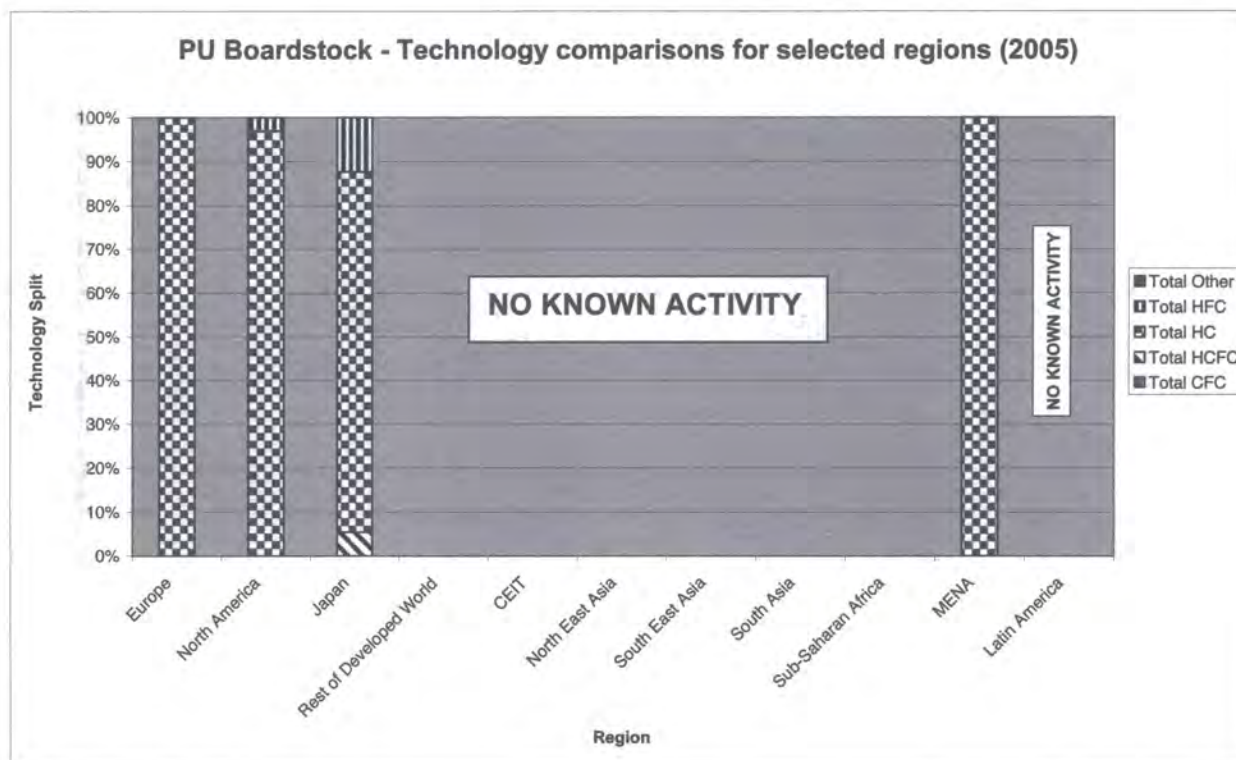
It is likely that hydrocarbons will remain the long term blowing agents in this sector but HFC-245fa and HFC-365mfc (and blends based on them) will continue to find niche applications for end uses where the most stringent foam flammability standards are required. Cost considerations are likely to inhibit their wide-scale use.

Data Summary

The current global distribution of blowing agent use in the boardstock sector is shown below:



The transitional status for each of these regions and choice of technologies is shown in the following graph:



Additional Regional Observations

The only Article 5(1) activity identified is situated in the MENA region and relates to an operation in Iran which is believed to operate with flexible facings. The predominance of PU Boardstock use in the United States (mostly for residential sheathing applications) is also illustrated bearing in mind that the respective sizes of the overall insulation markets in Europe and North America are similar.

PANELS - CONTINUOUS

Current Technology

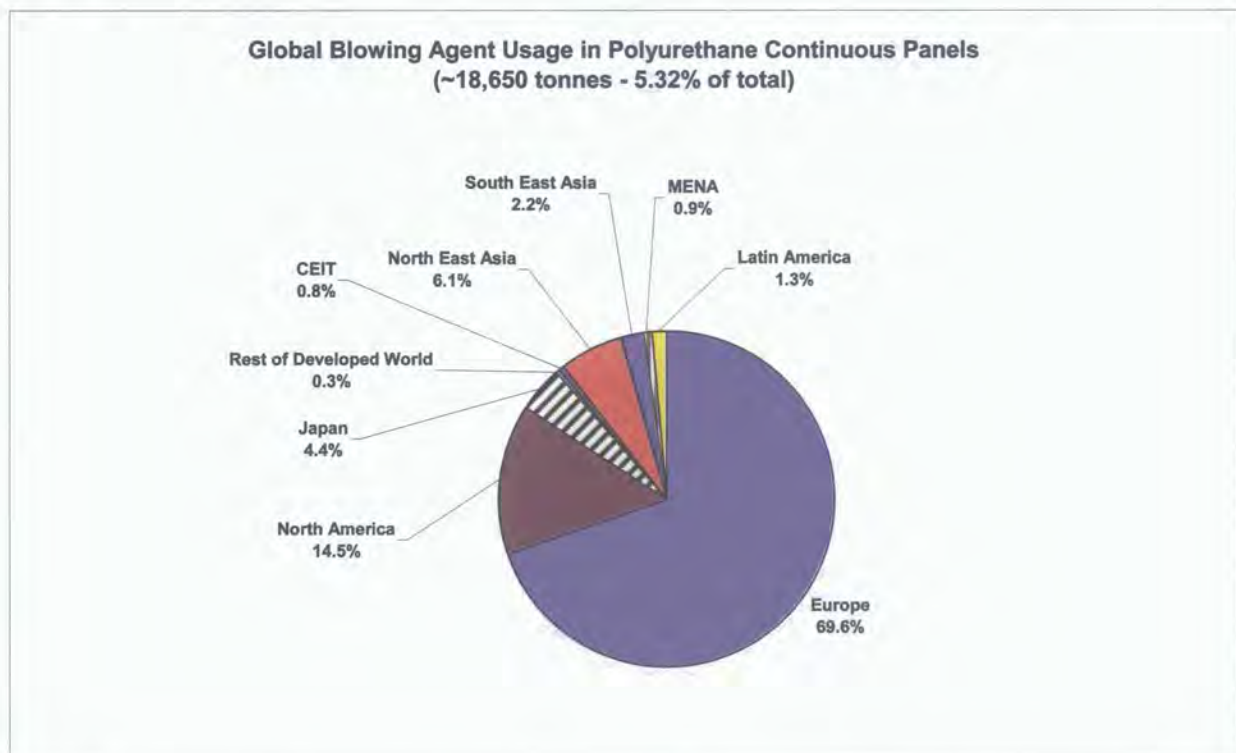
Europe has by far the largest share of the global continuous panel market. The bulk of this capacity uses hydrocarbon as its primary blowing agent. Hydrocarbon technology is also the predominant choice in North America and Japan, although there is some residual HCFC-22 use in the United States pending HCFC phase-out in 2008-2010. The use of CFC-11 has been replaced in nearly all developing country enterprises. The main blowing agent in developing country regions is HCFC-141b.

Latest Technology Trends

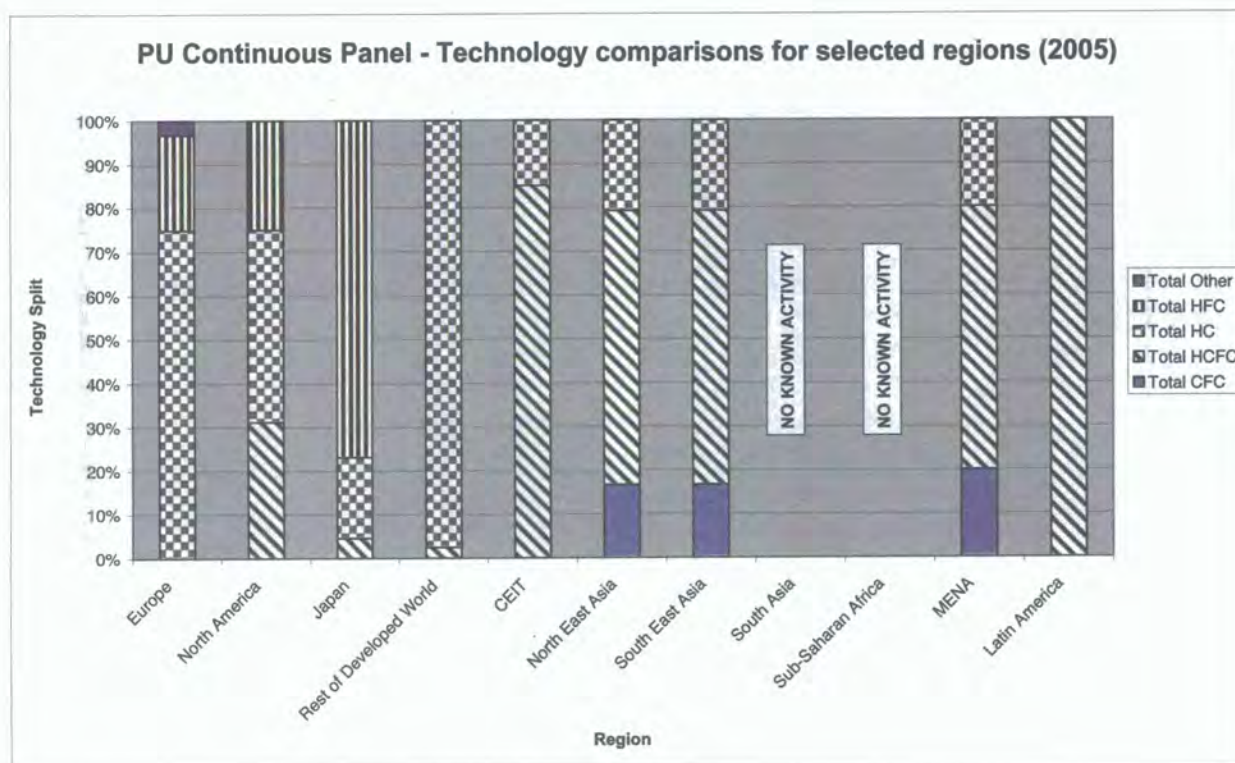
The option to use HFCs will be necessary for end applications where the most stringent end product flammability and insurance requirements are needed. In developing countries the use of HCFC-141b is projected to continue for many years to come.

Data Summary

The current global distribution of blowing agent use in the continuous panel sector is shown below:



The transitional status for each of these regions and choice of technologies is shown in the following graph:



Additional Regional Observations

The technology trends in this sector show a strong regional bias and it is self-evident that selection decisions are driven by divergent local market requirements which vary by sub-sector.

PANELS - DISCONTINUOUS

Current Technology

Although, in 2001, HCFC-141b was the most widely used blowing agent in this sector, the phase-out schedules in developed countries has forced the industry into new technology options. The most widespread in the majority of developed regions are HFCs, primarily because of the process safety afforded by the transition. Considerable usage of HCFCs continues in North America because of the preference for HCFC-22 based technologies. Meanwhile, where equipment investment has been possible both cyclo-pentane and n-pentane have been used in the European and some developing country markets for several years.

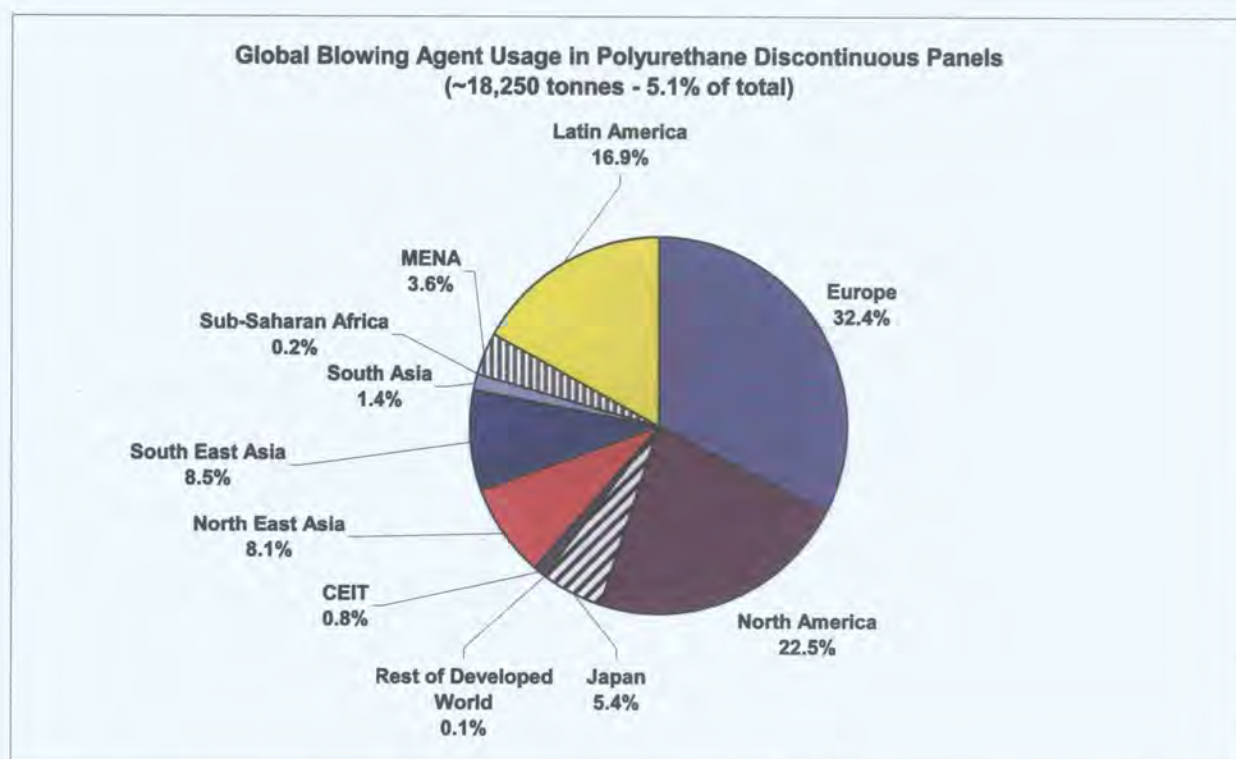
In developing countries, HCFC-141b has been the predominant replacement for CFC-11, although some CO₂ (water) and other non-fluorinated technologies have also been used.

Latest Technology Trends

There is likely to be some further extension of the use of hydrocarbon technologies in this sector, driven by cost, as existing equipment is replaced. However, HFCs are expected to maintain a prominent role in this application for the foreseeable future.

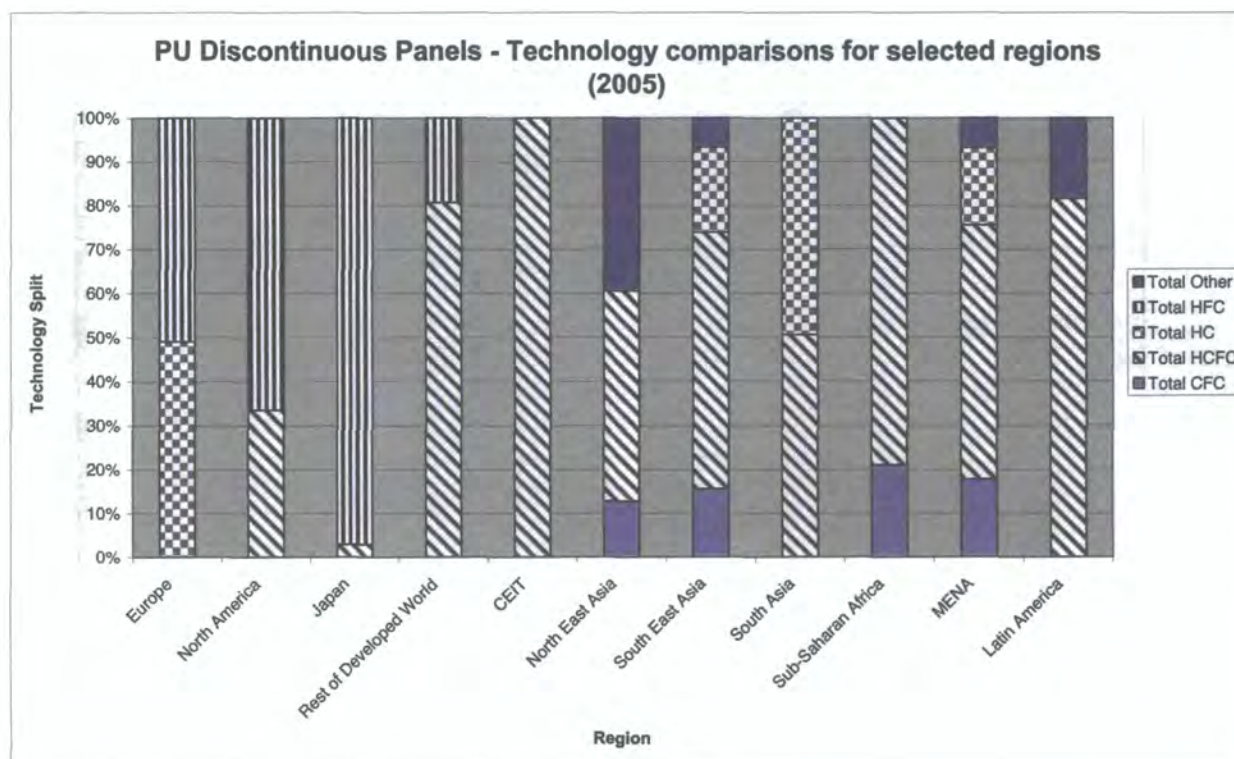
Data Summary

The current global distribution of blowing agent use in the continuous panel sector is shown below:



This graph illustrates the widespread operation of discontinuous panel operations around the world. With the exception of the South Asia region, the production levels seem to be related primarily to population levels.

The transitional status for each of these regions and choice of technologies is shown in the following graph:



Additional Regional Observations

The continuing reliance on HCFCs in this sector is self-evident in developing countries, although hydrocarbon technologies continue to be introduced on the back of earlier decisions, particularly where the capital costs can be addressed under the Multilateral Fund.

SPRAY FOAM

Current Technology

As with discontinuous panels, transitions have broadly been forced by regulation on HCFC-141b in developed countries. The transition in the United States has perhaps proved the most difficult. Throughout non-Article 5(1) countries, HFCs have been the preferred technologies, primarily on the basis of safety, although some interest continues in CO₂ (water) and hydrocarbons. The use of CO₂ (water) is in applications where the higher (about 50%) foam thickness to give equivalent insulation value can be accommodated. HCFC-141b continues to be used to some degree in Canada and Australia..

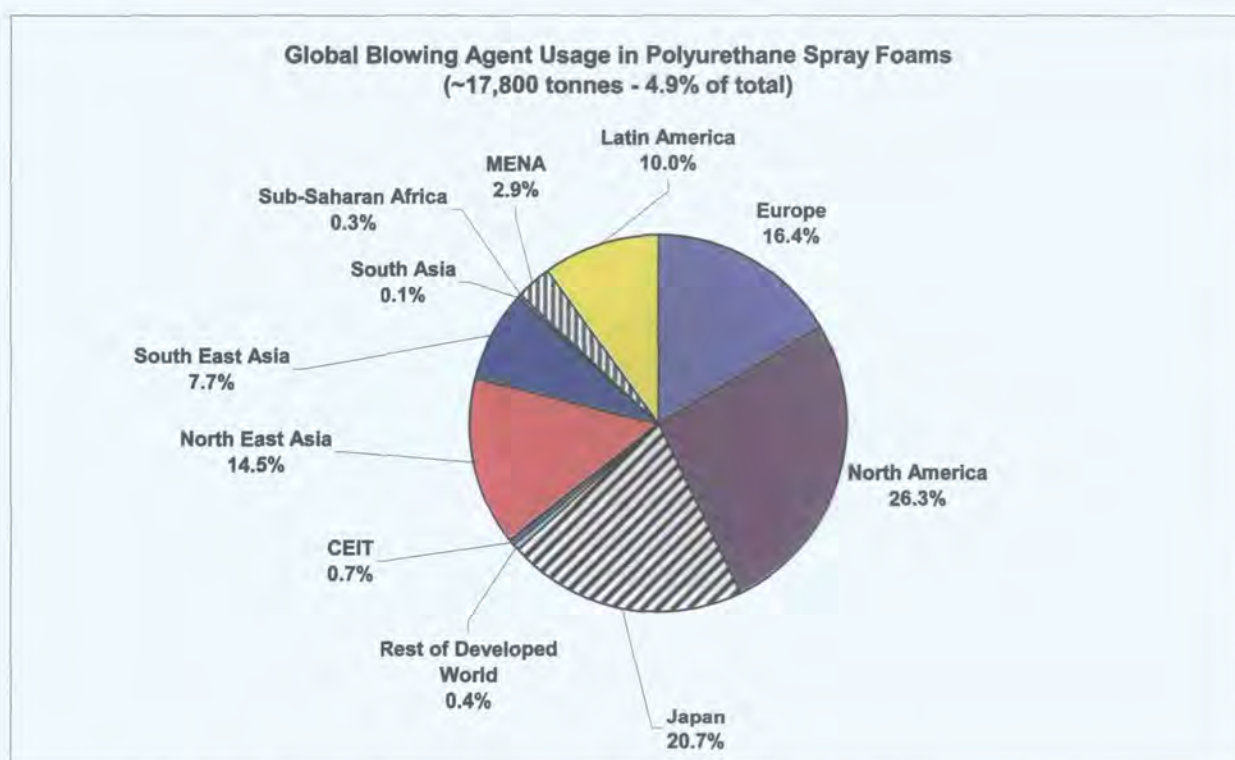
For developing countries, the transition from CFC-11 to HCFC-141b is virtually complete except for a small continued use in North East Asia and perhaps an even smaller amount in Chile. Based on experience in developed countries, there is expected to be little appetite for further transition to other alternatives in the short-term.

Latest Technology Trends

Super-critical CO₂ systems are continuing to display potential in Japan and commercial systems and equipment are being offered on a widespread basis. However, market penetration is understood to be no more than 10-15% at this stage. In other developed countries, HFCs are likely to continue to dominate this market in the foreseeable future.

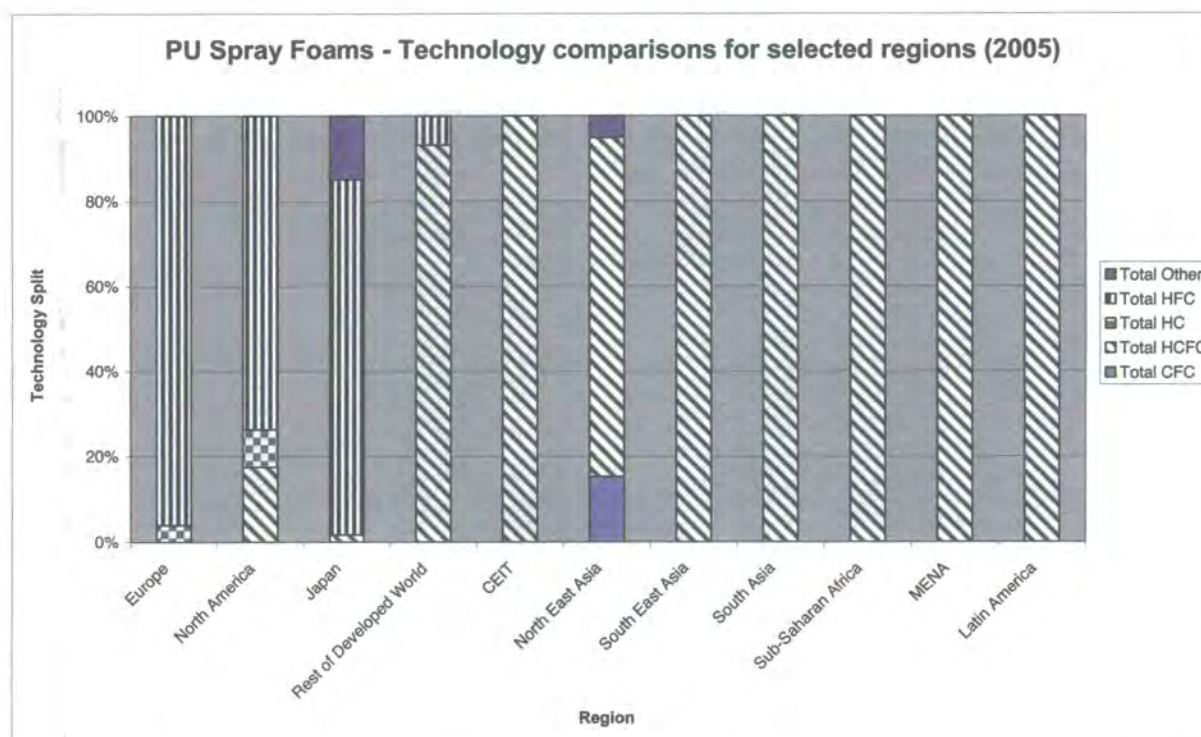
Data Summary

The current global distribution of blowing agent use in the PU Spray Foam sector is shown below:



As before, the widespread use of spray foam technologies is demonstrated with well-established markets in both North America and Japan. Markets are growing rapidly in Europe and in some Article 5(1) regions, where the utility of spray foams is assisting in the retrofit of many existing buildings.

The transitional status for each of these regions and choice of technologies is shown in the following graph:



Additional Regional Observations

As stated previously, the dominance of HFC-based technologies in developed countries and HCFC-based technologies in developing countries is self-evident from this graph.

ONE-COMPONENT FOAM

Current Technology

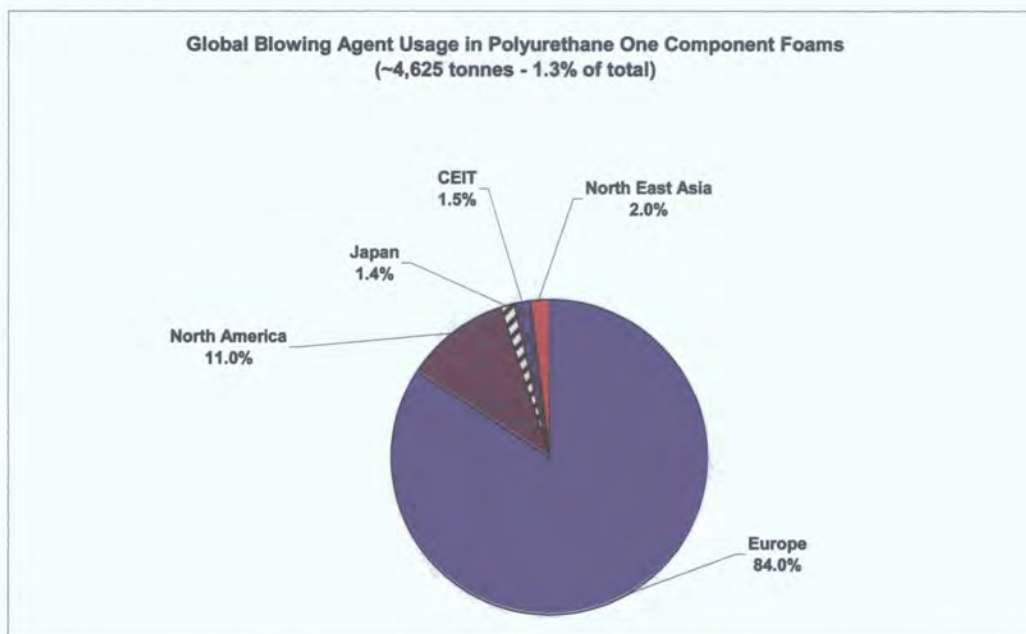
The European share of one-component foams (>80%) continues to be the dominant component of the global market. With the phase-out of HCFC use in developed countries complete, with the exception of HCFC-22 in the United States, the replacement technologies have either been HFC-based or, increasingly hydrocarbon-based. The switch to hydrocarbons has required process and product safety measures, but regulatory pressure in Europe seems to have provided the necessary incentives. Phase-out of HFCs in the EU for this application is now anticipated in 2008. Most formulations involve blends which are often quite complex.

Future Technology Trends

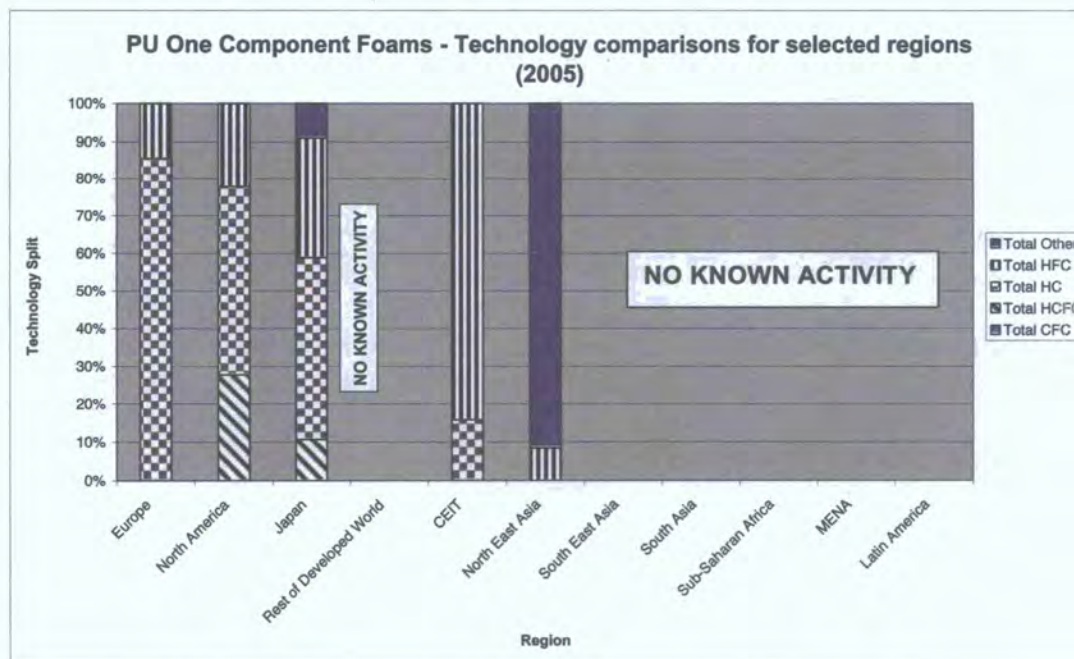
Growth is expected to continue in this application as demands for air-tightness in buildings increase. However, for new manufacturing capacity, it will remain possible and, indeed, more cost-effective to design for hydrocarbons from the outset.

Data Summary

The current global distribution of blowing agent use in the One Component Foam sector is shown below:



The transitional status for each of these regions and choice of technologies is shown in the following graph:



Additional Regional Observations

Although the composition of OCFs in the North East Asian region stands out as unusual, it needs to be recognised that most gaseous propellants/blowing agents can be used in this application. In addition, the volume of OCFs produced in China is generally low, as indicated in the preceding graph.

PIPE-IN-PIPE (including moulding of pipe sections)

Current Technology

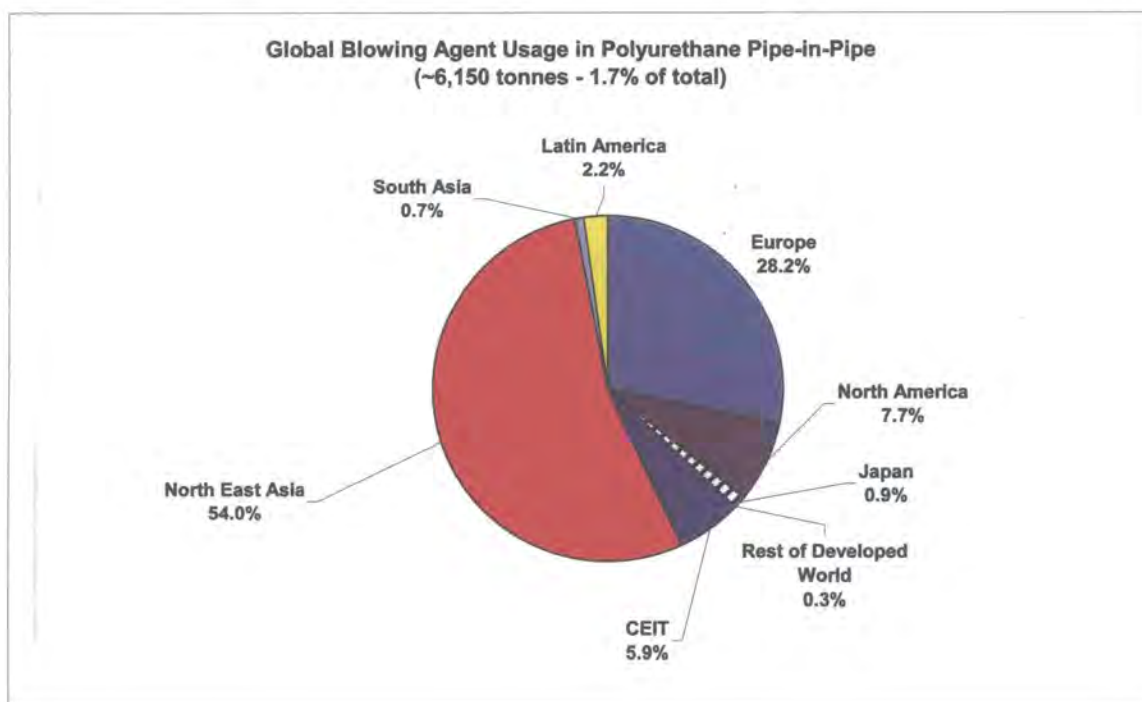
The main blowing agents in use where HCFC phase-out has occurred are HFCs, hydrocarbons and CO₂ (water). In Europe cyclo-pentane remains the industry standard. In developing countries (most notably North East Asia), HCFC-141b has been the replacement for CFC-11 and there has been no discernable transition directly to hydrocarbons.

Latest Technology Trends

The replacement of HCFC-141b with cyclopentane is the most likely next step in developing countries.

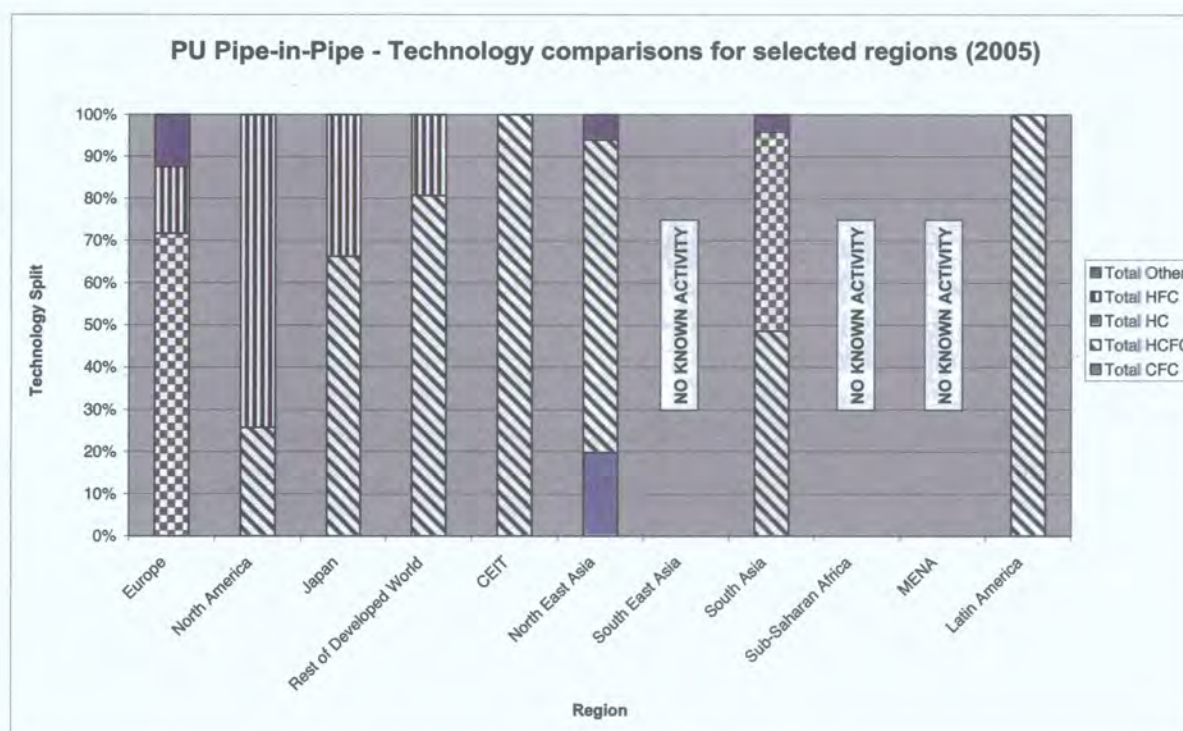
Data Summary

The current global distribution of blowing agent use in the pipe-in-pipe sector is shown below:



It can be seen that the utilisation of district heating in the centralised Chinese system has a major effect on the overall blowing agent consumption in this sector. Technology decisions in this region will therefore have a considerable impact on the overall footprint of this sector.

A summary of the transitional status for each of these regions and choice of technologies is shown in the following graph:



Additional Regional Observations

When compared to 2001, the reduction in dependence on CFC-11 technology is substantial, with HCFC-141b being the preferred technology choice. There has been little if any in-roads from European hydrocarbon technologies at this stage.

BLOCKS – PIPE SECTION

Current Technology

Although there is still some residual CFC-11 use in this sector, HCFC-141b represents the bulk of blowing agent use in developing countries.

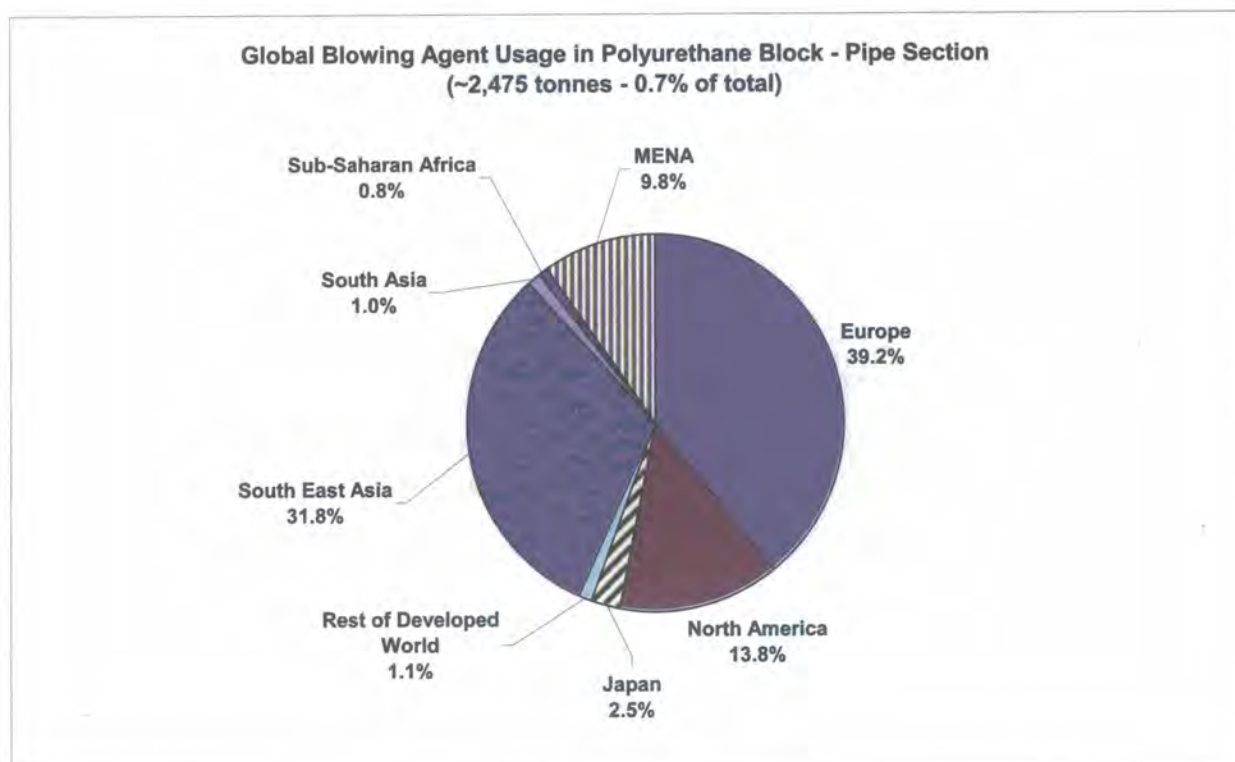
For non-Article 5(1) countries, there has been greater uptake of hydrocarbon technologies than had been originally anticipated, particularly in Europe. HFC-based technologies have accounted for the balance of transitions in developed countries.

Latest Technology Trends

There are no obvious further transitions expected on the block foam sector in the short-term, although further transitions to hydrocarbon will be possible as existing equipment is replaced.

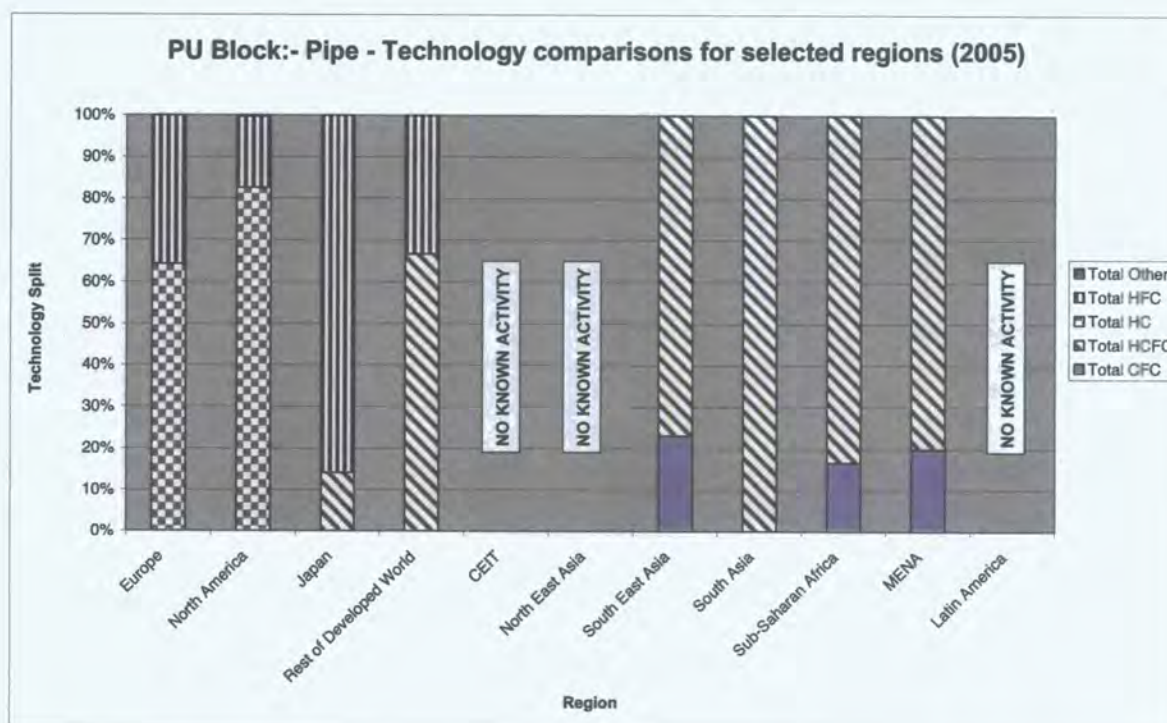
Data Summary

The current global distribution of blowing agent use in the PU Block (pipe section) sector is shown below:



The differences in development of the PU block foam market in Europe and North America is interesting, bearing in mind that both insulation markets are roughly the same size. This seems to relate to the dominance of the mineral fibre lobby in the pipe insulation sector of the North American market. It can be seen that the versatility of process and relatively low investments costs has allowed it to get a foothold in most regions of the world to a greater or lesser degree.

The transitional status for each of these regions and choice of technologies is shown in the following graph:



Additional Regional Observations

There are some surprising omissions in the regions although we have recorded these under the heading 'no known activity', they could equally read as 'no data available'.

BLOCKS – SLABSTOCK

Current Technology

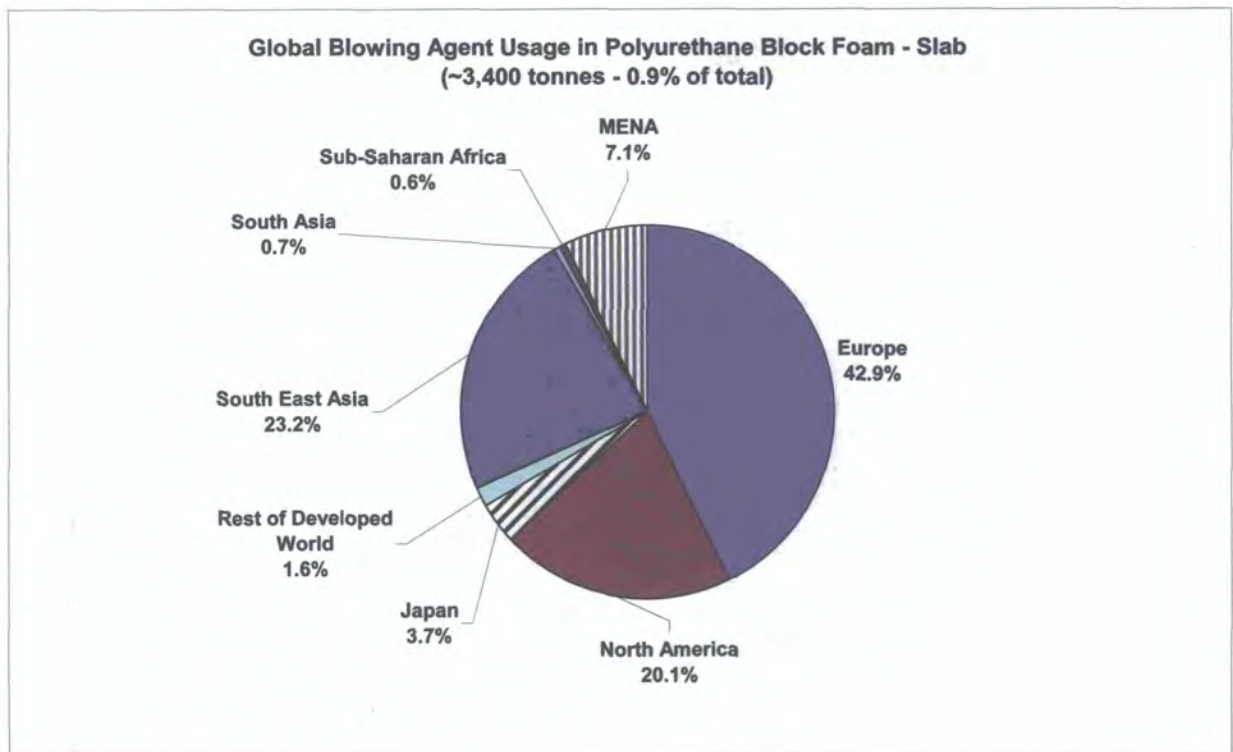
Comments are as for the Block (pipe section) sector, since the basic block manufacturing facilities are identical and often shared.

Latest Technology Trends

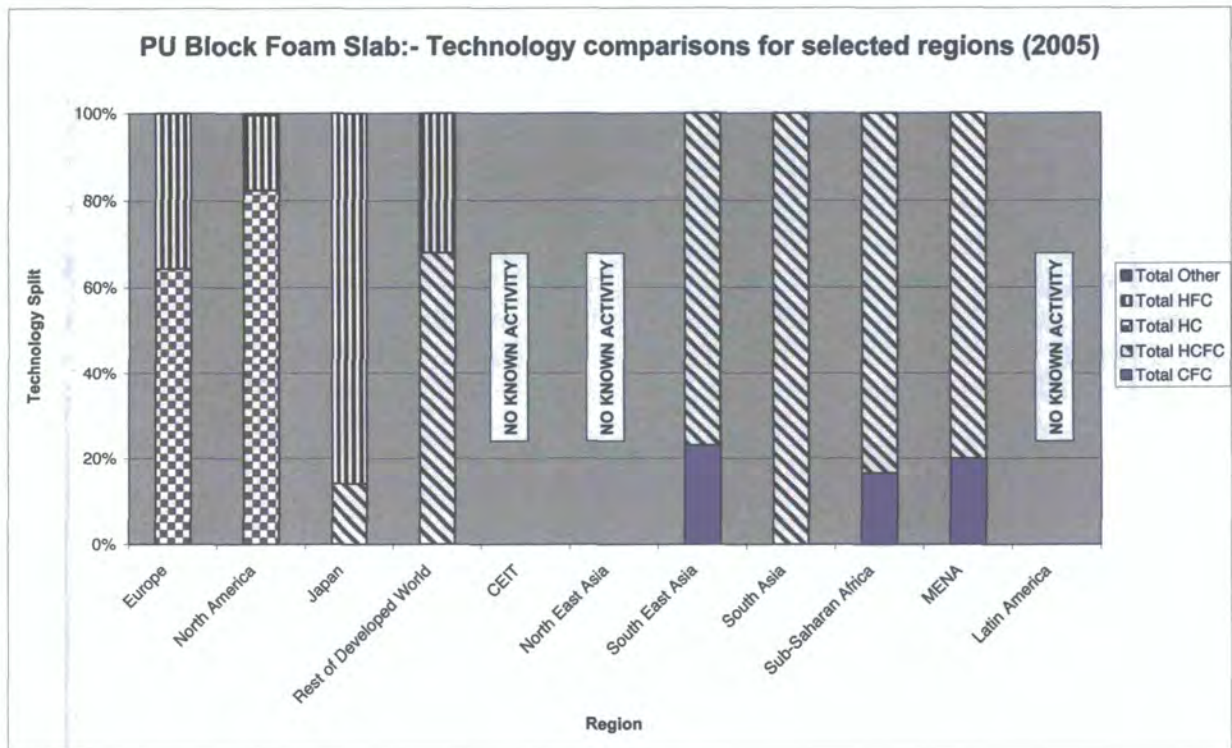
Comments are as for the Block (pipe section) sector, since the basic block manufacturing facilities are identical and often shared.

Data Summary

The current global distribution of blowing agent use in the PU Block (slab foam) sector is shown below:



The transitional status for each of these regions and choice of technologies is shown in the following graph:



Additional Regional Observations

Comments are as for the Block (pipe section) sector, since the basic block manufacturing facilities are identical and often shared.

FLEXIBLE POLYURETHANE FOAM

SLABSTOCK

Current Technology

The remaining use of CFCs in flexible PU slabstock has, according to recent project assessments, been phased out. However, only future country reporting will finally confirm this fact. Certainly, from a technical perspective, there is no justification for their continued use. In the flexible slabstock area, there is no known use of fluorocarbons as replacement technologies. Accordingly, this sector does not pose any further challenge to the Montreal Protocol objectives. The main technologies now in use are methylene chloride and carbon dioxide (CO₂ (LCD)). Other, more minor technologies also exist and, between them all, they cover all applications. However, processing is sometimes more challenging and in some cases more expensive. This is specifically the case for low density/high hardness foams where the high process temperature ("exotherm") limits the effectiveness of some current replacement technologies.

Methylene chloride continues to be under scrutiny from a health and safety perspective. However, the pressure for replacement has not grown substantially since 2001.

Liquid carbon dioxide, while successful in developed countries, specifically when the use of methylene chloride is restricted or forbidden, proved to be a serious challenge in most Article 5(1) countries. The combination of a complicated technology with virtually unchallenged use of easy-to-process methylene chloride proved a major burden for an initially enthusiastic embrace of the environmentally preferable LDC option. In the USA there is also considerable use of acetone and in Europe some use of variable pressure technology. On a smaller scale, special additives are used—frequently as co-technology to limit the amount of methylene chloride required. There is also very limited use of n-pentane, formic acid and MDI based foams—the latter generally for speciality products. Forced cooling, a previously popular technology in the USA has virtually disappeared because of perceived increased emissions of TDI and fire risk.

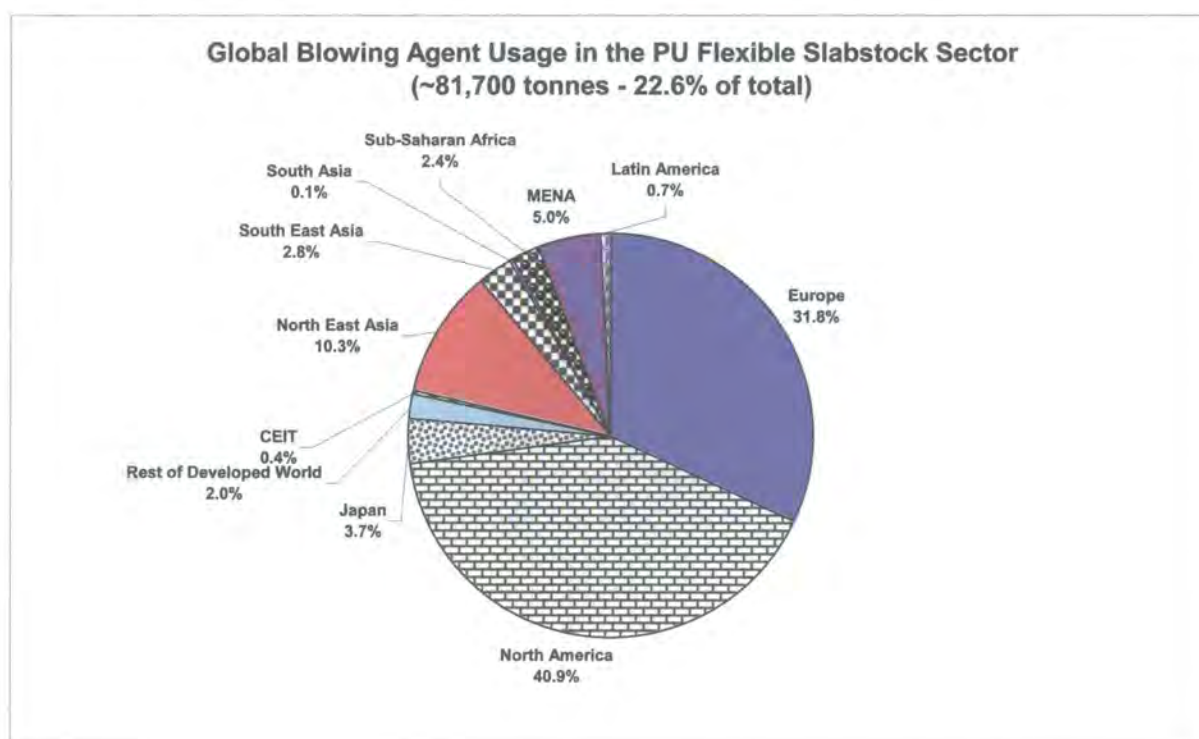
Latest Technology Trends

Continuing environmental pressure to reduce emissions of volatile organic compounds, keep the industry stakeholders focusing on technologies that avoid these compounds or are otherwise environmentally beneficial. Legally intricate definitions, specifically in the some states in the USA, have allowed the exemption of acetone as a volatile organic compound while hydrocarbons continue to qualify as such. This clouds the issue. True environmentally beneficial technology with good process performance are Variable Pressure (VPF), Liquid Carbon Dioxide (LCD) and Exotherm Management (EMT technologies. Because of high investment costs and

complicated processing, VPF technologies have not lived up to their promise, while LCD has proven to require sophisticated in-house engineering skills. EMT continues to be particularly of interest for companies with lower sophistication levels since it combines the option to produce all-water based foams at acceptable process temperatures with simple processing, cost-effectiveness and low conversion costs. It is most easily applied in box-foam applications and is therefore the most potent—maybe the only—“third generation” technology for small enterprises.

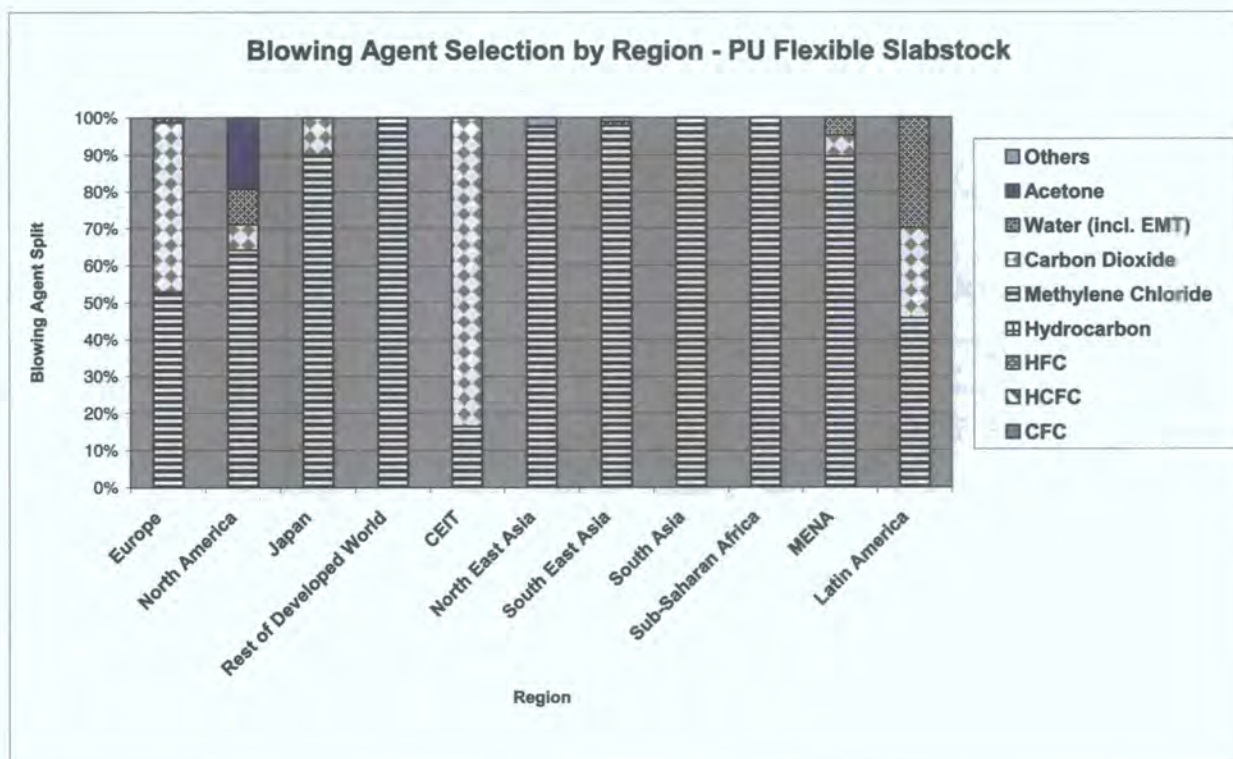
Data Summary

Although a full assessment of the global spread of blowing agent use in flexible slabstock has not been carried out for this report, the current global distribution of flexible slabstock foam production is believed to be broadly unchanged since 2001 and is shown below:



It should be noted, however, that data on slabstock production in developing countries are often difficult to ascertain. Nevertheless, anecdotal reports suggest that the developed country share of manufacture has reduced since 2001 in the face of increased competition from Asian imports, mostly within imported flexible foam-containing products.

The transitional status and choice of technologies is shown in the following graph.



Additional Regional Observations

The use of replacement technologies other than methylene chloride in some developing countries may be overstated. While many enterprises have installed LCD technology (CO₂ (LCD)) and some variable pressure technology, the actual use may be far less. The use of these technologies is technically challenging and many enterprises use methylene chloride alongside. In the USA, many states have a maximum allowable emission of methylene chloride per set time period. Companies may produce as much as they can with methylene chloride and then continue with other technologies.

MOULDED

Current Technology

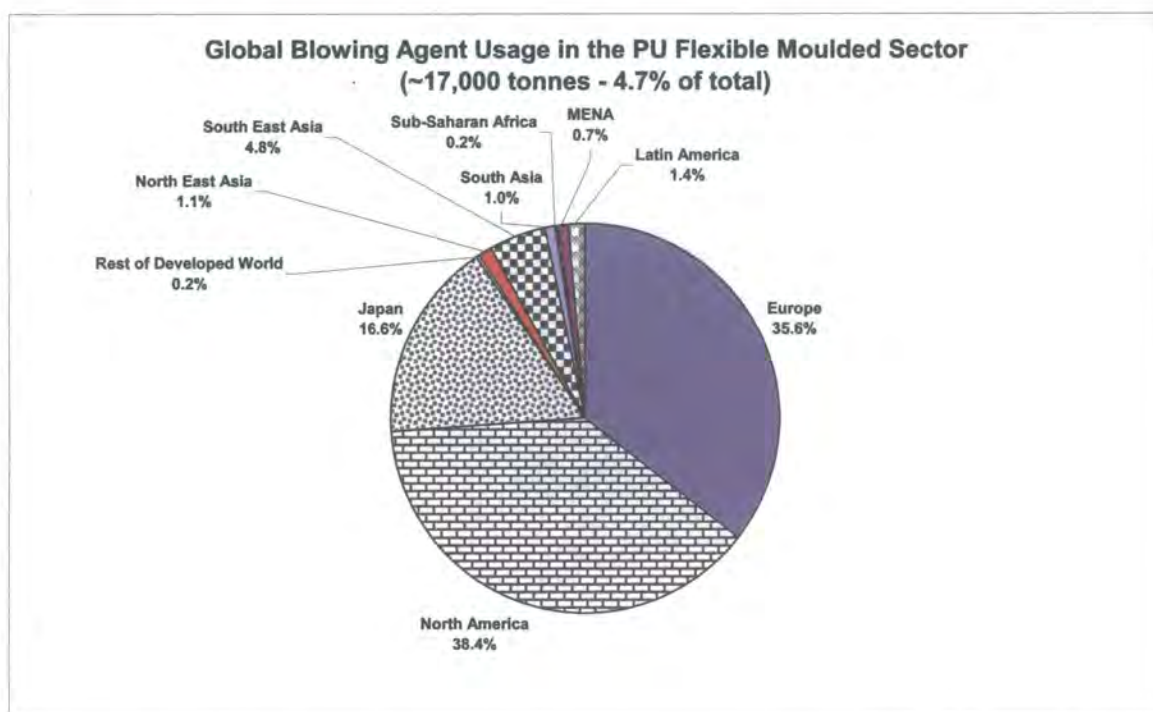
All-water-based technology is predominant in cold cured foams. In hot-cure applications there is also use of methylene chloride. In very low density/soft foams (e.g pillows) there is some use of LCD or GCD but generally, this technology did not get the same attention as in slabstock applications—most likely because there is no exotherm problem and water-based technology performs well in most cases. In developing countries there is now very little, if any, use of CFC-11 at all. HCFC-141b is used in exceptional circumstances such as highly filled acoustical foams but is not essential as a replacement in this industry. The use of HCFCs in this industry is not allowed in most developed countries.

Latest Technology Trends

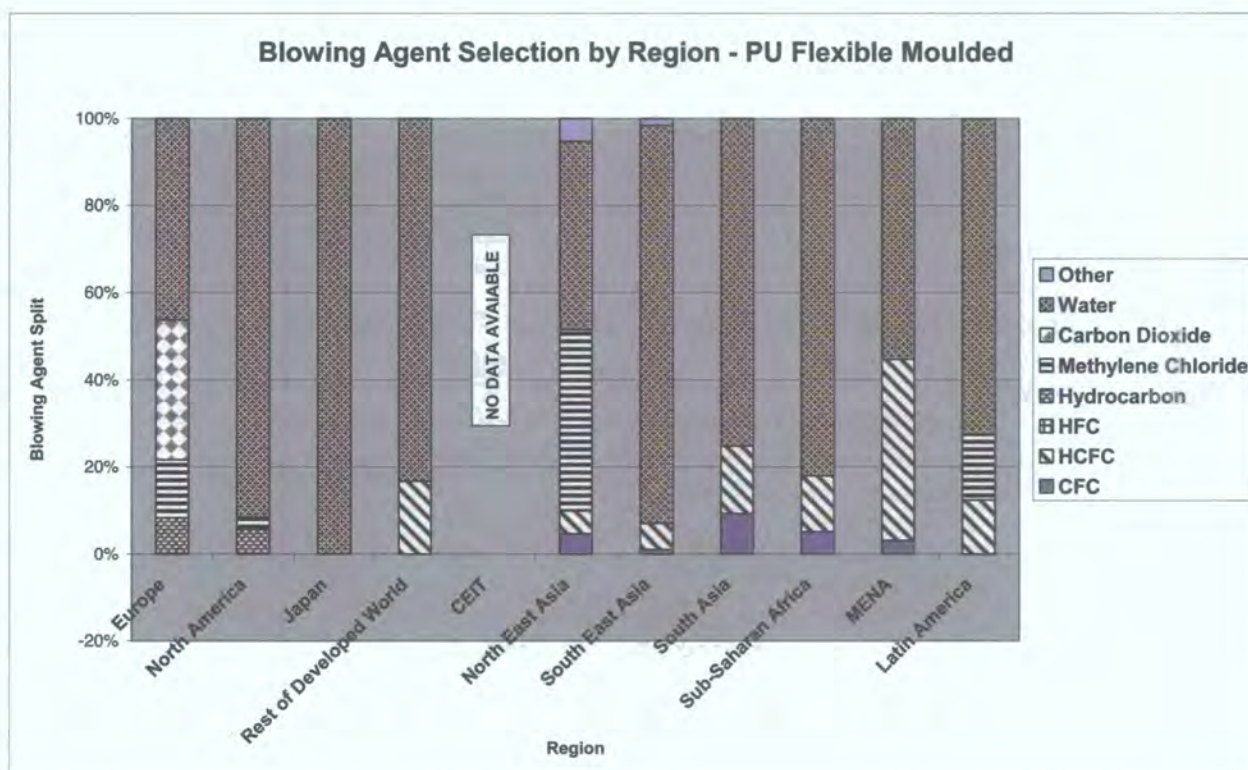
There are no significant technology trends in this industry related to blowing technology. The remaining HCFC use can be phased out without any technical challenges and while avoiding major investments, although there can be a cost penalty for low density applications.

Data Summary

The current global distribution of flexible moulded foam production is shown below:



The transitional status and choice of technologies is shown in the following graph.



Additional Regional Observations

As mentioned, the remaining HCFC use is related to low density or highly filled applications in developing countries. The conversion to HCFC-free systems may carry a density penalty or require the use of foams with a high TDI content. These systems would require strict control of workplace emissions.

INTEGRAL SKIN AND MISCELLANEOUS FOAMS

This sector includes both rigid and flexible integral skin applications and also non-insulating rigid foam applications for packaging, leisure (e.g. surf boards), floatation and floral foams.

Integral Skin

Current Technology

In integral skin foams, CFCs were used not only as blowing agent but also as skin-enhancer and, in some systems, viscosity cutter. These additional functions—which have different importance across a range of differing applications have triggered a multitude of (zero/low ODP) replacement technologies that are frequently application specific.

Rigid integral skin foams have almost universally converted to all-water-based systems. In most of these applications, skin formation is triggered through densification (mould pressure) rather than condensation. Accordingly, subsequent coating may be required and densities can be increased. However, since densities in this application are already relatively high, this is not a major issue.

This is not the case for flexible and semi-flexible integral skin foams. The related cost penalty arising from significantly increased densities and the poor skin formation associated with water blown systems has made the use of pentane, hexane and HFCs attractive in developed countries and has caused almost universal conversion to HCFC-141b in developing countries. Other issues relate to the availability of preferred blowing agents in developing countries and acceptable physical properties such as abrasiveness and skin development. One of the drivers in the technological development was early legislation in the USA and the EU, which prohibited the use of HCFCs in all non-thermal insulation applications (except, initially, in safety related automotive products).

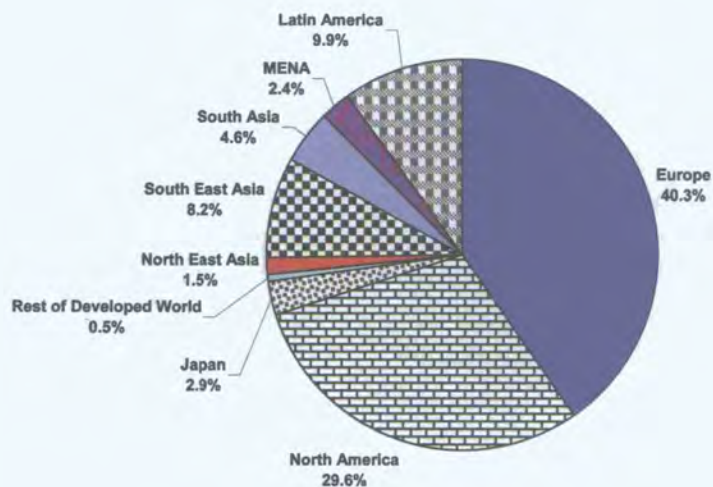
Latest Technology Trends

An interesting recent trend in the integral skin sector has been the use of various HFCs in the manufacture of shoe soles in Europe. Although consumption is relatively small, it stands out as one of the few applications for open-celled polyurethane foams where HFCs have been necessary. The technology has been under close review in the light of the recent F-Gas Regulation in the EU, but continues to be justified for performance reasons.

Data Summary

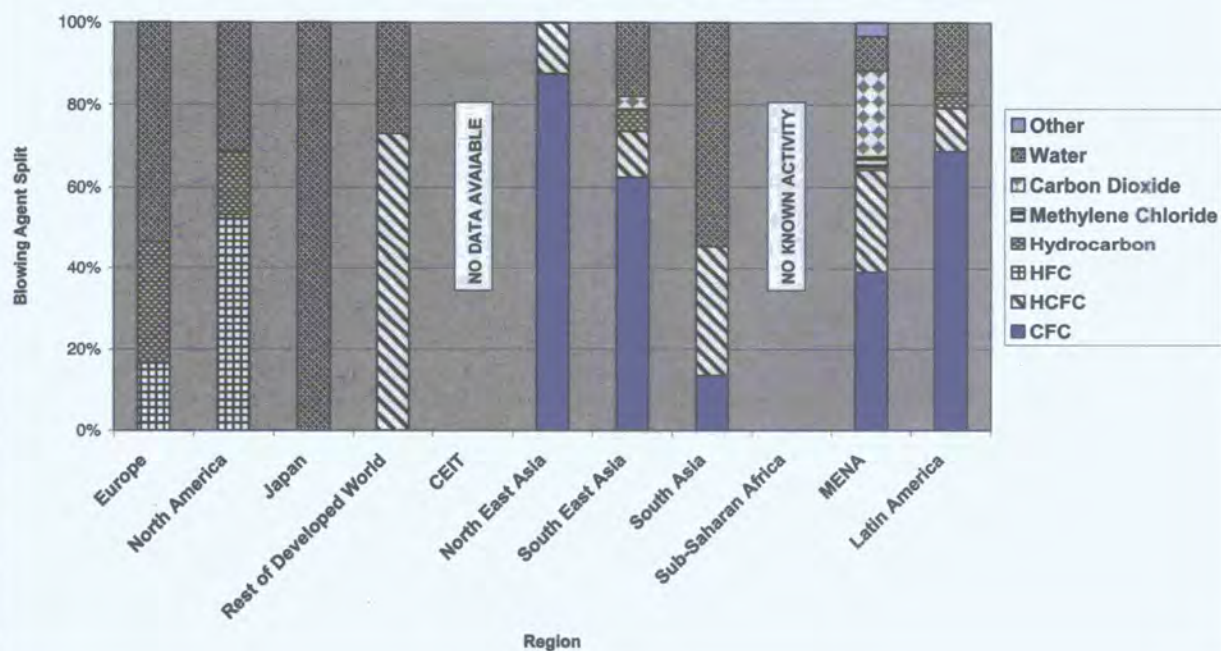
The current global distribution of PU Integral Skin foam production is shown below:

**Global Blowing Agent Usage in the PU Integral Skin Sector
(~11,000 tonnes - 3.0% of total)**



The transitional status and choice of technologies is shown in the following graph.

Blowing Agent Selection by Region - PU Integral Skin



Additional Regional Observations

Because of the relatively small market for integral skin foam products and the wide variety of technical requirements the development of suitable non-ODS alternatives in this sector has been a low priority for chemical suppliers. This is specifically the case for developing countries where densities in general are lower and technologies that are acceptable in developed countries do not always perform. The introduction of adequate—cost-effective and technically acceptable—non-ODS technologies in these countries is a concern. While future introduction of liquid HFCs will allow the entire range of technical requirements, the related costs may be prohibitive and the availability a concern.

POLYOLEFIN FOAMS

There are three prime product types in the uncross-linked polyethylene foam sector: sheet, plank and tubular. All of these have used CFCs in the past. This is in contrast to cross-linked polyethylene foams which are produced for specialist applications and have typically been blown with inert gases such as nitrogen. The transition issues facing sheet, plank and tubular products are broadly similar and these are therefore considered together in this review.

Current Technology

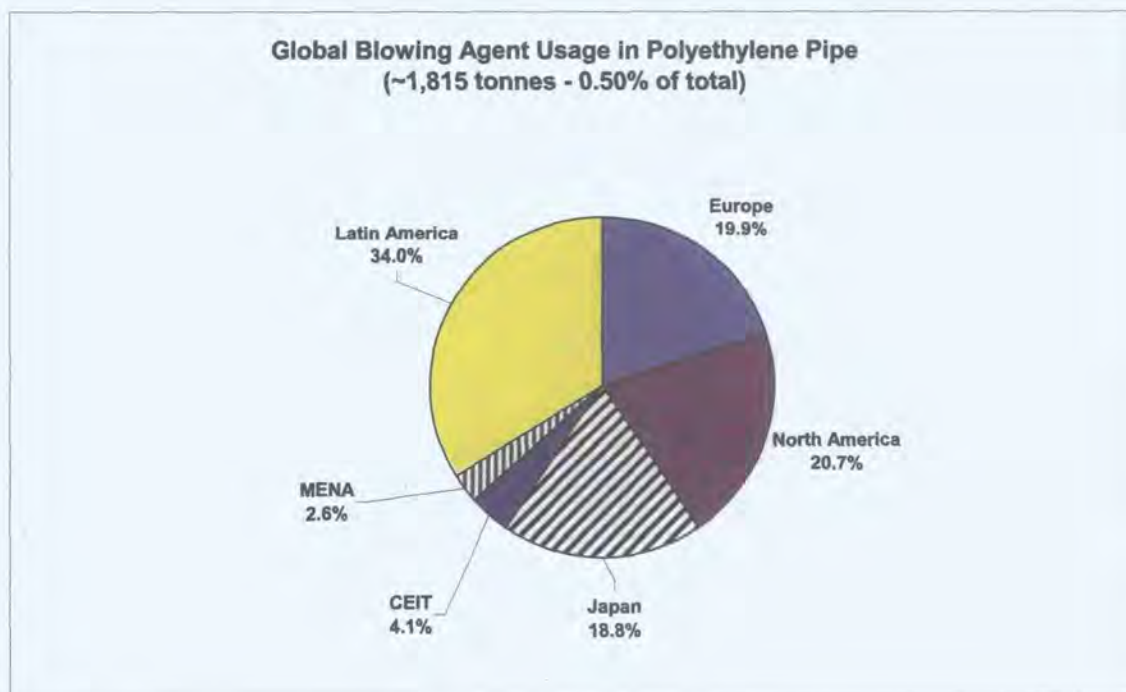
With the use of HCFCs phased-out in several non-Article 5 countries as early as 2000, the primary technologies currently in use are based on various hydrocarbons. However, use of HCFC-142b continued in Japan until 2004 but is now virtually phased-out in favour of hydrocarbons and, to a lesser extent, HFC-134a.

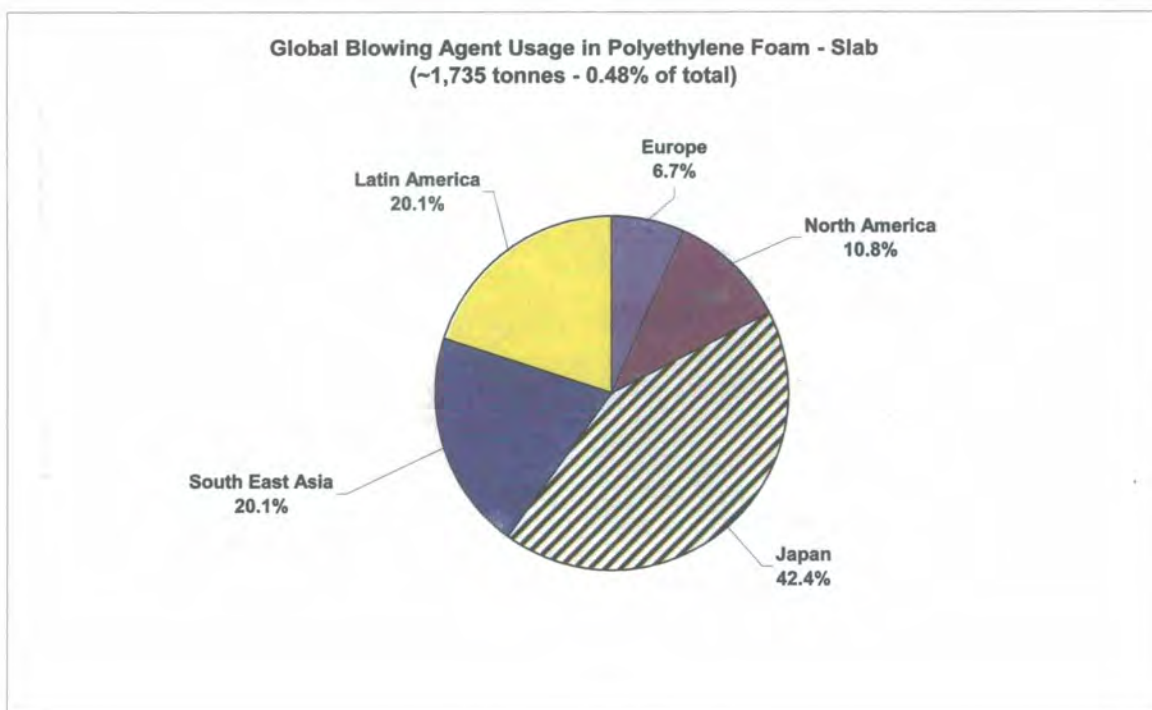
Latest Technology Trends

Hydrocarbons (most notably iso-butane) are expected to remain long-term substitutes in this sector, except where specific thermal or flammability performance is required.

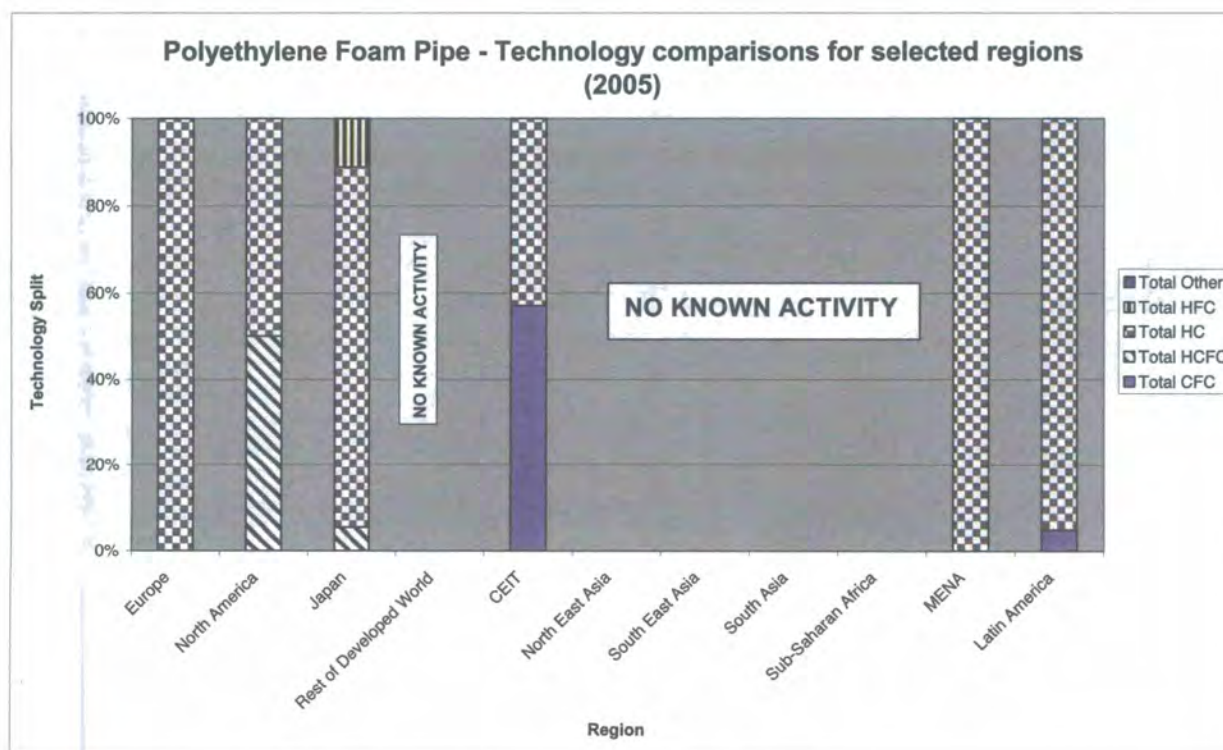
Data Summary

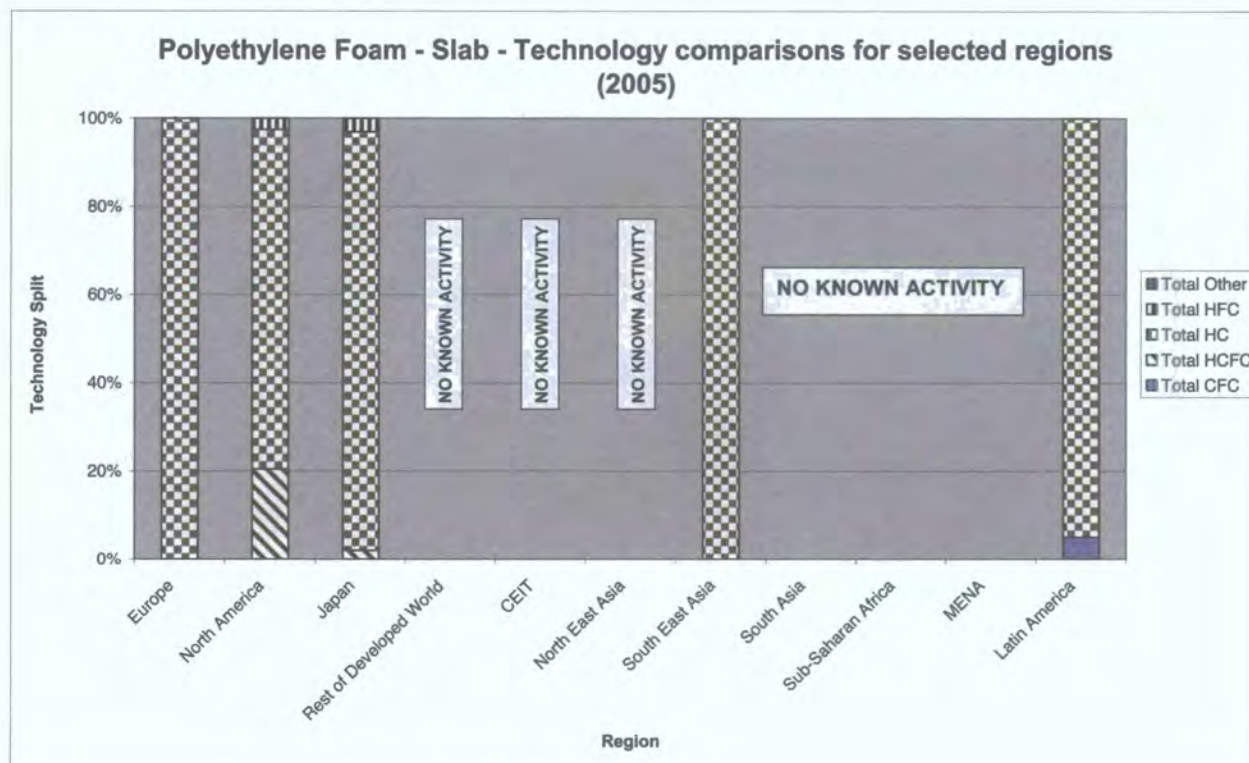
The current global distribution of extruded polyethylene foam production for pipes (tubular) and slab (sheet or plank) applications are shown separately below:





The transitional status and choice of technologies is shown in the following graph.





Additional Regional Observations

Although hydrocarbon use is more widespread in extruded polyethylene foams than in XPS board, it is assumed in this resume that the polyethylene market in the United States of America continues with partial use of HCFCs, bearing in mind that the use of HCFC-142b and HCFC-22 will be allowed until at least 2008. However, currently, SNAP rules limit HCFC use to insulation applications only and future SNAP provisions may lead away from HCFC use altogether prior to the phase-out in supply of HCFCs in 2010.

EXTRUDED POLYSTYRENE FOAMS

SHEET

Use of CFCs or HCFCs, is considered technically unnecessary in both Non-Article 5 and Article 5 Countries and have been banned by a significant number of countries. A wide range of alternative blowing agents have been evaluated for use in polystyrene sheet foam including: atmospheric gases (CO_2 (LCD), nitrogen); hydrocarbons (butane, isobutane, pentane, isopentane), HFCs (HFC-134a, HFC-152a); and hydrocarbon / CO_2 (LCD) blends.

Current Technology

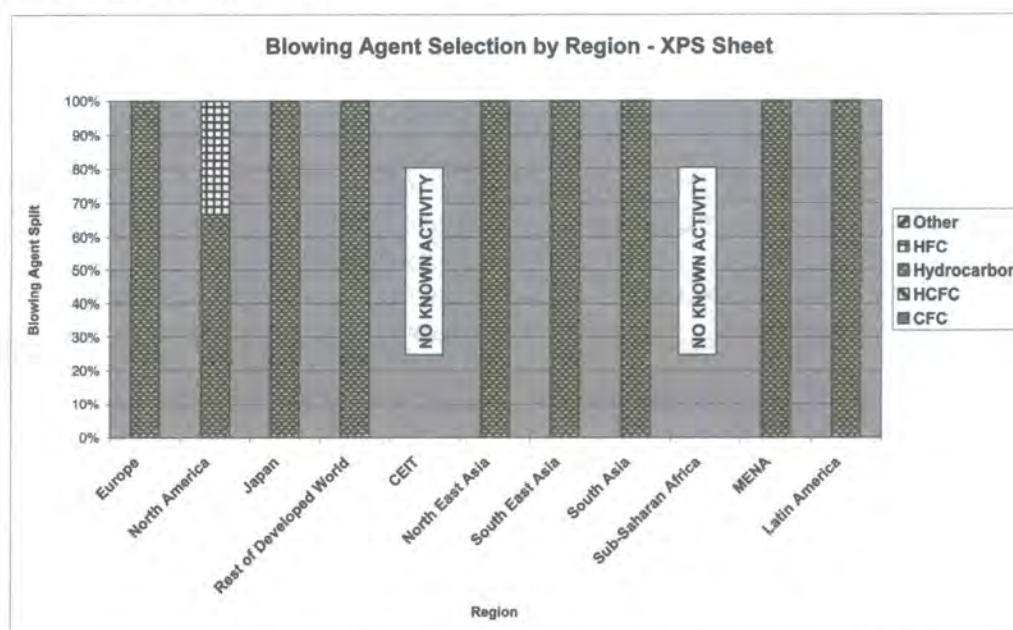
Hydrocarbons (butane, isobutane, pentane, isopentane), HFCs (HFC-134a, HFC-152a); and hydrocarbon / CO_2 (LCD) blends, have found a range of commercial use with hydrocarbons being the dominant selection in most regions. HFC-152a also been used significantly in the United States to overcome local VOC emission regulations.

Latest Technology Trends

Few future developments are expected. However, capital investment required for the handling of flammability issues and on-going concerns over VOC emissions will be limiting factors in further expansion of hydrocarbon containing systems.

Data Summary

A global assessment of blowing agent quantities in use within the XPS sheet market has not been conducted for this sector because of difficulties in collecting information from a very diverse and diffuse packaging industry. However, an assessment of the transition technologies has been made and is shown below:



Additional Regional Observations

There is a need to ensure that XPS sheet projects are sufficiently funded to avoid unnecessary transitions to emissive HFC-based technologies.

BOARDSTOCK

Current Technology

CFC's have not been a significant factor in this segment since the early 1990's. HCFC-142b and HCFC-22 found widespread use in non-Article 5 countries as initial replacements, but these have been phased out in Europe and Japan. In Europe, the primary replacement technologies have been HFC-134a, HFC-152a and CO₂ (or CO₂/alcohol), while in Japan there has also been significant use of hydrocarbons (notably iso-butane). In North America, the transition away from HCFCs has been more difficult because of particular product requirements, especially in the residential sector. HCFC-142b, therefore, remains the dominant blowing agent.

There has been substantial growth in markets for XPS board in a number of Article 5 countries, most notably in China and some middle-eastern countries. This has increased the demand for HCFCs by in excess of 20,000 tonnes per annum since 2001. The split between HCFC-142b and HCFC-22 remains unclear at this time, but work is on-going to clarify this aspect.

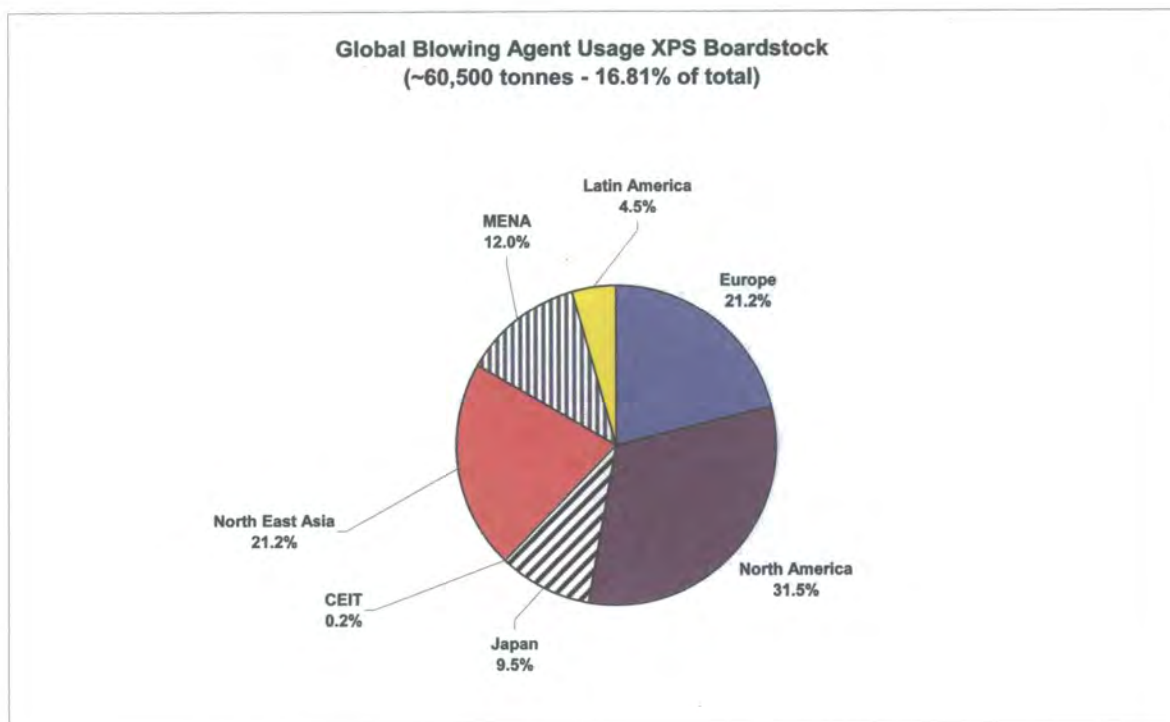
Latest Technology Trends

Investment criteria continue to be a barrier to further investment in CO₂-based technologies in Europe, although pressures are likely to increase concerning the on-going use of HFCs. The recently introduced F-Gas Regulation within the EU will re-visit the use and emissions of HFCs from foams in a review scheduled to occur prior to 2010. Meanwhile, in North America, HFCs are expected to be the primary blowing agents when the use of HCFCs is phased-out in 2010.

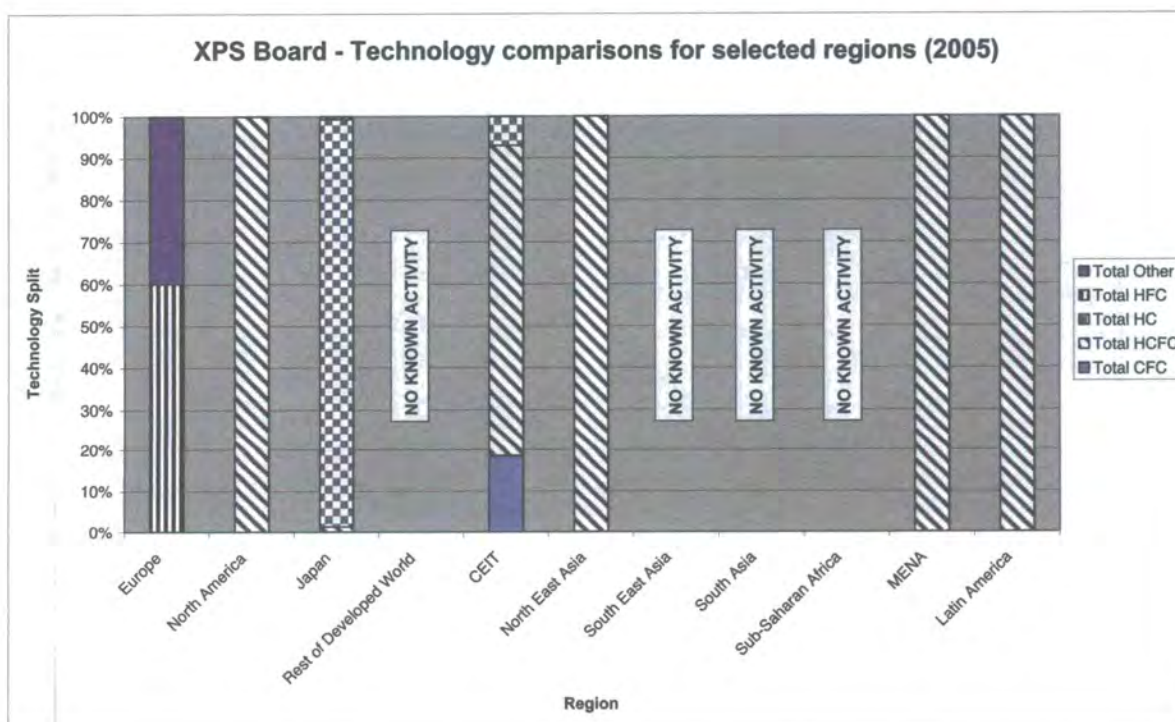
For Article 5 countries, the relatively low cost of investment in locally produced manufacturing plant and the high demand for improved thermal performance in buildings is expected to drive further rapid growth of XPS board production. Prior to 2015, the predominant blowing agents are expected to be HCFCs. It is estimated that a further 30,000-50,000 tonnes of annual consumption could be added to the 2005 assessment in that time-scale, with considerable on-going emissions during manufacture.

Data Summary

The current global distribution of extruded polystyrene boardstock foam production is shown below:



The transitional status and choice of technologies is shown in the following graph.



Additional Regional Observations

Emission rates from XPS board continue to be a significant discussion point in various regions. There are clear differences between product types, applications and average thicknesses which make generalisations difficult. Sheathing products in North America are typically wide and thin, which makes the use of HCFC-142b essential to retain the thermal performance. In Japan, the loss of blowing agent is seen as less critical for the application. This factor, coupled with different fire safety standards, makes the use of hydrocarbon more palatable.

PHENOLIC FOAMS

BOARDSTOCK

Current Technology

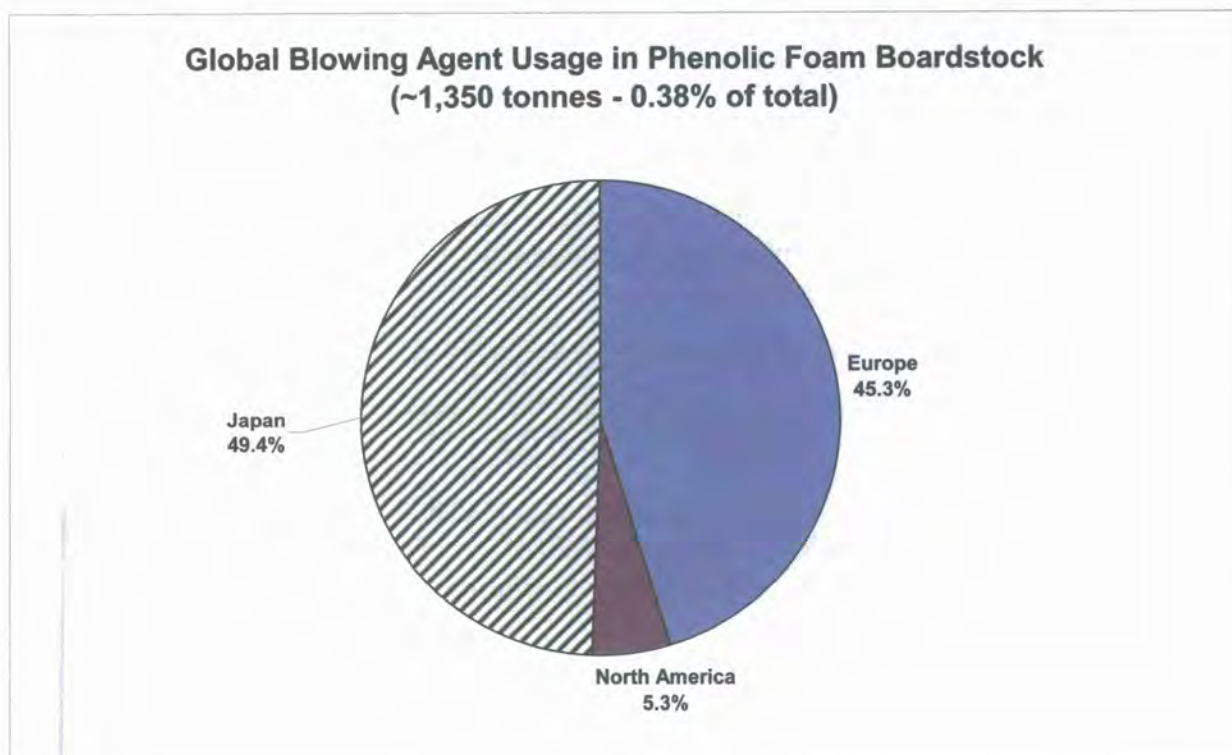
In the main global phenolic foam markets, transitions from HCFC-141b have taken place, with the predominant blowing agent replacement being hydrocarbons rather than HFCs in both Europe and Japan. One European producer continues to use 2-chloropropane for its production.

Latest Technology Trends

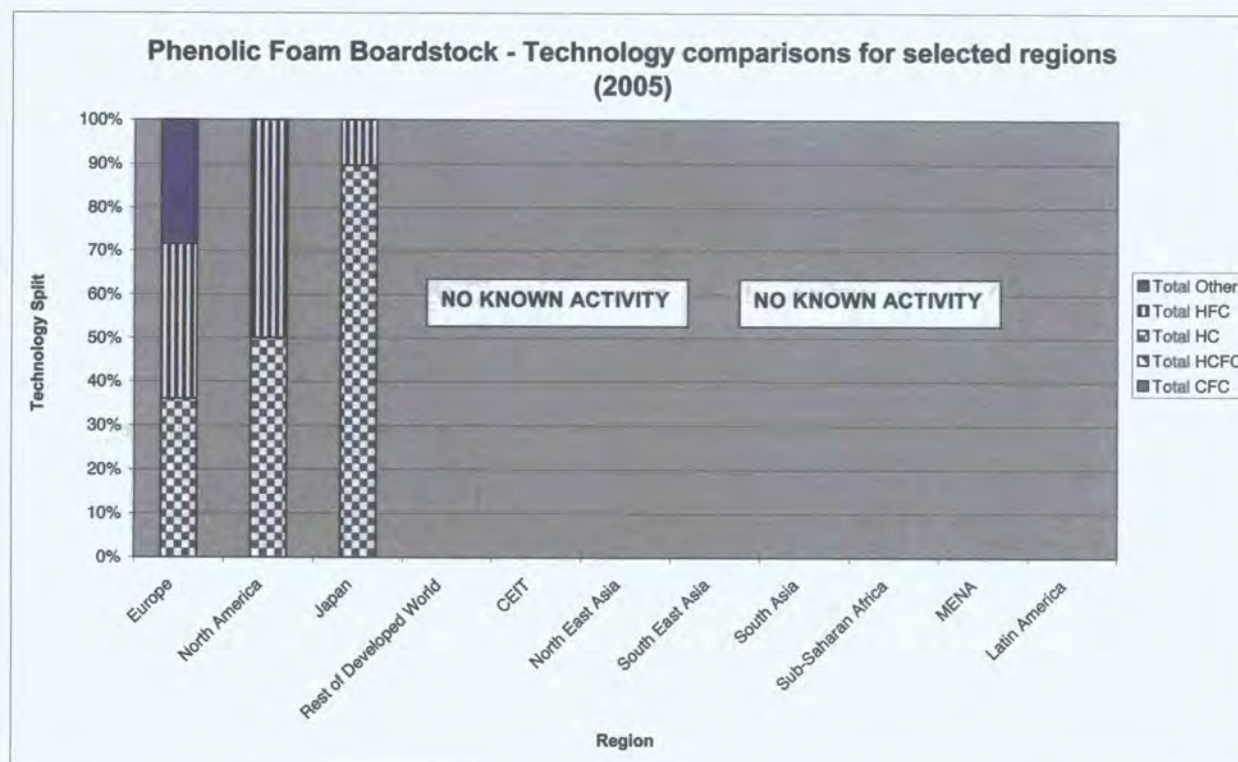
The original concern over hydrocarbon technologies was whether they would be capable of meeting the required fire performance standards. However, to a large degree, this has been achieved without the need for major formulation changes (e.g. the use of flame retardants). However, the position is not static and fire standards will continue to be reviewed in key market sectors.

Data Summary

The current global distribution of phenolic boardstock production is shown below:



The transitional status and choice of technologies is shown in the following graph.



Additional Regional Observations

The manufacture of phenolic foam boardstock on North America is limited and is mainly focused in Canada, where there is still potential for the use of HCFCs. However, it is understood that the tightness of the HCFC market under the current consumption cap has been sufficient to encourage transitions since 2001. Further work is on-going to clarify the precise position in this small and relatively specialist market.

PIPES AND BLOCKS

Current Technology

As with phenolic boardstock, transition has occurred out of HCFCs since 2001. Again there has been more focus on hydrocarbon-based technologies than had been anticipated, partly because of the introduction of novel continuous manufacturing techniques for pipe-sections.

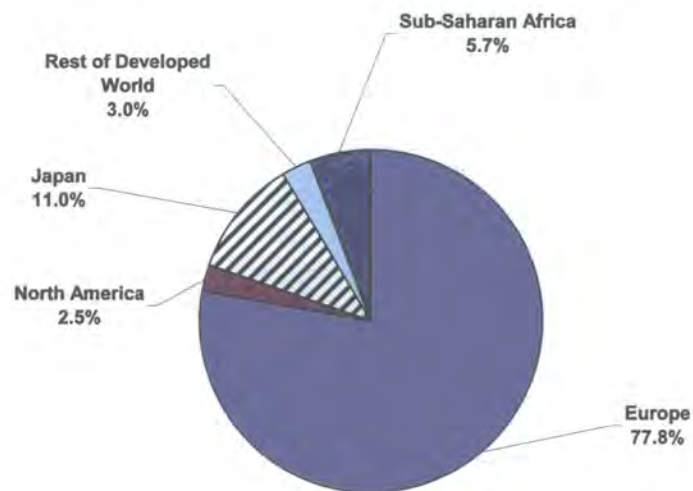
Latest Technology Trends

Little further development is expected in this sector in the short-term, although increased regulatory pressure on HFCs in Europe might force some further consideration of hydrocarbon technologies in due course.

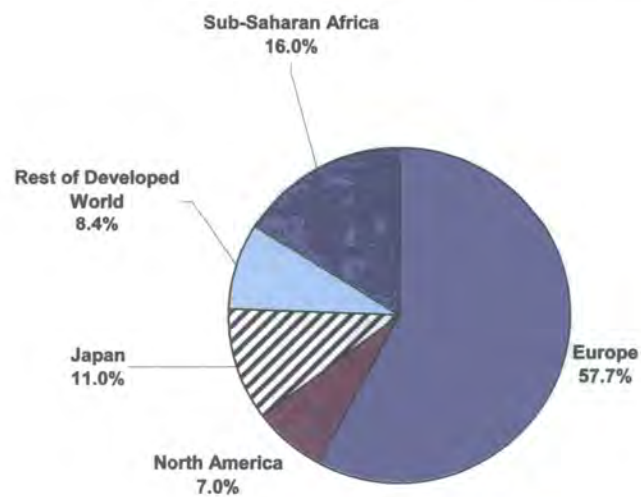
Data Summary

The following graphs show market activities for pipe-section and slabstock individually:

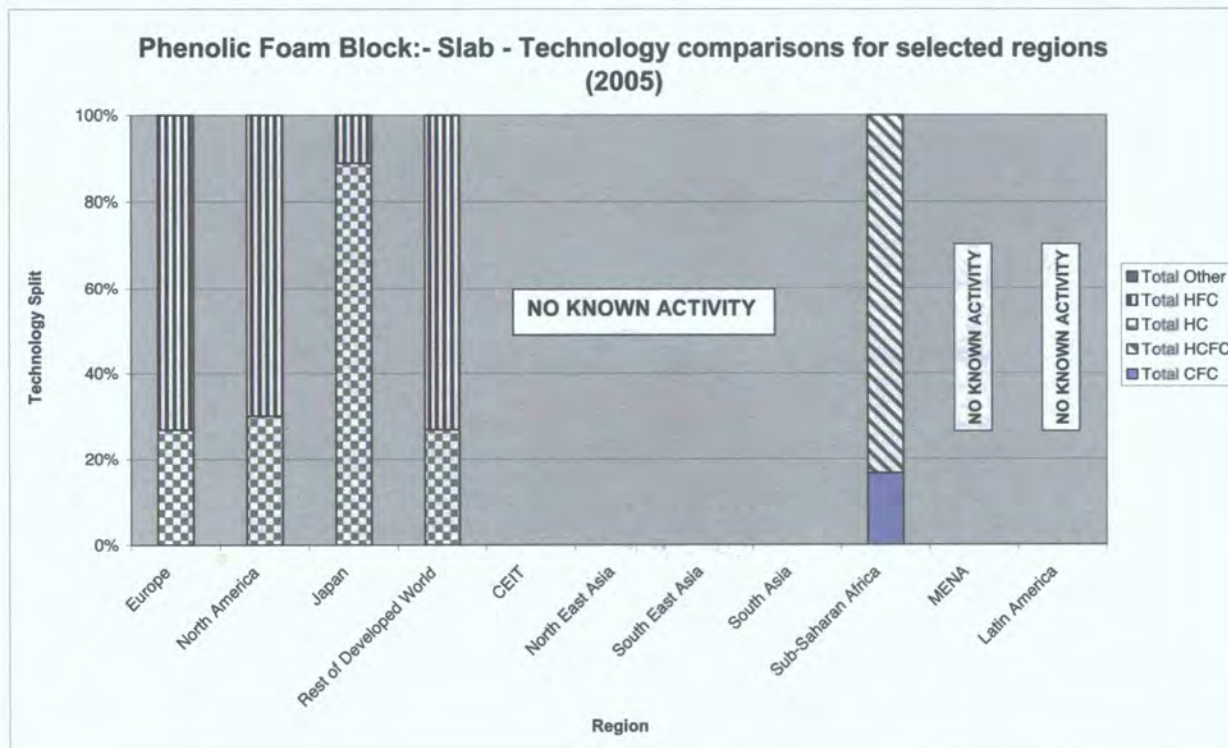
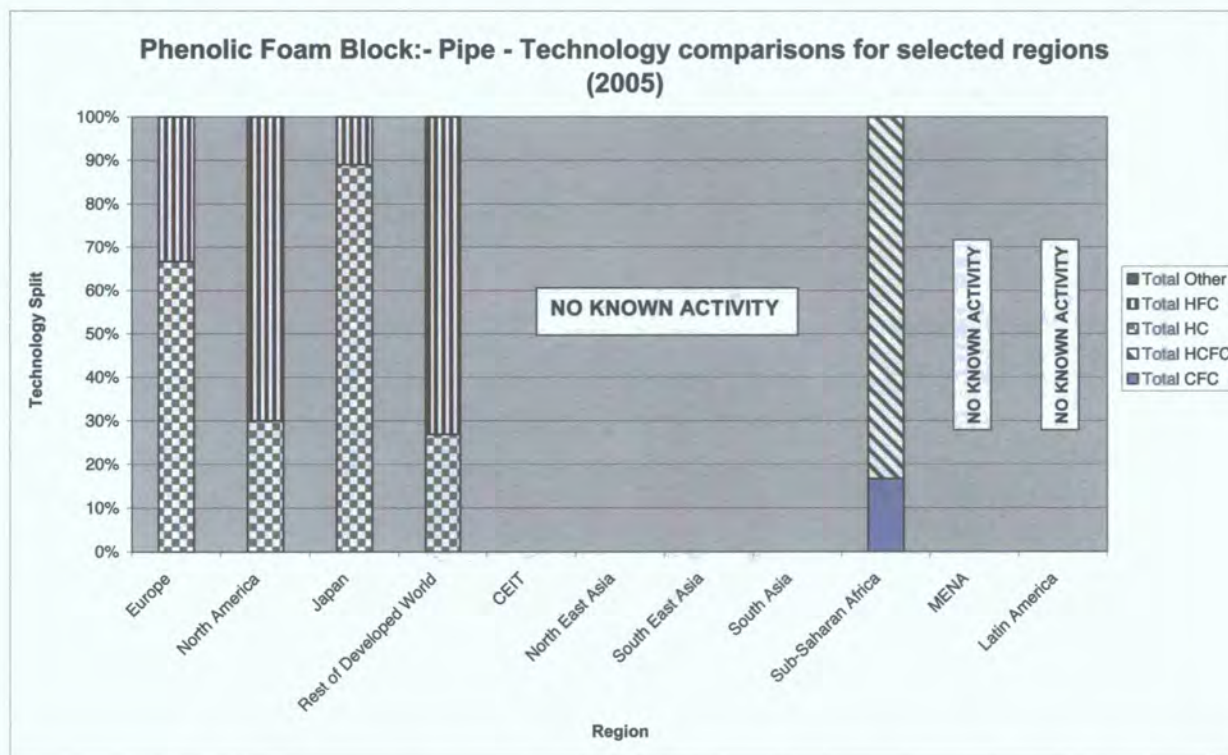
Global Blowing Agent Usage in Phenolic Foam Block - Pipe Section
(~575 tonnes - 0.16% of total)



Global Blowing Agent Usage in Phenolic Foam Block - Slab
(~200 tonnes - 0.06% of total)



The transitional status and choices of technology are shown for both pipe-section and slabstock below.



Additional Regional Observations

There has been some rationalisation of discontinuous phenolic block foam in India (South Asia) and so the focus is now primarily on non-Article 5 countries with the exception of the one plant operating in South Africa. Further information is required on the blowing agent selection at that plant, but HCFCs are understood to be the primary blowing agent.

PANELS

Current Technology

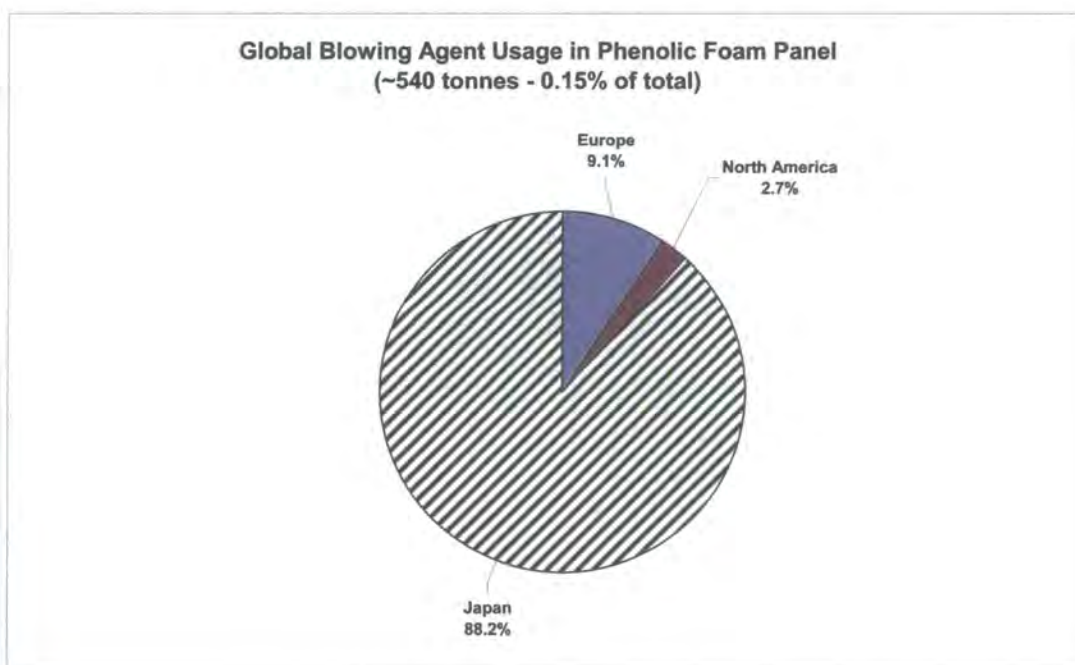
This is an emerging market in Europe, primarily for cold storage and equipment protection facilities. In Japan, however, phenolic foam panels have been produced as office partitioning for some years. Transition out of HCFCs has largely been completed in these regions with HFCs being the primary substitute.

Latest Technology Trends

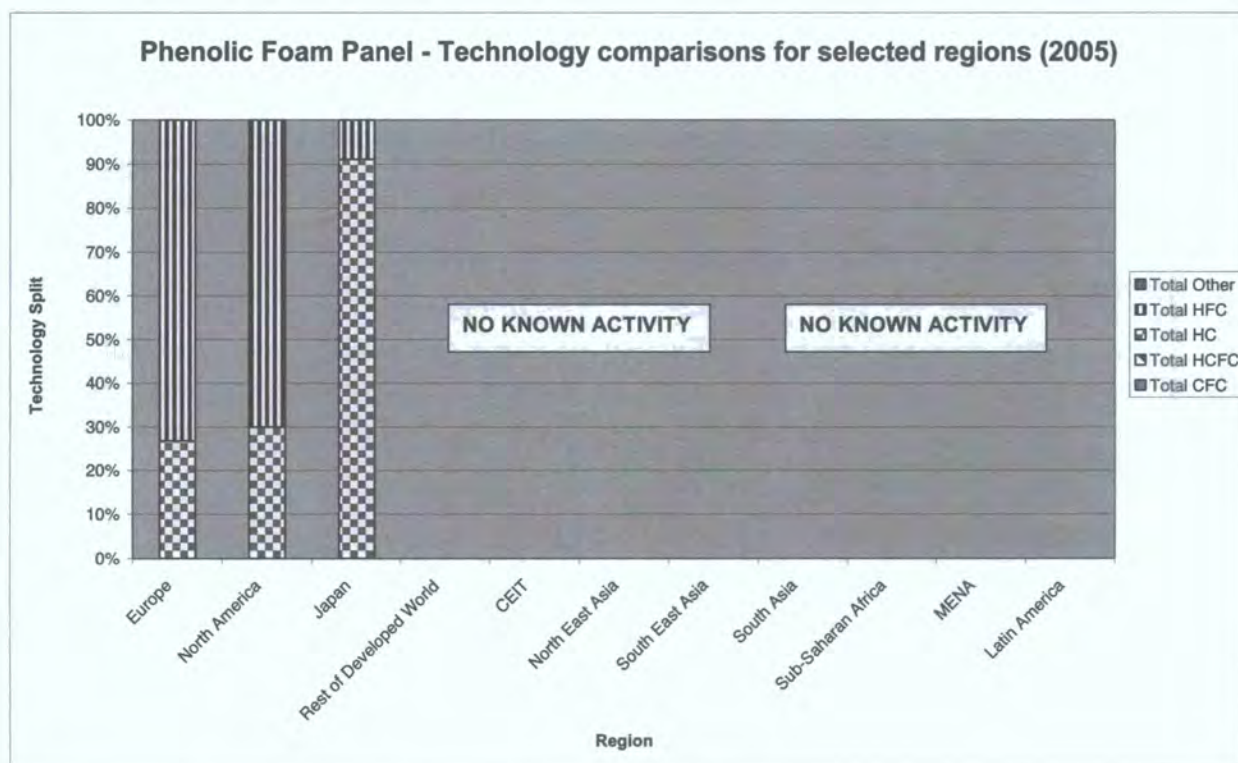
As with phenolic block foam technologies, there is not expected to be any significant additional change in technology in Europe unless the F-Gas regulations tighten further. However, pressure on the continuing use of HFCs in Japan has forced earlier consideration of hydrocarbons for the office partitioning market.

Data Summary

The current global distribution of phenolic foam panel production is shown below:



The transitional status and choice of technologies is shown in the following graph.



Additional Regional Observations

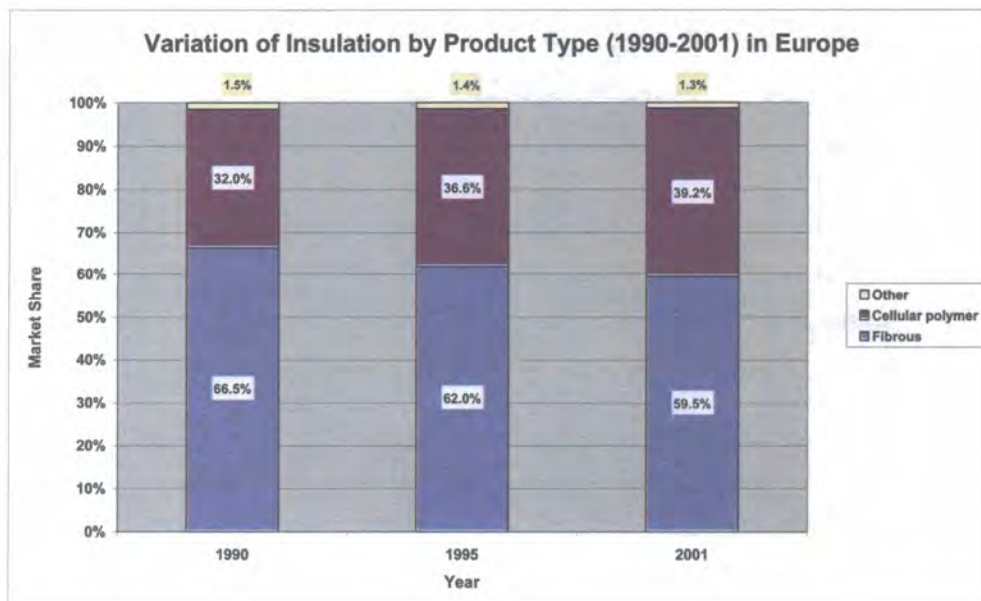
The future development of the phenolic panel market will depend considerably on the attitude of regulators and, perhaps more significantly, global insurers to the fire risks associated with steel-faced panels. This is most likely to be led by Europe where emphasis on polyisocyanurate formulations is already widespread.

CHAPTER 2: FUTURE TRENDS

TRENDS IN DEVELOPED COUNTRIES

There has been sustained growth in foam markets in most developed countries over the last five years – particularly where the primary requirement is for insulation. The Special Report on Ozone and Climate summarised the three main drivers for insulation as follows:

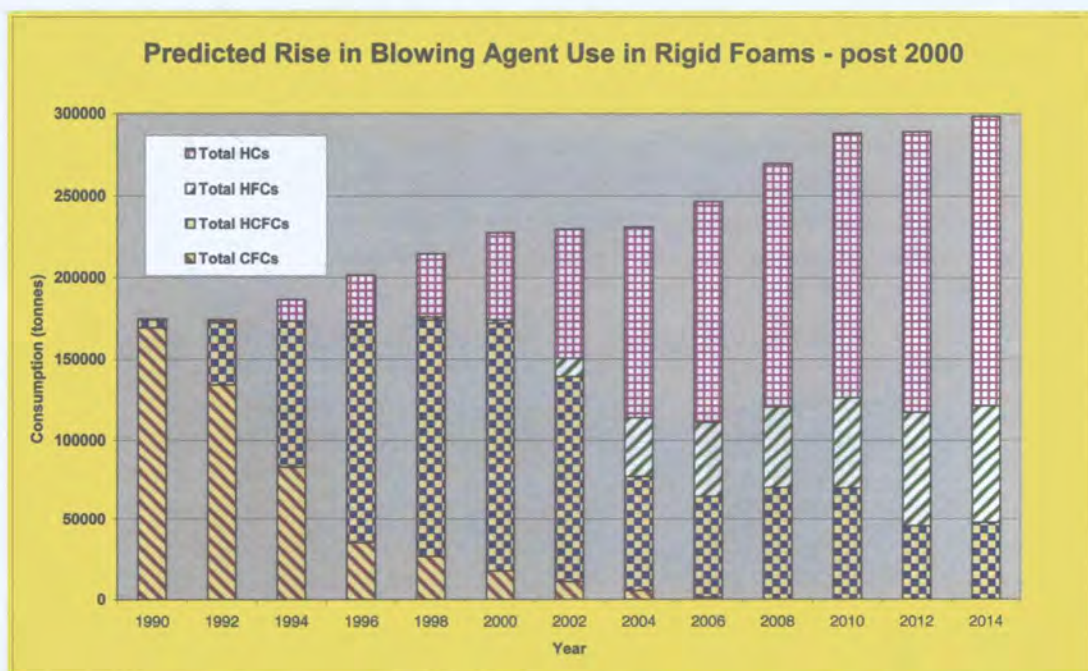
- (1) Overall economic activity based on GDP (as a default) or on the number of units being produced in a given year. Considering the major uses of foams, this would be the number of buildings built/refurbished or the number of appliances (e.g. domestic refrigerators or freezers) being manufactured.
- (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 in Europe over the ten years from 1990 to 2001 has been moving gradually towards foams (see graph below). 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.

The market growth drivers in developed countries will apply to applications and products which are already, in 2006, free of most ODS use as these regions phase out the use of HCFCs. The major markets of the EU banned HCFCs from 2004 and most of the applications, in both the US and Japan, are now also free of HCFC use.

The dominant growth factor in applications such as insulating foams for buildings and for appliances will continue to be energy-related over the next 5-10 year period as energy efficiency of new and existing buildings is optimised – driven by both the energy security and the climate change debates. The following graph illustrates the global projections in blowing growth within rigid foams by type as forecast in the Special Report:



At the time of the development of this graph in 2004/5, most of the growth was expected to be driven within developed countries. However, recent information (see next section) has suggested that there may be further significant growth arising from increased interest in energy conservation in developing countries. Potentially as much as 40,000-50,000 tonnes (13-15%) of additional consumption could be added to this current projection from additional growth in areas such as China and Latin America.

Those applications and markets using HFCs may come under further pressure from legislation on climate in some developed countries unless there are well reasoned and convincing arguments that there is a net benefit to the environment through their use (e.g. through TEWI or LCCP). Within the EU, the recently introduced F-Gas Regulation (Reg. EC842/2006) has delayed any significant action on the use of HFCs in foams until the first full review of the Regulation in 2011. Such a review may well involve life-cycle assessment and there will be increased emphasis on end-of life treatment with the objective of recovery/destruction with minimal emissions. Focus on blowing agent life cycle profiles will not be limited to regulatory frameworks, since some green building programmes already insist on stringent GWP limits. This will place the burden of proof onto blowing agent suppliers to demonstrate compliance.

Meanwhile, the United States will complete its phase-out of HCFC use in the foam sector by 2010. This may possibly take place in two stages with most remaining PU uses for HCFC-142b and HCFC-22 being banned from 2008 and their usage in XPS manufacture being addressed in 2010.

Particularly with respect to HFCs, economic drivers to further extend the use of hydrocarbons will remain, particularly where current product short-comings can be overcome. Where reliance on HFCs continues, further use of blends will be practiced to optimise processing factors such as miscibility as well as the insulating efficiency of the foams.

TRENDS IN DEVELOPING COUNTRIES

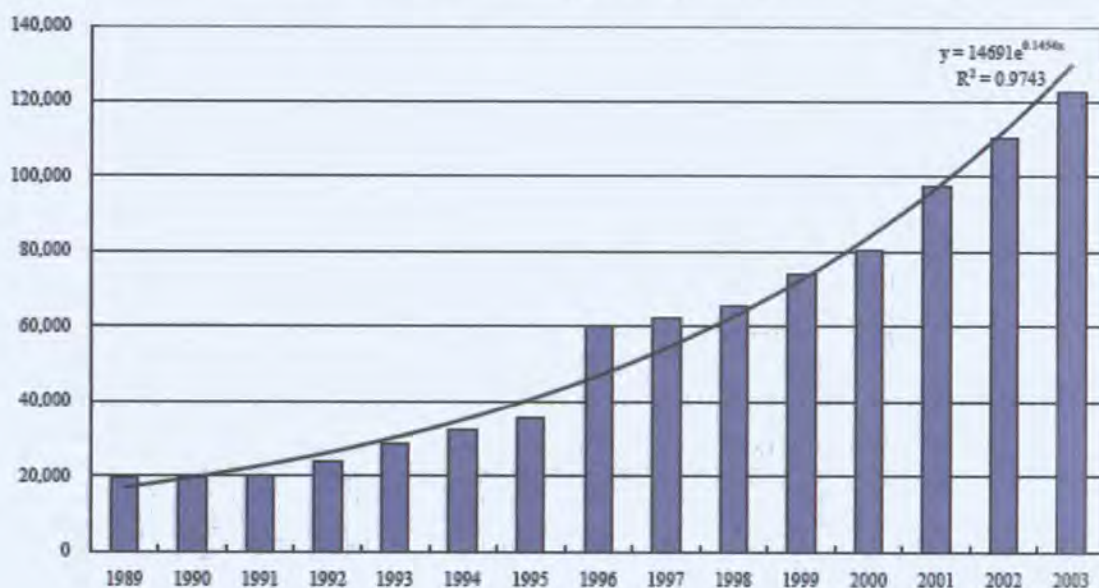
As the significance of the surge in the economies of some of the largest developing countries emerges, attention is being drawn to the need to ensure that infra-structure investments are tailored to minimise environmental impacts. One of the most substantial single elements under consideration is the growth in construction projects in general, and buildings in particular. In China alone, the rate of building completion had increased to over 1.2 billion m² in 2003. As the longevity of the environmental footprints of such buildings is being recognised, Governments and international agencies are seeing the urgent need to enforce energy efficiency compliance on new constructions, even though the speed of construction is often acting against such measures.

In order to provide additional fiscal incentives to encourage good practice, UNEP has recently launched the Sustainable Building and Construction Initiative (SBCI). Amongst other things, this initiative is targeted at setting baselines for energy efficiency through a series of 'model buildings'. This could then provide the basis for the inclusion of projects exceeding the baseline performance within the Clean Development Mechanism – thereby providing an additional return (in carbon credits) for low-energy buildings.

With such a level of interest in providing better thermal performance within buildings, it is little surprise that the markets for thermal insulation of all types are burgeoning in developing countries – particularly where the climate warrants action. In China, this growth has primarily

centred round the increased use of extruded polystyrene (XPS). In contrast with developed countries, simple XPS extruders can be purchased relatively readily and, being locally manufactured, are reasonably priced. It is almost certain that the product specifications for such materials are less demanding than those in parallel developed country markets but, in a situation where the key market drivers are availability and cost, this is less of an issue than might be envisaged.

中国竣工面积（万平方米） Floor Space Completed (unit: 10 000 sq.m)



Local market intelligence suggests that 2 million cubic metres (m³) of XPS is currently being produced in China with existing capacity to produce 3 million m³ in total annually. However, this capacity is expected to double within the next 5 years requiring an additional 16,000-20,000 tonnes of blowing agent annually. This blowing agent figure is based on an average foam density of 40 kg/m³ and a blowing agent percentage of 10%. Both are higher than currently adopted in developed countries, but the figures represent typical formulations for emerging markets. There may be some optimisation of these formulations over coming years which could bring the increased consumption to the lower end of the predicted range.

XPS foam board can utilise either HFC-142b or HCFC-22. However, HCFC-142b produces a foam of better quality since, when HCFC-22 is used as a blowing agent, it tends to be lost from the cells more quickly with a resulting loss in thermal performance. Nonetheless, HCFC-22 is likely to be more readily available and recent reports have suggested that it could be up to 45% less expensive in some regions. In summary, definitive data about the split between HCFC-142b and HCFC-22 consumption remains hard to come by and the FTOC is continuing to seek further clarification on this matter. In view of the volumes involved, this clarification will be important in assessing likely growth in demand for each HCFC and the capacity increases that such growth might require. There are also implications for emissions, in view of the relative rates of blowing agent release.

The expected developing country freeze in HCFC consumption in 2015 will be a particular challenge for the foam sector if the growth rates remain as anticipated. This is particularly the case for XPS where the alternatives are less obvious than they might be for polyurethane foams. HFC blowing agents are not expected to make significant in-roads in the short-term except where they are required for exported goods to developed country regions. Hydrocarbon and CO₂ technologies will remain attractive options from a cost perspective, but will need strong technical support if they are to be instigated on a wide-scale. The issues are elaborated further in the following section.

Coupled with the projected growth in foam demand, many developing economies are expected to become more self-sufficient in other basic raw materials with polyurethane facilities now on stream in China and India and are due for expansion by 2010. These units will initially be targeted at satisfying local demand but, in time, may well become the manufacturing base for global markets where lower labour costs are an increasingly decisive factor. As demand also increases for bio-chemicals, there could be additional impacts on local agriculture.

BARRIERS TO ON-GOING TRANSITION

Progress in the phase-out of ODS usage in the foam sector has been hampered by a variety of both process and product-related factors. Some of the product-related factors, have been particularly problematic since issues such as building code revision and fire standard development are usually slow processes and unlikely to be hurried by single issues such as ODS phase-out.

This section provides a review of the factors influencing phase-out in both Article 5(1) and non-Article 5(1) countries. Interestingly, it has been found that there are often common barriers in both environments, many of which are focused around the particular constraints of small & medium sized enterprises (SMEs). Ironically, the SME-related factors can be more severe in non-Article 5(1) countries than in their Article 5(1) counterparts, where support funding is available through the Multilateral Fund. The drivers behind these issues are explored in more detail in subsequent paragraphs.

Common Barriers

Although regulatory phase-out mechanisms have been in-place for many years in some regions, the reality of achieving phase-out requires the coincidence of four key factors:

- The availability of suitable technology
- The potential for cost-effective transition and on-going use of the technology
- Market acceptance of the technology and products manufactured by it
- A 'level playing field' for all suppliers to the market

Experience has shown that regulation alone does not ensure any or all of the above and that appropriate motivation to innovate also needs to be present. This usually arises from the

long-term need to satisfy market requirements and this will often be sufficient to support substantial investment (e.g. in the appliance sector). However, other markets may be much less secure and may not have the critical mass to support such investment. This is often the case in specialist, niche applications or in markets where there is strong competitive pressure and price sensitivity is a major component.

Where barriers are significant it will be inevitable that the final on-set of regulation will force a change, but this may drive certain segments or manufacturers out of commercial practice to the detriment of the overall market and/or economy. When poorer energy efficiency is the result even global environmental objectives can be compromised. This is a 'balanced call' and regulators need to be vigilant to ensure that they understand the dynamics of transition in each case, since these can vary dramatically from sub-sector to sub-sector. This is one of the reasons why this report continues to contain a comprehensive description of the sectors (see Appendix 1).

It is interesting that, for the most part, these principles apply as much in non-Article 5(1) countries as in Article 5(1). Indeed, it can be argued that barriers of the type outlined are more acute in the non-Article 5(1) environment, since they are often being tackled for the first time there. A good example of such difficulties was the recent experience of the US administration, with the phase-out of HCFC-141b from the PU systems house sector (spray and poured in place foams). In this instance, local constraints on the availability of alternatives put immense pressure on the transition process, causing the regulators to re-consider phase-out strategies and timings.

SME Issues

The common barriers outlined above are even more accentuated at SME level. Depending on the definition of SME applied, it is important to note that the majority of foam producers, even in non-Article 5(1) countries fall into the SME category. Only the largest of the producers fall outside, as do most of the raw material suppliers. There is therefore considerable reliance on the supply-side to develop and support the introduction of new technologies. This leaves SMEs feeling vulnerable, even if their predicament is no worse than larger players in the market.

One of the over-riding requirements of the SME scenario is the need to avoid multiple transition steps. This has inevitably made SMEs more cautious than most in considering future technologies. In many cases, there are periods of innovation when there can be as many as 5-10 credible options available. However, as the innovation 'curve' moves towards maturity, there are usually two or three technologies that emerge as the true front-runners. SMEs are less concerned about being technology followers than the larger manufacturers and are much keener to avoid expensive mistakes. Accordingly, the transitions in these sectors will be naturally slower.

Overall transition costs are another major factor and these have two distinct components:

- (1) Capital costs
- (2) On-going operational costs

Because of a lack of financial resources, SMEs are often not as well placed to take advantage of long-term operational cost benefits, where they are attached to greater up-front capital costs. Accordingly, a transition process often leads to an overall weakening of their competitive position. This aspect has been negated to a certain extent in Article 5(1) countries where the Multilateral Fund can assist enterprises in respect of investment. However, investment constraints still exist in this environment, particularly in low-usage scenarios where cost-effectiveness criteria are often not met and enterprises are faced with the choice of either a large co-payment or a lower-cost interim technology. Some of these developing country aspects are explored more fully in the next section.

Specific Developing Country Issues

Advanced (sector) phase-out dates in several Article 5.1 countries

Most developing countries are approaching final phase-out in the foam sector. Ahead of the 2010 Montreal Protocol deadline, some Article 5.1 countries, like Brazil, China, Nigeria, Thailand, Malaysia, have established sectoral CFC-11 phase out programmes where technology options permit.

Voluntary advances in ODS phase-out have also been encouraged by the presence of multinational producers and customers, particularly in the domestic refrigeration sector (Electrolux, Whirlpool, General Electric, Bosch, LG, etc.). Specifically, foam producers with significant export potential have needed to be aware of the demand for ODS-free and sometimes HFC-free products. These factors have applied to domestic refrigerator and freezer imports from developing countries into the European Union and to drink vending cabinets (e.g. as required by Coca Cola and others).

Key role of Multilateral Fund

The funding and technology transfer provided by the Multilateral Fund have played a significant and positive role in the speeding up ODS phase out. The assistance has been extended to those countries that combine a developing country status with low ODS use.

Limited R&D Capacity

The limited research and development (R&D) capacity of local suppliers and manufacturers, a common feature in most of Article 5(1) countries, make them strongly dependent on technology from developed countries. Another factor is the existence of trade barriers which make more advanced technologies from external suppliers too expensive to apply. These points, combined in some countries with insufficient information on new viable options and frequent delays in availability of non-ODS technologies, negatively affect the on going phase down programmes.

As a counterpoint to these arguments, the true globalisation of many multi-national organisations is increasingly encouraging inward investment in R&D within developing countries – particularly where there are strong emerging markets. Indeed, as the higher-education standards increase around the world, there is a clear corporate motivation to ‘internally outsource’ R&D to regions where employment costs are lower.

Coordination of Government regulatory programmes

There is a strong need for Government regulatory action programmes to coordinate with the industry or other public dependencies to ensure smooth transitions. Regrettably, this does not happen in all cases. In one country, as a result of an unplanned CFC-11 imports prohibition, the suppliers switched to HCFCs without informing their customers, which generated severe product quality problems.

Safety related issues

The introduction of hydrocarbons (c-pentane, butanes, LPG), a non-ODP option for PU and polystyrene foam, has been held back by safety factors which require increased investment cost, often to overcome poor operating training and discipline. This issue is specifically applicable for SMEs where, along with economic constraints, these requirements continue to limit the use of HCs, often resulting in other non-ODS technologies such as HFC-based formulations being adopted.

Blowing agent availability

Supply infra-structures for non-ODS technologies can also be a barrier in some developing country regions. This is often demand-driven and it is therefore generally difficult to be an early-mover in the adoption of these technologies in a country. As a consequence, the reliance on interim technologies such as HCFCs is substantial. However, despite earlier concerns, the general supply/demand balance for HCFCs remains positive – partly driven by inward investment in production capacity within the developing countries themselves. In turn, this is causing some concern amongst developed country governments who are seeing the proliferation of manufacturing capacity as an unintended consequence of their own HCFC phase-out strategies. With the only real recourse now being a potential adjustment to the Montreal Protocol itself, there remains concern among some Article 5(1) users about the future possibility of supply/demand imbalances for critical HCFCs in an accelerated phase-down environment. This extends to the maintenance of adequate geographic supply chains.

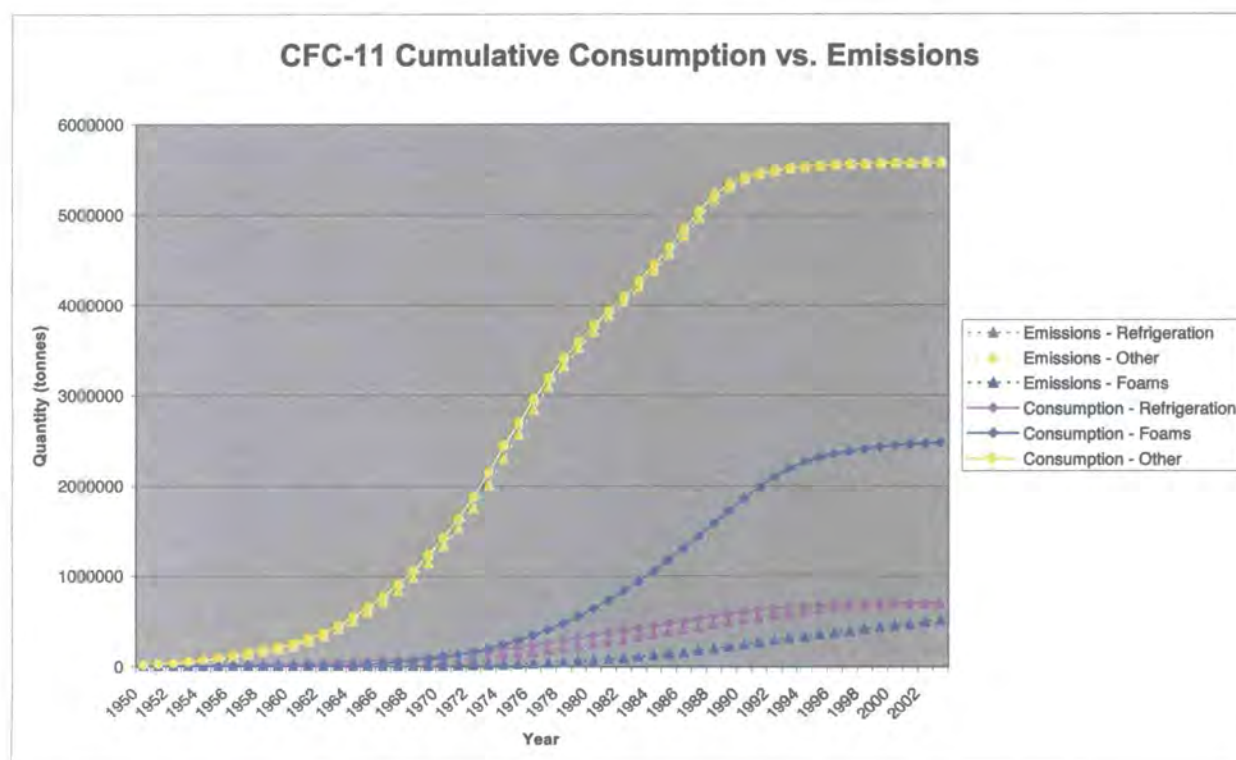
Long term ODS replacement

The MLF policy of one time funding for CFC replacement continues to create problems for the implementation of long term solutions in countries where phase out technology has been or is being focused on transitional options, like HCFCs.

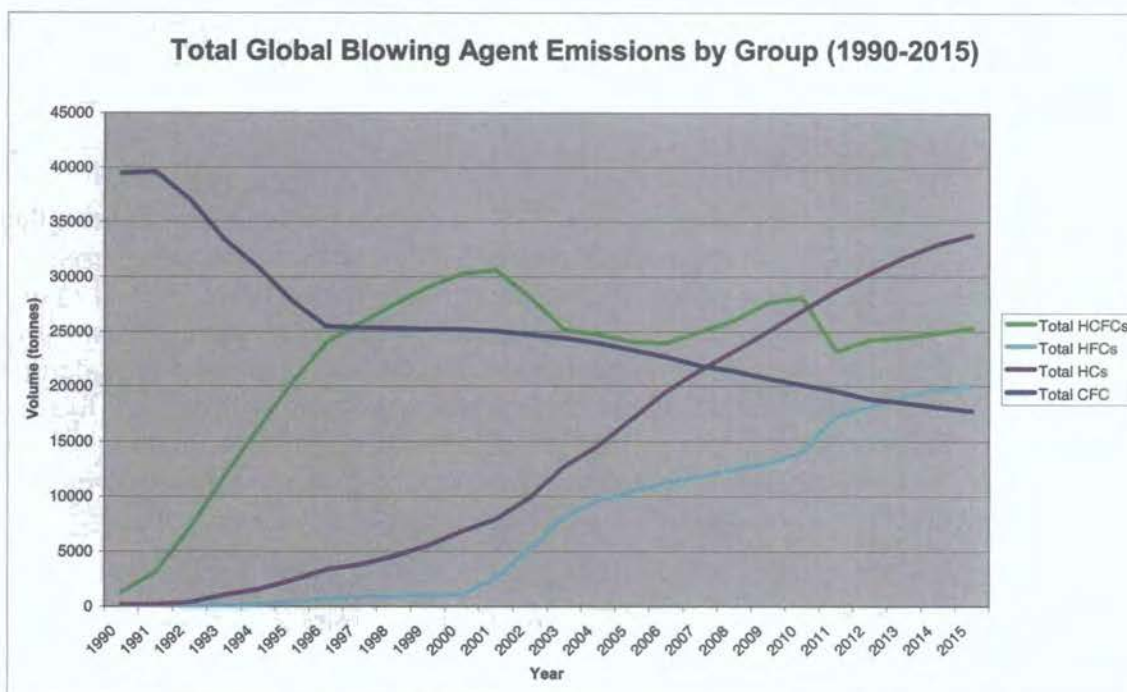
CHAPTER 3: BANKS AND EMISSIONS

BASELINE EMISSION ESTIMATES

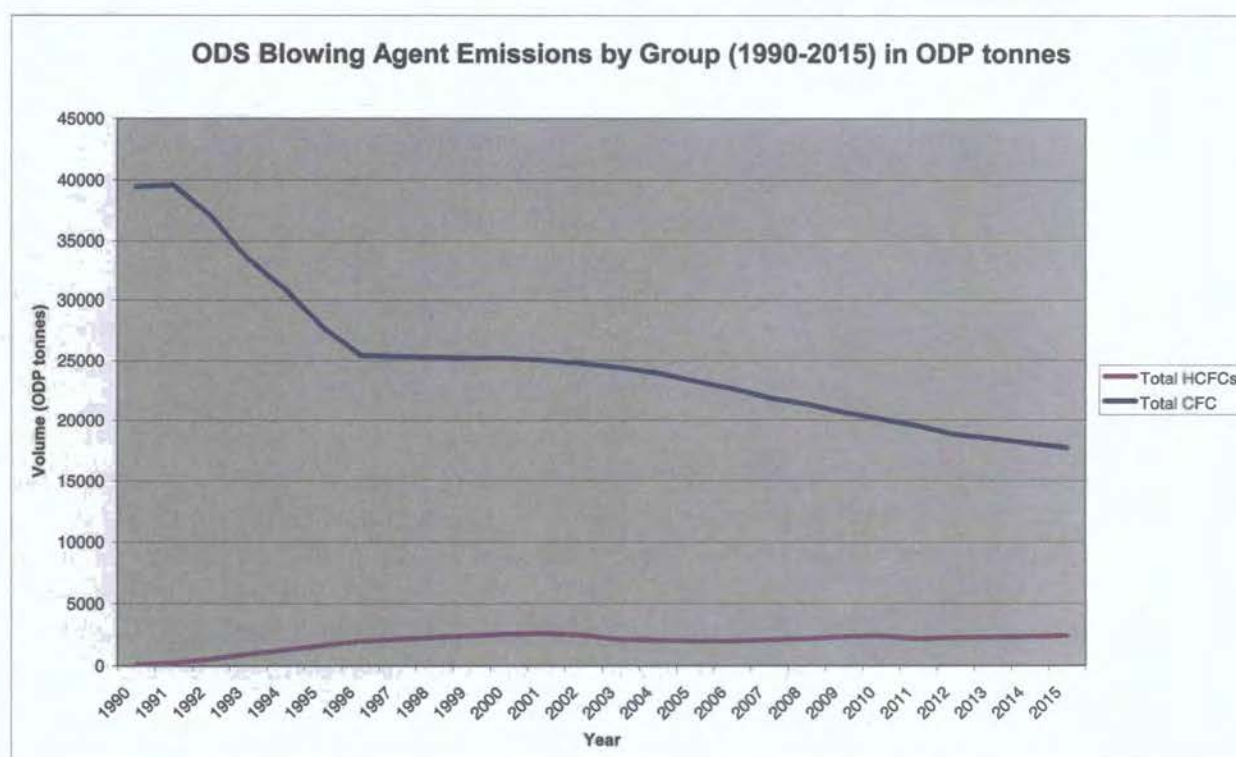
In order to understand the on-going impact of ODS release on the stratosphere, there is a need to understand the timing of such releases (emissions). In many cases, the emissions take place at the point of use (so-called emissive applications) and it is therefore normal to assume that emissions will follow within one year of consumption. However, there are two primary sectors of historic ODS use where emission is delayed because the applications are defined by the on-going benefits of ODS retention. These are in refrigeration and in closed cell foams. The latter use employs the excellent gaseous thermal efficiencies of the ODS to improve the overall thermal performance of the foams in question. The following graph shows the relationship between the timing of CFC-11 consumption and emissions for the major applications:



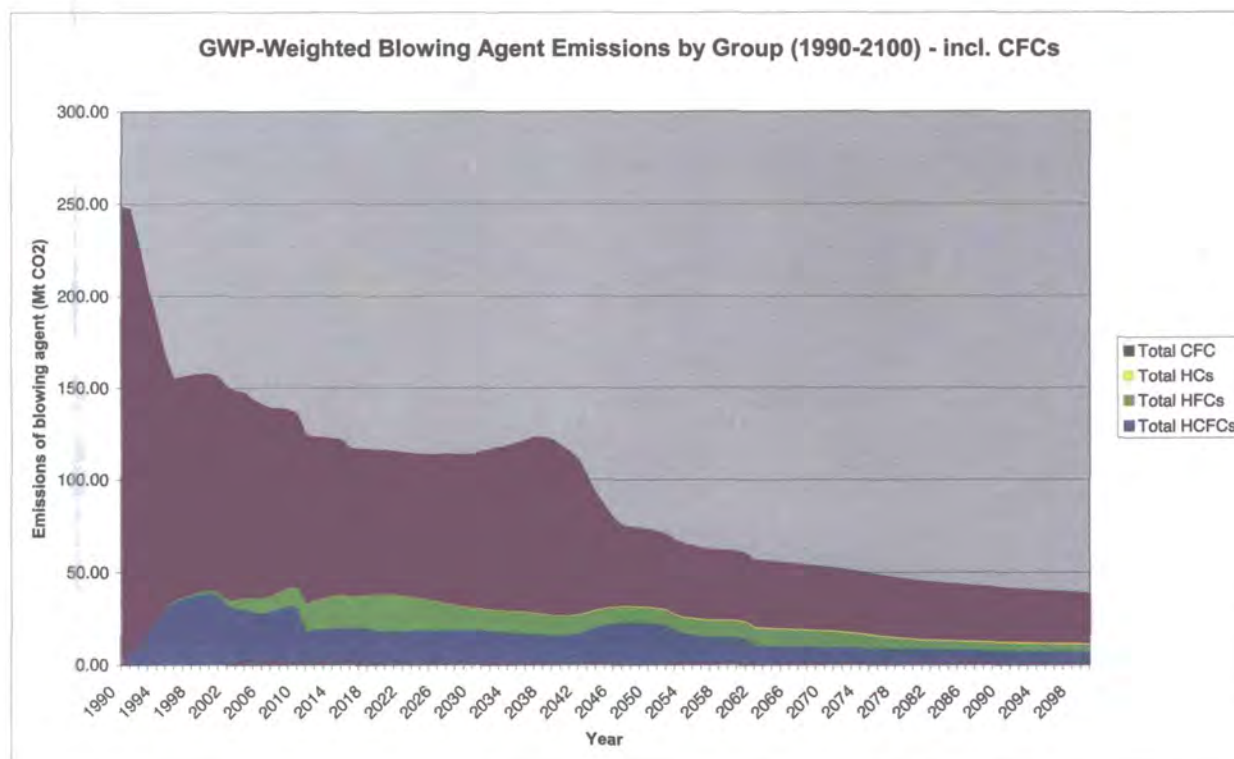
It can be seen that emissive 'other' applications (e.g. aerosols and solvents) have accounted for the bulk of consumption and use of CFC-11 through its history. However, closed cell foams represent by far the largest potential bank of CFC-11 with a difference between cumulative consumption and cumulative emissions of nearly 2 million tonnes. Since the last Assessment Report was published, the Foams End-of-Life Task Force Report (2005) and the IPCC/TEAP Special Report on Ozone and Climate (SROC-2005) have assessed the significance of such estimates on current and future releases for a number of blowing agent types, leading to forward projections of annual emission in real tonnes as shown in the following graph:



This graph indicated that the annual emissions of CFCs would continue well into the future and would only be superseded by all of the other blowing agent groups in around 2013. Even then, the ozone depleting impact of CFC release would far outweigh other ODS blowing agent types well into the future, as shown below:



The importance of on-going CFC-11 emissions became even more obvious when, in support of SROC (2005), the forward emissions from foams were assessed in terms of global warming potential through to 2100.

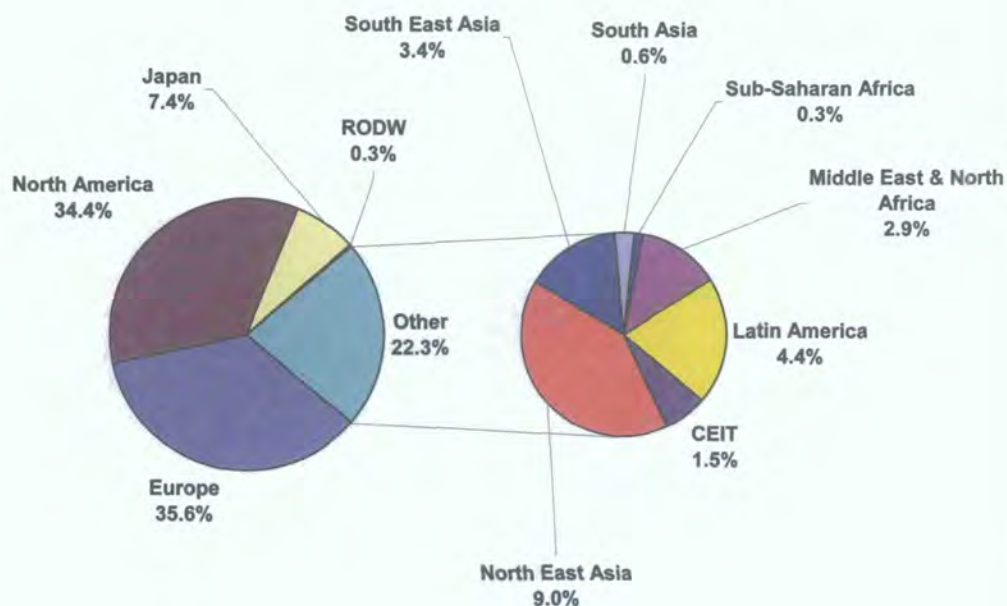


However, since all of these delayed emission forecasts were based on bottom-up assessments of consumption and emission, with the application of emission functions for foam sub-applications derived under the auspices of the UNEP Foams Technical Options Committee, there was a need to validate and verify the size of the potential banks.

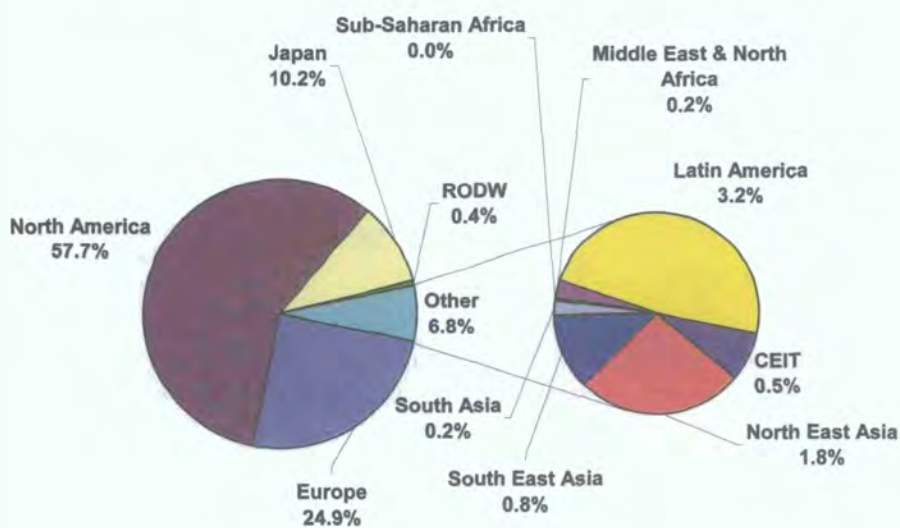
BANK ESTIMATES AND UNCERTAINTIES

The 2002 bank estimates and their geographic location, as derived from the same data as used in business as usual scenarios within SROC (2005) are shown in the following graphs for both CFCs and HCFCs:

CFC Foam Banks - 2002 (1.81 million tonnes)



HCFC Foam Banks - 2002 (1.12 million tonnes)



Points of interest from these two graphs are the comparative splits between bank sizes in developed and developing country regions for CFCs and HCFCs respectively, indicating that,

as of 2002, HCFC bank development in developing countries was in its infancy. In addition, it is interesting to note the comparative ratios between European and North American bank sizes for HCFCs, with North America being the dominant bank location for HCFCs with over 57% of the total – primarily as a result of widespread use of HCFC-141b in appliance and PU boardstock applications.

However, as regulators wrestled with the significance of this information, there was a need to find ways of verifying that these banks were indeed in place. This matter had become particularly important because emission estimates derived from atmospheric concentration measurements were indicating that bottom-up methods were under-estimating emissions.

A series of studies was therefore initiated to assess the situation. This included the following landmark activities:

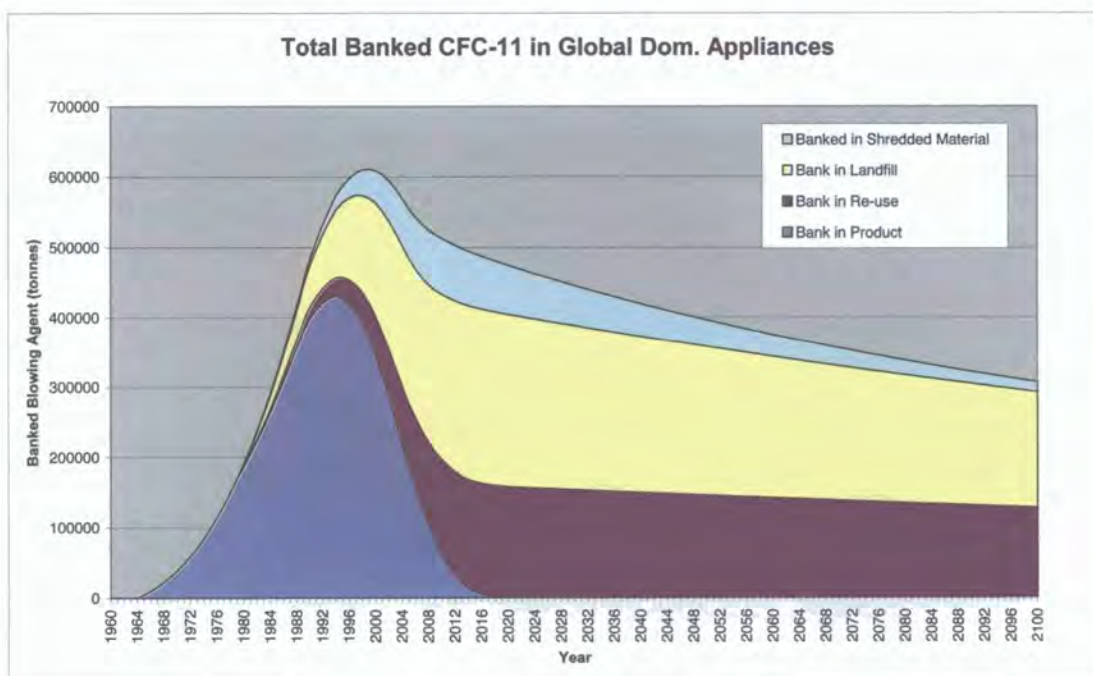
- Four year JTCCM Study in Japan looking at the retention of blowing agents in foams in buildings in order to derive bank sizes and evaluate potential recovery options
- Work by domestic refrigerator manufacturers to determine the retained blowing agent in a typical refrigerator at end-of-life
- Assessments of in-use emissions from extruded polystyrene (XPS) in studies such as Vo & Paquet (2004)
- Work sponsored by American Home Appliance Manufacturers and US EPA to assess the fate of blowing agents in end-of-life refrigerators which go to landfill (Kjeldsen et al.)

More recently, there has been additional work in the area of steel-faced building panels conducted in the UK (Kingspan, 2006) and projects in this area continue to spring up. Many of the above are covered in some detail in the Foams End-of-Life Task Force Report (2005) and also in the SROC (2005), and hence it is only necessary to summarise the conclusions here. These are:

- (1) That steel faced foams (both appliances and architectural panels) retain very high percentages (typically >90%) of their original charge
- (2) That emissions from board products are strongly related to the thicknesses produced and that the product mix could vary with time and region
- (3) That current end-of-life practice is less emissive than first thought. Even when foams are shredded in auto-shredding equipment losses seldom reach >40%.

The implication of (3) is that substantial banks of blowing agent transfer into waste streams and hence it is necessary to split bank discussions (where banks are defined as 'consumption not yet emitted') into reachable and non-reachable banks. The following graph for

appliances illustrates how banks are perceived to develop with time, based on current end-of-life practices:



In summary, the work carried out on foams in the field has broadly supported the choice of emission functions already being practised in the bottom-up models. However, there is a need to further develop these models to take into account the time-dependency of emission functions. For example, the manufacture and use of thicker boards in recent years will result in a decrease of the weighted average emission rate of the installed stock overall. Similarly, improvements in processing efficiency can lead to lower emissions during manufacture and installation with time.

In assessing the discrepancies between bottom-up and atmospherically derived emissions (known as 'inverse modelling'), there was a need to broaden the investigation to include three potential sources of uncertainty:

1. The under-estimation of use and emissions in the foam sector (affecting CFC-11, HCFC-141b and HCFC-142b projections in particular)
2. The under-reporting and misallocation of consumption of these chemicals resulting in the omission of consumption in emissive activities
3. The under-estimation of the lifetime of these chemicals in the atmosphere, resulting in an over-estimation of annual emissions by 'inverse modelling' from atmospheric concentrations

A Task Force was established under the TEAP and has recently reported its findings to the Parties. This Task Force included members from both the Science and Technical &

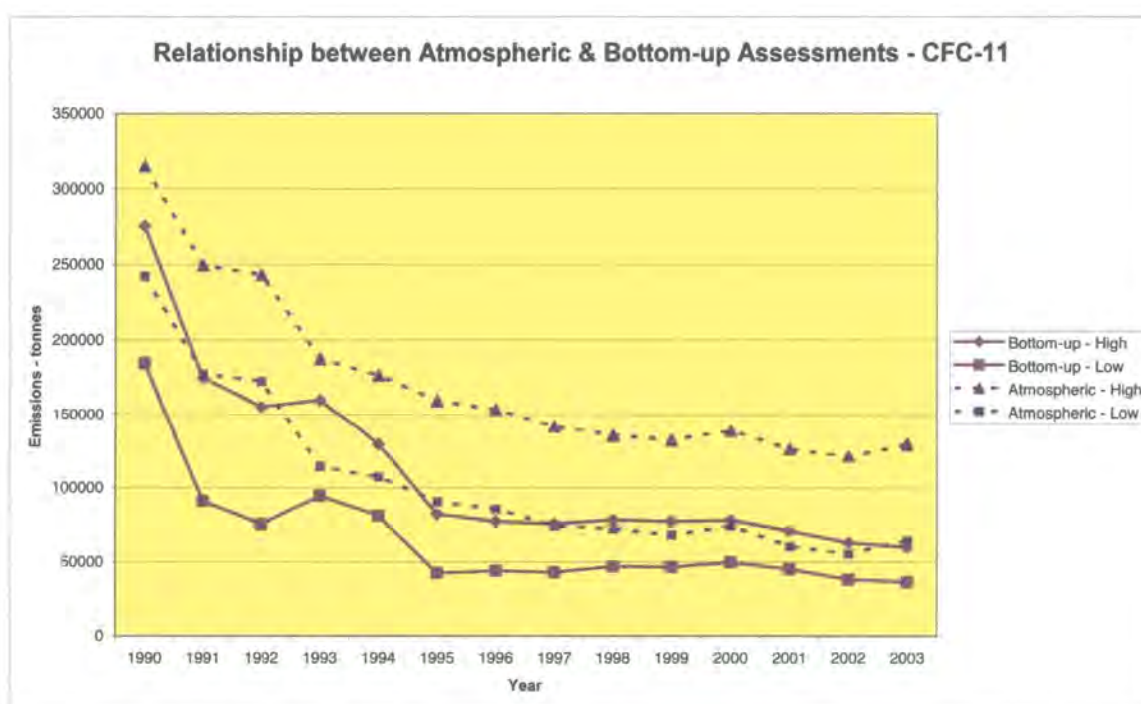
Economic Panels and hence takes into account all of the potential sources listed above. In deriving consumption estimates the Task Force has increasingly relied on UNEP data collection efforts under the Protocol rather than AFEAS sources previously relied upon because the manufacture of ODSs has increasingly moved to non-AFEAS producers in the last 15 years. However, this brought one problem with it, in that UNEP data is not collected by end-use pattern.

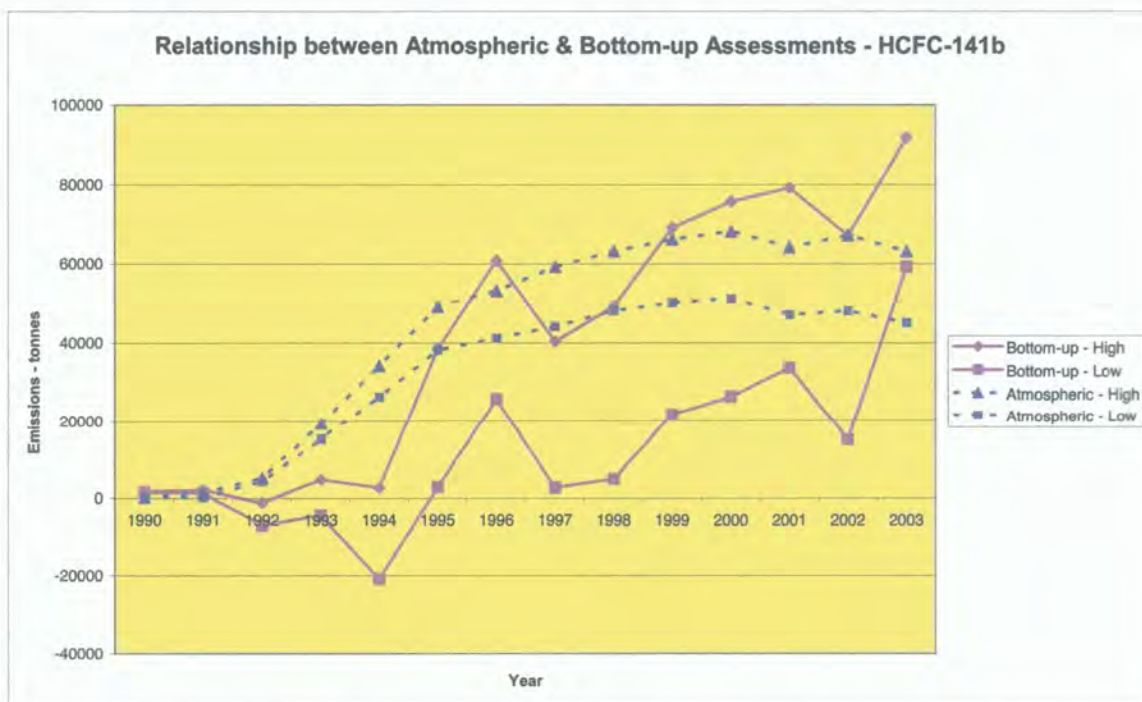
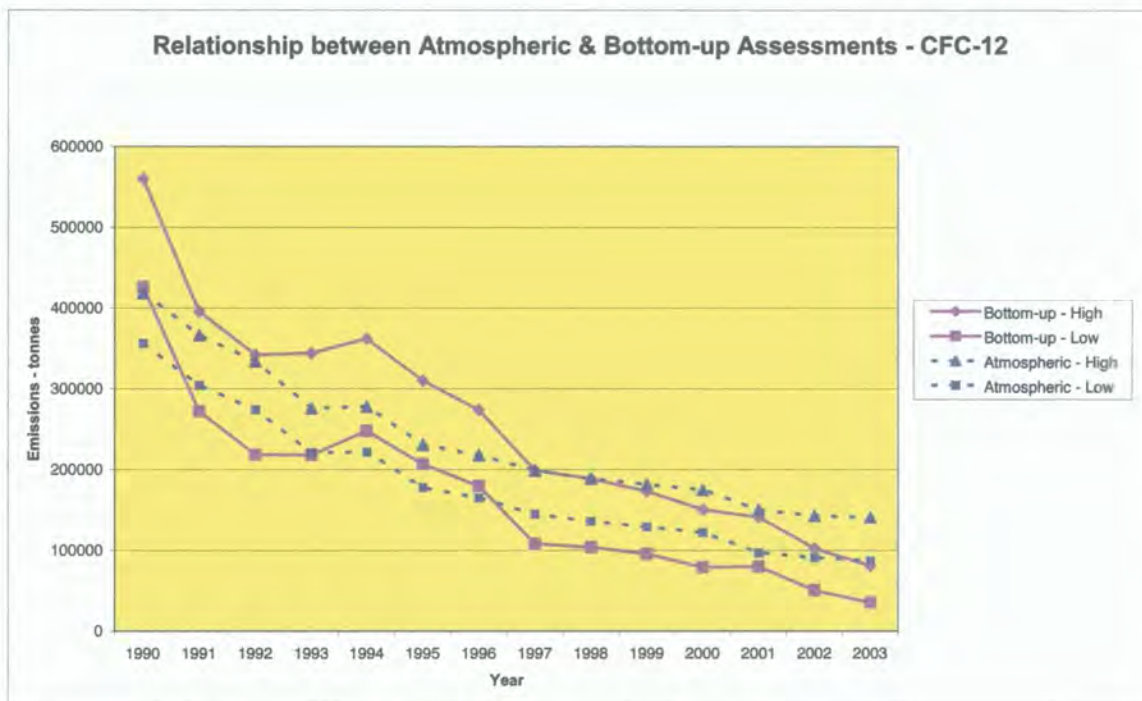
In order to work with this situation, the authors assumed that, since the only major delayed emission sectors were foam and refrigeration, all other consumption would be considered as emitted within one year of consumption. The equation used is basically as follows:

$$E_y = FE_y + RE_y + (UC_{y-1} - (FC_{y-1} + RC_{y-1}))$$

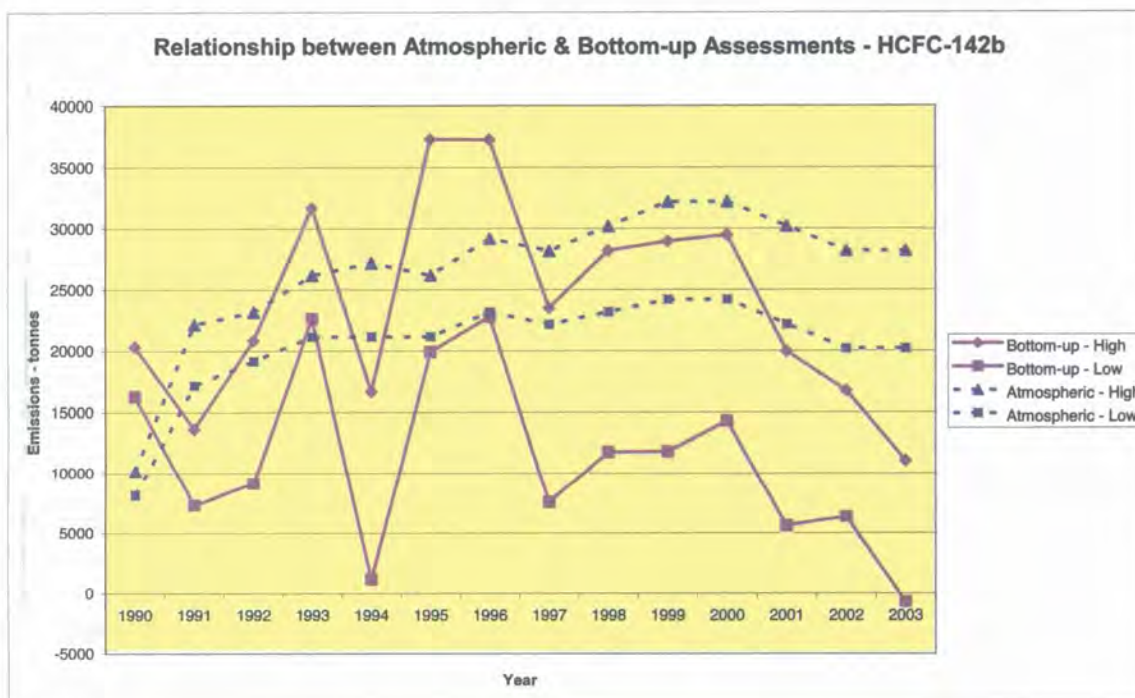
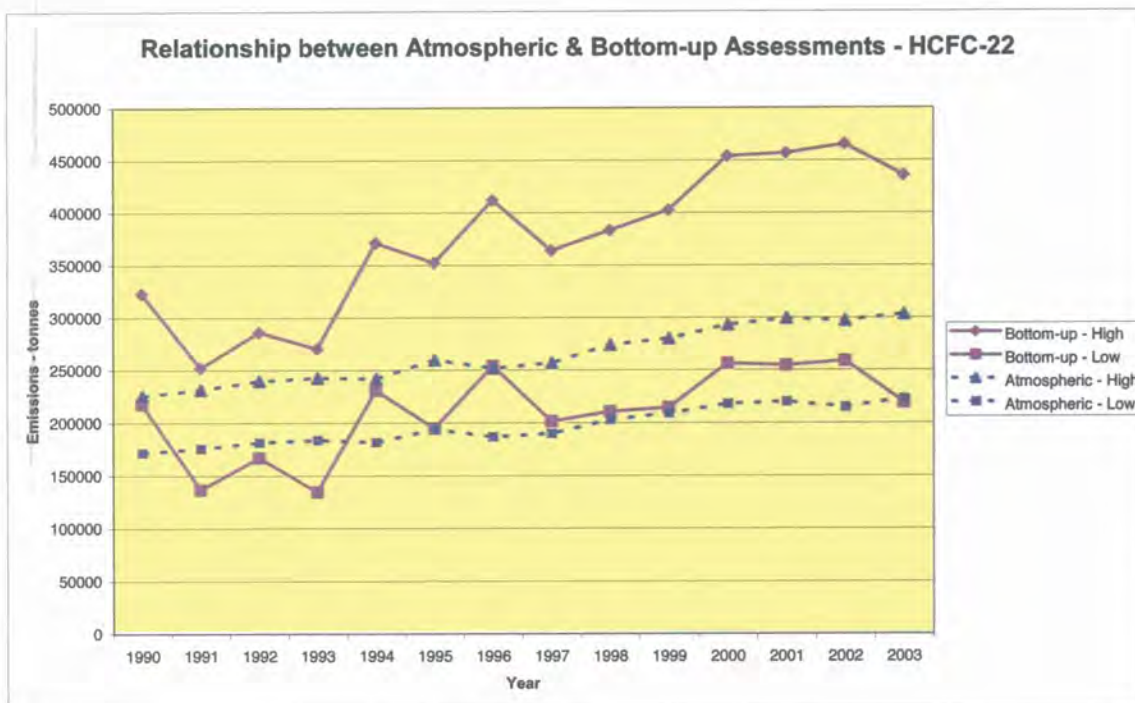
where E_y = Estimated emissions for year 'y'
 FE_y = Estimated foam emissions for year 'y'
 RE_y = Estimated refrigerant emissions for year 'y'
 UC_{y-1} = Declared UNEP consumption for year 'y-1'
 FC_{y-1} = Assessed consumption in the foam sector for year 'y-1'
 RC_{y-1} = Assessed consumption in the refrigerant sector for year 'y-1'

Using this approach the following assessments were possible for the five ODS blowing agents of interest:





In the instance of HCFC-141b (above), the match between bottom-up and atmospherically derived emissions in the early years of use was distorted by the lack of reporting to UNEP as a consequence of the inevitable time-delay involved in signing the Copenhagen Amendment.



These assessments enabled the Task Force to reach the following conclusions:

- *No single data source from UNEP, AFEAS or any of the bottom-up methods adopted can be considered as providing a uniquely accurate snapshot of the*

total situation. Accordingly, on-going development in the quality of each source will remain important.

- *There is considerable variability in consumption and resulting emissions estimated year-to-year in the early phases of introduction of a new chemical while reporting practices become established*
- *There is particular sensitivity to the completeness and accuracy of the UNEP consumption dataset because differences between the dataset and bottom-up analysis are assumed to be representative of emissive applications.*
- *There is still work to be done with HCFC-142b in establishing its emission sources and particularly rates of loss from thermoplastic foams. This may include the continuing development of more versatile bottom-up models.*

For CFC-11, a chemical primarily used as a blowing agent over its history, the following specific conclusions were reached taking into account that the discrepancies between emissions derived from bottom-up methods and those derived from atmospheric measurements are largest for CFC-11 :

- *There is no concrete evidence to suggest that CFC-11 emissions from closed cell foams are being under-estimated at present, although there is potential that first-year losses could have been higher than forecast in the earlier years of specific technologies.*
- *The currently estimated bank of CFC-11 in foams would not, in itself, be sufficient to make-up the cumulative difference between bottom-up and atmospherically derived estimates over the period of use in foams.*
- *The discrepancy between bottom-up and top-down emissions estimates for CFC-11 suggests the potential for additional emissive uses for CFC-11 that are, as yet, unaccounted for within the UNEP dataset.*
- *The global atmospheric lifetime of CFC-11 and other gases have substantial uncertainties that directly affect emission estimates from the top-down approach. A lifetime of 65 (52-88) years would be required to minimise the discrepancy between CFC-11 emissions derived from top-down and bottom-up methodologies. Because this lifetime is larger than the best estimate, CFC-11 lifetime of 45 (35-57) years, which is derived from modelling and observation-based methods, it is unlikely that the entire emissions discrepancy results from an error in the CFC-11 lifetime.*

Finally, the study's conclusions addressed the levels of confidence that could be placed in current bank estimates, stating the following:

- *It remains true that atmospheric projections of future halocarbon emissions and atmospheric mixing ratios depend upon the size and character of present day banks and the rates of emissions from these banks as well as emissions resulting directly from future production and use.*
- *In comparison with the situation described in Annex 11B of the Special Report on Ozone and Climate, it has been possible to reconcile the various methods used to derive emissions from bottom-up modelling and from atmospheric measurement for most ODS. The only possible exception is CFC-11. This reconciliation has been partly due to a reassessment of the impact of atmospheric lifetimes and mixing ratios on the one hand and uncertainties in consumption patterns and emission functions on the other.*
- *This provides further evidence that there is no fundamental error in either approach but that appropriate caution is necessary in relying on either dataset independently of the other.*
- *In the case of CFC-11, it may be necessary to carry out further analysis of the use patterns represented in the UNEP consumption dataset before drawing further conclusions on the size of present-day banks and likely future emissions.*

This series of conclusions has fundamentally under-pinned the current approach developed by the Foams Technical Options Committee and reported previously and the bank estimates so derived. However, it has highlighted the need for on-going refinement of models together with the closure of data gaps relating to the UNEP consumption dataset. This can only be achieved realistically by the introduction of end-use analysis within the UNEP reporting process. Parties may therefore wish to consider this option.

RECOVERY ACTIVITIES

The commercial recovery of blowing agents has continued to be limited to appliances in the four year period covered by this assessment. The primary reason for this is that most thermal insulation situated in buildings has yet to be decommissioned and reach the waste stream. Significant flows into this waste stream are not expected to emerge until after 2010, thereby giving some further time for governments to consider their waste strategies in the light of continually emerging information on the technical and economic feasibility of recovery.

In this context, the steel-faced panel project conducted by Kingspan (Kingspan, 2006) has confirmed the technical potential for recovery via existing refrigerator recycling plants, but has provided information that casts serious doubt on the economic feasibility of such a recovery process if it remains unaided by fiscal incentives.

In Japan, the JTCCM project has made comparisons between direct foam incineration and blowing agent recovery/destruction options for building insulation. In the latter case, the efficiency of recovery is highly dependent on the particle size of the foams at demolition. The study concludes that the costs of the two routes are relatively similar, but that, at best, these are around 4-5 times higher than the cost of recovering refrigerant (i.e. around \$150 per kg of blowing agent recovered). In situations where there is less retained blowing agent, the costs can be ten times higher.

With these cost considerations in mind, the Japanese Government has decided to adopt a strategy of promoting voluntary action on blowing agent recovery from buildings via its Construction Material Recycling Law. This is in contrast to earlier thinking which suggested that a mandatory approach could be applied. In parallel, the Government is also keenly promoting non-HFC policies to avoid future recovery burdens of this nature.

Meanwhile, commercial recovery of blowing agents from refrigerators continues in both Europe, Japan and, to a lesser extent, in some areas of the United States. The first two regions have mandatory provisions for recovery. However, in the EU, there is still some concern about the level of recovery actually being practiced in some Member States. Although a comprehensive review is still required into this aspect, most commentators are of the view that recovery of blowing agent might not be more than 50% of the potential blowing agent available. This is less to do with the efficiency of the recovery process from single appliances, and more to do with the enforcement and policing of the regulation itself. This is less of a problem in Japan, but, even there, some concerns exist about the operation of recovery mechanisms. In the United States, recovery programmes are typically voluntary in nature and are often funded by utility providers seeking to promote the early retirement of the appliance stock in order to improve overall energy efficiency. These programmes are only legally required to recover refrigerant, but the more environmentally responsible sponsors are including foam recovery in their specifications. Because of the lack of critical mass, foam recovery/destruction often needs to be carried out manually under these programmes. More detail is available on these approaches in the Foams End-of-Life Task Force Report (2005). A similar approach is also now spreading into Canada at state level.

In summary, the experience on recovery activities is mixed and it is clear that further incentives may be necessary to increase the levels of recovery. This is the subject of the last section of this chapter.

FUTURE TRENDS AND DRIVERS

For appliances, the bank of CFC-11 in developed countries is already well in decline and the one of the main on-going sources of recoverable CFCs will be in appliances which are re-used (or have extended lives) as secondary refrigerators (beer coolers etc.). In developing countries, the situation is very different and much of the product stock in use is still containing CFCs. The opportunity therefore still exists to recover these blowing agents using technologies already developed and optimized in developed countries. This will be particularly the case

around the large conurbations where the installation of full refrigerator recycling plants could be envisaged. A further incentive for the early retirement of appliances in developing countries could be the need to upgrade the energy efficiency of the stock in order to limit overall electricity demand and to delay the need for new generating capacity investments. This line of thinking is particularly well advanced in places such as Colombia and mechanisms for introducing such projects are being considered both nationally and under the MLF.

For building insulation, the challenge is still ahead. As noted in the previous section, there are still substantial concerns about the economic feasibility of blowing agent recovery, even in the most accessible of building product types (e.g. steel-faced insulated panels). It is believed that such economic hurdles are unlikely to be overcome unless fiscal incentives are introduced to make the recovery of blowing agents a more attractive proposition. One of the most obvious ways of doing this would be to find a method of recognising the incremental value of ODS recovery to the climate change agenda. This potential value was clearly identified in the IPCC/TEAP Special Report on Ozone and Climate and has been carried forward at the Workshop on Practical Measures for Emissions Reduction held in parallel with OEWG-26 in July 2006.

At present, the Kyoto mechanisms do not recognise the prevention of ODS emissions as of potential value to the climate, even though it is understood that the Montreal Protocol does not explicitly mandate the avoidance of emissions from the banks. The following table illustrates the scope of coverage:

	<i>Kyoto Mechanism</i>		
	EU ETS	Joint Implementation	Clean Development Mechanism
CO ₂	Yes	Yes	Yes
Non-CO ₂	No	Yes	Yes
ODS Recovery	No	No	No

Despite this lack of inclusion within the formal Kyoto mechanisms, the voluntary carbon market is beginning to recognise the potential environmental benefit of ODS recovery and sees the value of driving this by way of a flexible mechanism in order to maximize recovery and destruction. However, one of the main short-comings of the current voluntary market is that there is no formal registry to document the retirement of credits generated. For this reason the voluntary sector is at risk of becoming increasingly marginalized as concern over the validity of credits increases. Protocols such as “Gold Standard-VER” are targeted at guaranteeing the quality of credits generated voluntarily and these may well be helpful in under-pinning a future voluntary approach provided that Governments are also prepared to recognize the role that the voluntary sector can play in filling gaps left untouched by the regulated mechanisms.

In preliminary conversations on this matter, concern has been expressed that such credits could swamp the market in view of the high relative global warming potentials of most ODS. However, this concern needs to be tempered with the slow expected flow-rate of CFC-containing building insulation into the waste stream over the coming years. In this context, there will also

need to be further consideration about whether net or gross GWPs should be used as the basis for any such credits.

In summary, the availability of high quality recovery credits would be a reliable way of providing the inertia to overcome the existing economic feasibility barriers for ODS recovery. Protocols would still need to be developed to facilitate this process, but, just as importantly, signals will also be required from governments to confirm whether a voluntary recovery credit scheme would be acceptable, even if its robustness can be assured. The only other alternative would be for the integration of ODS recovery crediting systems into the existing Kyoto flexible mechanisms – a process that would certainly take more political will. Parties may wish to consider these or other options for overcoming the economic barriers to this important area of emissions avoidance.

APPENDIX 1: DESCRIPTION OF SECTORS

RIGID PU FOAM PRODUCTS AND APPLICATIONS

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

Used in a large variety of products, polyurethane foams can be classified into three major categories: rigid, flexible and integral skin/expanded elastomers. Product applications include insulating materials for buildings and appliances, cushioning products for furnishings and automobiles, packaging for protection of high-value products, automobile instrument panels and steering wheels and shoe soles.

RIGID DOMESTIC REFRIGERATOR AND FREEZER INSULATION

Rigid polyurethane foams are the dominant insulation used in refrigerators and freezers. In these products the foam serves as a key element in the structure of the appliance, as well as a very effective insulation. The foam must have adequate compressive and flexural strength to ensure the integrity of the product under extreme temperature conditions during shipping, as well as heavy loading during usage of the appliance. It must maintain both its insulation effectiveness and structural properties throughout the design life of the product. Using CFCs, foam manufacturers were successful in developing formulations which met all of these requirements. As substitutes are developed, care must be taken to ensure that properties are not compromised to the extent that the overall performance of the appliance is degraded.

Although the basic requirements for refrigerator/freezer foam insulation are similar for most manufacturers, unique manufacturing facilities, local market conditions and regulatory requirements resulted in a situation where unique requirements were developed for specific markets. For example, the importance of energy consumption in the US and Japanese markets led manufacturers to use formulations with higher levels of CFCs to achieve lower conductivities than were required in the European market.

Production Process

Liquid chemicals are injected between the outer shell and the interior liner of an appliance cabinet where they react, flow and expand to form rigid polyurethane foam throughout the cavity. Substantial fixtures are provided to support the walls which are under pressure from the foam. Typically, a few percent (<5%) of the blowing agent escapes from the chemical mixture and is vented during the foaming process. Production systems do not readily lend themselves to recovery of this lost blowing agent, so it has generally been vented directly to the atmosphere.

Over time, foam suppliers have developed formulations (using CFCs) which have properties (viscosity, reaction speed, exotherm, etc.) that meet the needs of production processes. With any new blowing agent, these properties must be maintained in order to produce quality products and control costs.

OTHER APPLIANCES

This category encompasses all "appliance" applications other than domestic refrigerators and freezers. The main applications are:

- **Water Heaters** -- Where foam insulation leads to a significant saving in energy consumption, particularly in designs where the space for insulation is limited.
- **Commercial Refrigerators and Freezers** -- Which are typically much larger than domestic units and includes open top display units.
- **Picnic Boxes (Coolers)** -- With a premium on insulation value and strong lightweight structures.
- **Flasks and Thermoware** -- Several types of articles require the same characteristics as picnic boxes.
- **Refrigerated Containers (Reefers)** -- A very stringent application with emphasis on durability and minimum wall thickness whilst maintaining insulation value.

Production Process

All the listed applications are produced by direct pour or injection of the foam chemicals between the inner and outer surfaces of the article. Most are held in moulds or jigs during the foaming process. Refrigerated containers are also produced by foaming section by section into a large pre-assembled jigged structure.

CONSTRUCTION – BOARDSTOCK/FLEXIBLE-FACED LAMINATION

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

In buildings, the largest use is in commercial roof insulation. Other uses include insulation for walls, cavities, internal linings (including agricultural buildings), exterior ventilated facades (Europe) and sheathing for residential construction (North America).

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

- **Low thermal conductivity** -- High values of energy efficiency can be achieved by using comparatively thin layers of foam insulation. Laminated foams with impermeable facers offer the highest degree of long-term insulation value. The low thermal conductivity was originally derived from the fine, closed-cell polymer structure combined with CFC-11 as the main blowing agent. Retention of low thermal conductivity is a key concern when considering alternatives.
- **Fire performance** -- PIR and fire retarded PUR foams provide excellent fire test results under a variety of test procedures;
- **Compressive strength** -- This property is very important in roofing applications because of the construction and maintenance traffic that a roof system, including the insulation, must bear;
- **Ease of processing** -- One advantage of the product is its ease of manufacturing combined with its excellent adhesion to a whole range of facing materials; modern, economic processes allow production rates of greater than 50 metres/minute and,
- **Ease of use and handling** -- Laminated products are lightweight, offered in a variety of thicknesses, provide excellent structural rigidity, and, in the case of PIR when used on roofs, can be sealed with hot bitumen and be used without separation technology.

Production Process

There are two principal types of continuous laminating machines:

- The continuous horizontal laminator is the standard type of laminator and is used to produce products with two flexible facers, e.g., aluminum foil, paper or roofing felt; one flexible facer and one rigid facer; and,
- The inverse laminator variation used to produce one rigid facing in sheet form. The chemical components are metered and mixed from the mixing head onto the pressure conveyor where external heat may be applied to promote faster curing before the foam is moved to the cut-off saw area. This product can also be produced using slabstock production methods.

The two main centres of manufacture are Europe and North America. In Europe, PUR foam is made with added fire retardant to obtain the desired fire properties as well as PIR. The latter is gaining market share. The term flexible faced lamination is commonly used. In North America, boardstock is a PIR product and no fire retardants are normally used. There is little production by this technique in developing countries.

CONSTRUCTION AND TRANSPORT: SANDWICH PANELS

Products and Applications

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

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

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

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

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

Production Processes

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

- Continuous Process

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

- Discontinuous Process

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

SPRAY POLYURETHANE FOAM INSULATION

Products and Applications

Sprayed foams are used for in situ application of rigid thermal insulation. Their major use is in roofing applications, especially in North America and in Southern Europe. Worldwide, sprayed foams are used for residential and commercial buildings, industrial storage tanks, piping and ductwork, and refrigerated transport trailers and tanks. Spray foam is applied by contractors in the field in accordance with the instructions of manufacturers of spray foam systems.

Production Process

Spray foam is applied using a hand-held pressurized spray gun, in which separate polyol and isocyanate liquids are metered under pressure, mixed and then dispensed. Different formulations or processing parameters impart specific properties to the foam, such as increased compressive strength, good dimensional stability at high heat and humidity, and greater high temperature stability. The ability of the formulator to adjust foam properties is beneficial, considering the foam is applied in a variety of climatic conditions.

The foam is sprayed directly from the mixing head onto the substrate. This method of application facilitates coverage of large and complex surfaces. For those applications where a thick layer of foam is needed, multiple thin layers of foam, of not less than 10 mm, are applied to create the thick layer. The sprayed foam needs to be highly reactive, especially for adhering to vertical surfaces during application. Pipes can also be insulated with spray foam by using a fixed spray gun and rotating and traversing the pipe.

OTHER RIGID POLYURETHANE FOAM APPLICATIONS

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

Slabstock

Product Applications

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

Production Process

Rigid slabstock is produced using either the discontinuous or the continuous manufacturing process. Traditionally, CFC-11 has served in both processes as the blowing agent.

- Discontinuous Process

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

- Continuous Process

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

In production by either method, the foam rises due to the expansion of the blowing agent and cures. Then it is cut into sections for use in the applications and products listed above. In general, rigid slabstock has neither a facer nor an impermeable liner attached to it.

PIPE-IN-PIPE/PREFORMED PIPE

Products and Applications

Foam-insulated pipe-in-pipe sections typically have an inner steel pipe which is surrounded with foam insulation which, in turn, is protected by a plastic outer skin. These pipes are installed underground and are used to transport hot water from a central boiler to surrounding dwellings. Similar pipes and others insulated with preformed pipe sections are used in production units and chemical plants for the transport of hot or cold fluids. Large diameter insulated pipes may have post-applied elastomeric or bituminous coatings to provide a permanent water barrier. The foam density is typically in the range 70-80kg/m³ to meet requirements on strength and durability.

Production Processes

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

Continuous processes have been introduced in which the foam is injected onto the inner pipe, cured and the outer plastic cover is then extruded onto the foam through an annular die.

ONE COMPONENT POLYURETHANE FOAM

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

Production Process

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

One component foams are supplied in pressurized cylinders and aerosol cans fitted with a nozzle through which a thin strip of material is extruded. After application, the foam expands at room temperature and cures by reacting with moisture in the air. This characteristic is unique to one component foams. The foam continues to cure internally after becoming dry to the touch as moisture from the air diffuses into the foam. The total time needed for foam cure depends on temperature and relative humidity.

FLEXIBLE POLYURETHANE FOAMS

SLABSTOCK FOAMS

Products and Applications

Slabstock foams include both polyether and polyester-based foams of varying densities and firmness, in each of the generic categories; conventional, high-resilience (HR), and combustion modified high resilience (CMHR). They are widely used in comfort applications such as furniture, bedding, carpet underlay, and automotive interiors and technical applications such as sound dampening, air filters, fuel cells, and packaging. Available in a range of densities and firmness, the foams are produced in large blocks, which are cut/shaped for use in individual application. In applications requiring combustion-modified foams to meet fire safety standards, the foams include melamine, graphite, chlorinated phosphoric esters, or alumina trihydrate to improve the foam's fire resistance. Greater amounts of auxiliary blowing agents are normally used in these foams to offset changes in hardness and density resulting from the introduction of these solid additives. Applications are mainly in upholstered furniture and bedding. In some countries, this is limited to institutions and mass transit; however, in other countries, such as the UK, their use is compulsory for all domestic applications of upholstered furniture and bedding.

Production Processes

While the choice of process chemicals provides the basis for the resulting foam properties and costs, the production process has also a profound impact. A foam operation can be divided into a "wet part" and a "dry part". The wet part ranges from the chemical storage/blending to the metering/mixing of the chemicals, while the dry part constitutes of all the subsequent equipment used to process the chemical blend and the resulting foam.

Slabstock foams can be produced following a continuous process or a discontinuous process.

- Continuous Processes

In a typical continuous production line, the wet part consists of a storage/conditioning and metering system through which the liquid chemicals are metered to a mixing head. Feed formulation varies for different foam grades and between different foam producers. The metered stream from the mixing head is dispensed to a nozzle with a traversing pattern across the width of an inclined portion of the conveyor belt: this is termed the "laydown". The dry part consists of an enclosed continuous conveyor belt, called a "foam tunnel", that can be over 60 meters long. The conveyor belt is lined with paper or polyethylene film to make a "U" shaped retainer for the rising foam mass as it descends the slope. In the wet part, the laydown can be effected in different ways:

- Transfer directly on the conveyor: "Liquid Laydown Technology",
- Transfer through a pre-expansion device: "Trough Technology"
- Transfer through a direct expansion device: "Froth technology"

The dry part can be:

- An inclined conveyor
- A horizontal conveyor with fallplate
- A vertical three-dimensional conveyor system

The equipment industry frequently offers certain combinations such as:

- Maxfoam/Varimax - Trough technology with horizontal conveyor/fallplate
- Vertifoam - Trough technology with vertical conveyor system

These different processes are described in more detail below:

Traditional Slabstock Method

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

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

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

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

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

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

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

Maxfoam/Varimax

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

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

Currently the process of choice for most manufacturers, the Maxfoam/Varimax process for flexible foam production is less complicated and more efficient than conventional foaming (higher blocks, more density control and firmness control).

Vertifoam

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

In addition, the foam blocks produced are accurately shaped and trimming losses are low. All the skins on Vertifoam blocks are thinner and less dense than conventional blocks and have none of the heavy top and bottom skin. These thin skins allow rapid diffusion for cooling or recovery. Both square blocks and round blocks can be produced.

The Vertifoam process differs substantially from conventional horizontal foam machines that need high chemical throughput rates to produce large foam blocks. The high chemical throughput rates of conventional foam machines result in high capital costs and large heating and ventilation requirements.

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

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

- Discontinuous Processes

Box Foam

In many developing countries where manpower is abundant, two pre-batched liquid components are mixed together and then literally poured into a lined box, which then expands and cures into a final block.

The pressure to switch to the use of alternative blowing agents has led to the development of vacuum assisted box foam processes which, in contrast to their predecessors can have a high degree of sophistication.

MOULDED FOAMS

Products and Applications

Moulded Foams are mainly used in transportation applications such as seat cushions, back cushions, armrests, and headrests. A specialty market is the sound dampening in cars by back-foaming of carpets and firewall (shared with slabstock). Together, transportation uses account for at least 90% of the flexible moulded foams used worldwide. The other 10 percent used for furniture and a range of miscellaneous applications. Flexible moulded foam can be produced by either "hot cure" or "cold cure" with cold cure being the predominant process worldwide. Hot cure foams are used for automotive seating and headrests. Cold cure moulded foams are used in both automotive (seating, headrests, carpet ticking backing) and non-automotive (furniture) uses.

Production Processes

Moulded Foams

In the production of moulded flexible foams, chemicals are dispensed (usually a pre-blended two component system) to an open mould of a desired shape and size. Following mould cleaning and application of a release agent, the moulds are filled, sometimes manually, and then closed.

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

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

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

INTEGRAL SKIN AND MISCELLANEOUS FOAMS

Products and Applications

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

Integral skin and miscellaneous polyurethane foams include:

Integral Skin

- flexible (or semi-rigid) integral skin foams for steering wheels, headrests, armrests, shoe soles, beer barrels, etc;
- rigid integral skin foams for computer cabinets, skis, and tennis rackets;

RIM

- microcellular high-density foam for exterior body parts of automobiles;

Non-Insulation Rigid

- low-density packaging foam;
- floatation foam;
- floral foams; and,
- energy absorbing foams for side impact in automobiles.

The principal benefits of polyurethane use for these applications are physical performance, ease of processing, and cost. CFCs have essentially been eliminated in these foams in most developed countries.

Production Process

Integral skin foams are molded foams, manufactured either by injection into closed vented molds (i.e. steering wheels) or by pouring into open molds (i.e. skin soles). These foams are characterized by a high density outer skin and a low density, softer core. The density gradation results from (a) blowing agent condensation at the mold surface compacting the cells of the urethane foam, and (b) overpacking of the mold.

Microcellular high density foams (RIM) are manufactured via injection into closed molds, in many cases using large presses to maintain clamping pressure and produce parts within dimensional tolerances. The microcells form air nucleation and also from small amounts of CO₂ (resulting in most cases from residual water).

Non insulation critical rigid foams are manufactured via a variety of processes including spray, moulding or rigid slabstock, using conventional or high pressure urethane dispensing equipment.

Most integral skin and miscellaneous foams are open cell, where the blowing agents used in manufacture are emitted to the atmosphere during the foaming reaction or soon thereafter. Rigid integral skin and flotation foams are closed cell, but low thermal conductivity is unnecessary in these products.

EXTRUDED POLYSTYRENE

EXTRUDED POLYSTYRENE SHEET

Products and Applications

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

- Food Service and Packaging

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

CFCs were attractive blowing agents for some foam food service products because they contributed to the products' ability to insulate food and beverages at the proper temperature and to provide appropriate moisture resistance. In food packaging, CFCs also contributed to the products' moisture resistance; therefore, the end products eliminate the need for frequent in-store rew wrapping.

- Dunnage

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

- Laminated Foam Sheets

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

Production Process

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

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

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

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

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

EXTRUDED POLYSTYRENE INSULATION BOARD

Products and Applications

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

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

- boards with a smooth skin covering the two principal heat transfer surfaces,
- the main application of the self-skinned material includes insulation for roofs, floors, and walls in dwellings, commercial and agricultural buildings. In some northern countries, another major application is the protection of roads, airport runways and

railways against frost-heave by laying the insulation boards in the earth below the pavement and rail permanent way;

- boards with a planed or cut cell surface that provides grip for plaster, adhesive, and pour-in-concrete -- the main application for this product includes wall insulation of concrete buildings, tile and plaster backing, core material for sandwich panel construction, and low temperature space. There are a number of small specialty applications in most geographical markets as well.

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

Other properties of extruded polystyrene foam include:

- low thermal conductivity;
- resistance to freeze-thaw deterioration;
- excellent compressive strength and dimensional stability (low shrinkage);

and

- good handling properties, including low toxicity and low insulating gas diffusion loss with time.

Production Process

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

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

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

- it makes the gel foam
- and
- it contributes insulation value to the foam.

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

POLYOLEFIN FOAMS

Products and Applications

The general category of polyolefin foams includes products made from either polyethylene or polypropylene resins. These general foam types sometimes include other olefinic constituents, such as ethylene/vinyl acetate or ethylene/acrylic acid copolymer resins, as modifiers. Several different manufacturing processes are used for polyolefin foams, which result in different product forms.

One type of processing, which involves the crosslinking of extruded resin sheet and its subsequent expansion, uses only decomposable blowing agents, such as azodicarbonamide, and, as such, *this process will not be considered further here*. These products have different properties and are typically more expensive than polyolefin foams manufactured with physical blowing agents. They are not generally considered to be substitutes for most non-crosslinked polyolefin foam applications.

Polyethylene and, more recently, polypropylene resins are used in expandable bead products, which may be subsequently shape-moulded. These foam products are used primarily as moulded cushion packaging and automotive bumper systems. CFC-11 and CFC-12 were previously used as blowing agents. All bead producers now use hydrocarbons or carbon dioxide. Consequently, *no further comments will be made regarding these products*.

- Sheet products

Both polyethylene and polypropylene resins are extruded into sheet products. These sheet products are commonly used as protective packaging for furniture, electronic devices, and other goods. Other applications include flotation devices (such as life vests), construction materials, and gaskets. CFC-11, CFC-12, and CFC-114 have historically been used for most of these sheet products.

- Plank products

Polyethylene resins are used in the manufacture of extruded plank products. Their most frequent application is designed cushion packaging of electronic or other high-value goods. Some plank products are also used in military packaging, flotation, construction, aircraft seating and other applications. CFC-12 and CFC-114 were generally used in the manufacture of plank products.

- Tubular products

Polyolefin foam is also extruded in an annular shape i.e. as a tube, for use as thermal insulation for pipe. Applications include residential hot and cold water pipe insulation and similar near-ambient temperature applications. Historically CFC-12 or CFC-114 were used as blowing agents.

In most polyolefin foam applications, products are used because of specific properties. The most important of these properties is the material's ability to provide insulation from mechanical, vibrational, thermal and/or other environmental stresses.

Production Processes

In the case of extruded products, the resin is melted and mixed with the blowing agent(s). The resin and blowing agent are then passed through a die, where the product rapidly expands and cools.

- Sheet products

For sheet products, a circular, annular die is used to form a thin-walled hollow cylinder of foam. This foam tube is subsequently slit to produce a flat sheet that can then be rolled for storage or shipment. Sheet products are normally no thicker than 6 mm, and most are no thicker than 3 mm.

- Plank products

Typically, plank products are made using a specific die, which produces the particular cross-section desired. Each cross-section requires a different die. The plank is then cut to length and, if necessary, the edges are trimmed. Plank products can be from 12 to over 100 mm thick, are made up to 1200 mm wide, and are occasionally made in circular or other non-rectangular cross-sections. One process injects the foaming materials into a closed cavity to help dimension the product.

- Tubular products

Tubular pipe insulation also uses an annular die but one producing a reasonably small

diameter, relatively thick-walled foam product. The inside diameter of the tubing ranges from 6 mm to 125 mm with wall thicknesses of 5 to 50 mm.

All three foam types are closed cell products. Thus, most of their blowing agents are initially trapped within the foam. With very thin sheet products, a significant portion of the blowing agent may be lost at or near the die. For extruded plank, tubing and thicker sheet products, very little is lost at the die although some will be lost in trimming operations, which open the cells.

PHENOLIC FOAMS

Products and Applications

Phenolic foams represent only a small proportion of the foamed insulation materials used world-wide. However, their generic fire properties (particularly their extremely low smoke emission) have established the product in many applications previously served by other insulation products. Phenolic foam products have particularly gained acceptance in public and commercial buildings where fire concerns are often more significant. Cost usually rules against phenolic foams when considered for the domestic environment.

There is a significant level of substitution against fibrous products where cleanliness and moisture resistance can be offered without unnecessary loss of fire performance. This is particularly the case in the building services sector, where insulation is often exposed. Pipe laggings are an example. Uptake of the product has, however, been heavily dependent on local building methods and fire codes. In some Member States in Europe, laminate products are widely used for wall and roofing applications, particularly within the growing single-ply roofing market. However, in others, there is very little usage. Phenolic foam is making particular inroads in Japan, where the building methods and population density create a ready market. However, mixed experiences with phenolic technologies in North America have led to a virtual de-selection in several applications. More recently, activity in Europe has increased in the use of phenolic foams in rigid faced paneling for cool-rooms, doors and partitions.

There is still some residual usage of open-celled phenolic foam for specific market requirements. A prime example of this is its use for floral arrangements. The unique wetting properties of this particular product make it virtually irreplaceable. However, these properties are not reliant on the use of CFCs and most production had already switched to hydrocarbons on the basis of cost. Accordingly, floral foams are not considered further in this report.

More orthodox open-celled phenolic foams are still used in some countries, most notably the former Soviet Union, as prime insulation. As these foams exhibit poorer insulation characteristics than those made from the more recently developed closed-cell technologies outlined above, there has been pressure to transfer these technologies under license or other co-operative agreement.

Production Processes

- Discontinuous Processes

Several discontinuous processes have been developed for closed-cell foams, but undoubtedly the most prevalent is the Block or Bun process. This has been particularly dominant in Europe where the process lends itself to the varied requirements of Building Services market. Complex computer-controlled cutting equipment optimises yields from blocks when cutting pipe sections. Despite this, yields can be as low as 50% for the more awkward shapes.

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

Most, if not all, discontinuous processes have used CFC-11 and/or CFC-113 to obtain their high thermal efficiencies historically. Accordingly, most plant technologies, and their associated installed units, are unable to handle low boiling blowing agents. Additionally, few plants are flame-proofed. These factors have inhibited the move to alternative blowing agents, particularly the low boiling HCFCs and HFCs.

- Continuous Processes

Within the range of continuous processes, lamination with flexible facings is the most common. There has been less focus on rigid faced lamination and continuous block to date, although these may follow now that ODS-free technologies are established. The machines used for continuous lamination are, in the main, more capable of processing low boiling blowing agents than their discontinuous counterparts and, accordingly, CFC-114 was a common constituent within several technologies historically. It should be stressed that it is the process rather than the machinery per se which facilitates the use of these low boiling materials. Therefore, it is unlikely that much of the associated technology will be transferable to the discontinuous operations.

More recently, there have been strides to produce pipe section on a continuous basis and a successful commercial plant is now operating in the UK. This has also enabled a wider variety of blowing agents to be used in these products.

APPENDIX 2: REVIEW OF BLOWING AGENT OPTIONS

This Appendix has been produced specifically to provide relevant information to potential users on the characteristics and availability of the blowing agents referred to in this document. Efforts have been made to provide as much information as possible. However, commercial concerns about the disclosure of the locations of specific plants have made it impossible to provide a comprehensive review of potential geographic constraints. To avoid misleading anecdotal comments, the Committee has elected to omit any comments related to geographic limitations, except where their use is legally defined by patents. The Committee would refer the reader to the suppliers listed under each blowing agent cited for further information.

The major blowing agents being commercially used in the foam sector, or being considered for commercial introduction in the short-term, are shown in Table A-2.1 overleaf. This, table and the subsequent descriptive paragraphs, provide technical information on the blowing agents themselves and some information on usage patterns and commercial availability. It should be noted that there are no references to regulatory constraints in this Appendix. While, the impact of ODS Regulations is probably well known to the reading audience and does not require further iteration here, it might be useful to note, for example, that all fluorocarbons in the United States are not treated as Volatile Organic Compounds (VOCs) for regulatory purposes.

TABLE A-2.1 PHYSICAL AND ENVIRONMENTAL PROPERTIES OF MAJOR BLOWING AGENTS

	CFC-11	CFC-12	HCFC-22	HCFC-142b	HCFC-141b	HFC-134a	HFC-152a	HFC-245fa	HFC-365mfc	HFC-227ea
Chemical Formula	CFC13	CCl2F2	CHClF2	CH3CClF2	CO2FCH3	CH2FCF3	CHF2CH3	CF3CH2CHF2	CF3CH2CF2CH3	CF3CHF2CF3
Molecular Weight	137	121	86	100	117	102	66	134	148	170
Boiling point (°C)	24	-30	-41	-10	32	-27	-25	15.3	40.2	-16.5
Gas Conductivity (mW/m²K at 10°C)	7.4	10.5	9.9	8.4	8.8	12.4	14.3	12.5	10.6	11.6
Flammable limits in air (vol. %)	None	None	None	6.7-14.9	7.3-16.0	None	3.9-16.9	None	3.8-13.3	None
TLV or OEL (ppm) (USA)	1000	1000	1000	1000	500	1000	1000	N/A	N/A	1000
GWP (100 Yr.) ***	4000	8500	1700	2000	630	1300	140	820	840	2900
ODP	1.0	1.0	0.055	0.065	0.11	0	0	0	0	0
Producers (major)	Honeywell	Honeywell	Arkema Honeywell, Solvay DuPont Chinese producers	Honeywell Arkema, Solvay Chinese producers	Honeywell Solvay Arkema Chinese producers	Arkema, DuPont, INEOS, Honeywell Solvay Chinese producers	DuPont, Solvay	Honeywell Central Glass	Solvay	Solvay

Fluorinated Blowing Agents

	Methylene Chloride	Trans-1,2-dichloroethylene	Isopentane	Cyclo-pentane	n-pentane	Carbon Dioxide	Isobutane	n-butane	Methyl Formate (Ecomate®)
Chemical Formula	CH2Cl2	C2H2Cl2	CH3CH(CH3)CH2CH3	(CH2)5	CH3(CH2)3CH3	CO2	C4H10	C4H10	CH3(HCOO)
Molecular Weight	84.9	97	72.1	70.1	72.1	44.0	58.1	58.1	60.0
Boiling point (°C)	40	48	28	49.3	36	-139	-11.7	0.5	31.5
Gas Conductivity (mW/m²K at 10°C)	N/A	N/A	13.0	11.0	14.0	14.5	15.9	13.6	10.7
Flammable limits in air (vol. %)	None	6.7-18	1.4-8.0	1.4-8.0	1.4-8.0	None	1.8-8.4	1.8-8.5	5.0-23.0
TLV or OEL (ppm) (USA)	35 to 100	200	1000	600	610	N/A	800	800	100
GWP (100 Yr.) ***	N/A	<25	<25	<25	<25	1	<25	<25	<25
ODP	0	0	0	0	0	0	0	0	0
Producers (major)	Arkema	ExxonMobil Haltermann Chevron/Phillips Shell	ExxonMobil Haltermann Chevron/Phillips Shell	ExxonMobil Haltermann Chevron/Phillips Shell	ExxonMobil Haltermann Chevron/Phillips Shell	Chevron Bayer Huntsman Phillips	Bayer DuPont Huntsman Phillips	BOC	

Non-fluorinated Blowing Agents

Measured at 25°
Measured at 40°C
Measured at 20°C
Measured at 24°C
IPC-Report 1996
Measured at 0°C
Subject of on-going investigation at time of publication

HCFC-22

Description & Usage

HCFC-22 is a non-flammable gas liquefied under pressure. One main application is as a non-flammable mixture with HCFC-142b for PU and XPS foams. In rigid PU foam it has been used in combination with HCFC-141b.

Physical and Chemical properties

Chemical name:	Chlorodifluoromethane
Formula:	CHClF ₂
Molecular Weight ² :	86.4687
EC Number (EINECS):	200-871-9
CAS Number:	75-45-6
Density ³ (g/cm ³)	1.49 (-69 °C)
Boiling Point ⁴ (°C)	- 40.8
Vapour pressure (bar)	9.08 (20 °C), 19.33 (50 °C)
Gas Conductivity (mW/m. K)	9.9 (10 °C), 11.0 (30 °C)
Vapour density (air=1)	3.65 (20 °C)
Solubility (20°C, 1bar)	Slightly soluble in water (0.42 %) Soluble in most organic solvents

HSE properties

Toxicological data ⁵ :	
TLV (as TWA) (ACGIH-USA) 2001	1000 ppm, 3540 mg/m ³
TWA (NIOSH REL)	1000 ppm, 3500 mg/m ³
Decomposition temperature	480 °C
VOC	No
GWP ⁶ (100 years)	1780
ODP	0.05

² <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.

³ <http://ptcl.chem.ox.ac.uk/MSDS/CH/chlorodifluoromethane.html>. Consulted July, 2006.

⁴ <http://chemfinder.cambridgesoft.com/result.asp>, <http://ptcl.chem.ox.ac.uk/MSDS/CH/chlorodifluoromethane.html>, <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/83.html>. Consulted July, 2006.

⁵ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/83.html>. Consulted July, 2006.

⁶ IPCC TEAP Special Report 2005

Commercial Status

Producers⁷:

Asahi Glass, Arkema, Clariant, Daikin, ICI, Du Pont, Hindustan Fluorocarbons Ltd., Hoechst Marion Roussel S.A., Honeywell, Hunan Zhuzhou Chemical Industry Group Co. Ltd., Jinan Chemical Works, Produven, Quimobasicos S.A. de C.V., Rhodia, Shanghai Chlor-Alkali Chemical Co. Ltd., Shaowu City Fluoride Chemical Plant, Solvay, Tyco Sanmar.

⁷ <http://www.chemchannels.com/chemchannel/Advance/directory/directory.asp>. Consulted July, 2006.

HCFC – 141b

Description & Usage

HCFC-141b is a liquid at room temperature and does not have a flash point. HCFC-141b has been used as a foam blowing agent in almost all rigid and integral skin foam sectors.

Physical and Chemical properties

Chemical name:	1,1-dichloro-1-fluoroethane
Formula:	CH ₃ CFCl ₂
Molecular Weight ⁸ :	116.9501
EC Number (EINECS):	404-080-1
CAS Number:	1717-00-6
Density ⁹ (g/cm ³)	1.25 (10 °C)
Boiling Point ¹⁰ (°C)	31.9
Vapour pressure (bar)	0.78 (25 °C)
Gas Conductivity (mW/m. K)	8.8 (10 °C), 9.7 (25 °C)
Vapour density (air=1)	4.86 (25 °C)
Solubility	approx. 4.8 % (20 °C)

HSE properties

Toxicological data:	
TLV or OEL (USA, ppm)	500
WEEL, 8 hr. TWA, ppm	500
Decomposition temperature	> 200°C
Flammable limits in air (vol. %)	5.6-17.7
VOC	No
GWP ¹¹ (100 years)	713
ODP	0.11

⁸ <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.

⁹ idem

¹⁰ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/247.html>. Consulted July, 2006.

¹¹ IPCC TEAP Report 2005

Commercial status

Producers:

Arkema, Central Glass, DSL Chemicals (Shanghai) Co. Ltd., Hangzhou Fisi Chemical Co. Ltd., Redox Pty. Ltd. (Head Office - Redox Chemicals Pty. Ltd.), Shandong Dongda Chemical Industry Group Co., Solvay, Zhejiang Sanhuan Chemicals Co. Ltd., Zhejiang Sanmei Chemical Industry Co. Ltd.

HCFC – 142b

Description & Usage

HFC-142b is a gas at room temperature. It is used as a foam blowing agent for both polyurethane and extruded polystyrene foams. It can be used alone or as a blend with HCFC-22. A blend of 60/40 HCFC-142b/HCFC-22 (60/40) is non-flammable.

Physical and Chemical properties

Chemical name:	1-chloro-1,1-difluoroethane
Formula:	CH ₃ CF ₂ Cl
Molecular Weight ¹² :	100.4955
EC Number (EINECS):	
CAS Number:	75-68-3
Density/Specific gravity	1.22
Boiling Point ¹³ (°C)	-9.2
Vapour pressure (bar)	3.4 (25 °C)
Gas Conductivity (mW/m. K)	8.4 (10 °C), 11.5 (25 °C)
Vapour density (air=1)	4.18 (25 °C)
Solubility	0.14 %

HSE properties

Toxicological data:	
TLV or OEL (USA, ppm)	1000
WEEL, 8 hr. TWA, ppm	1000
Flammable limits in air (vol. %)	6-18
VOC	No
GWP ¹⁴ (100 years)	2270
ODP	0.066

¹² <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.

¹³ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/131.html>. Consulted July, 2006.

¹⁴ IPCC TEAP Report 2005

Commercial status

Producers:

Arkema, Asahi Glass Co. Ltd. (Corporate Office), Daikin Industries Ltd., Hangzhou Fisi Chemical Co. Ltd., Honeywell, ICI Japan Ltd., Kirovo-Chepetsky Khiminsky Kombinat OAO, Solvay, Ulsan Chemical Co., Ltd., Zhejiang Sanhuan Chemicals Co. Ltd., Zhejiang Sanmei Chemical Industry Co. Ltd., Zhonghao New Chemical Materials Co. Ltd.

METHYLENE CHLORIDE

Description & Usage

Methylene chloride, or dichloromethane, is a clear, colourless liquid with a penetrating ether-like odour. Pure, dry methylene chloride is very stable and will not produce corrosion in mild or galvanized steel, copper, nickel, lead or tin. In the presence of water, however, it may undergo very slow hydrolysis to produce small quantities of hydrogen chloride, which can lead to corrosion. This process is accelerated by elevated temperatures and the presence of alkaline or metals. Commercially available methylene chloride is normally inhibited with small quantities of stabilizers to avoid this process. Typical stabilizers are propylene oxide and cyclohexane.

Methylene chloride's combination of properties, such as a low boiling point, relative inertness, low toxicity and non-flammability have led to its use as an auxiliary blowing agent in the foam industry. Its low photochemical ozone creation potential (PCOP) and lack of ozone depletion potential (ODP) has increased its use dramatically in the recent years, making it a significant CFC-replacement in the manufacture of polyurethane foam. The U.S. EPA has recognized this by mentioning methylene chloride under the Agency's Significant New Alternatives Program (SNAP) as an acceptable alternative to ozone depleting solvents.

Physical and Chemical properties

Chemical name:	Dichloromethane
Formula:	CH ₂ Cl ₂
Molecular Weight ¹⁵ :	84.9328
CAS Number:	75-09-2
Density ¹⁶ (g/cm ³)	1.322 (20 °C)
Boiling Point ¹⁷ (°C)	39.8
Freezing Point ¹⁸ (°C)	- 96.7
Viscosity ¹⁹ (cp)	0.41 (25 °C)
Refractive index ²⁰	1.4244 (20 °C)
Vapour pressure (mmHg)	349 (20 °C)
Vapour density ²¹ (air=1)	2.93
Water Solubility	Slightly sol. (1.32 g/100 mL)

¹⁵ <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.

¹⁶ idem

¹⁷ <http://chemfinder.cambridgesoft.com/result.asp>, <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6392.html>. Consulted July, 2006.

¹⁸ <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.

¹⁹ <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6392.html>. Consulted July, 2006

²⁰ <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6392.html>. Consulted July, 2006

²¹ <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006

HSE properties

Toxicological data:

TLV or OEL (USA) (ppm)	35 - 100
Flash point (closed cup)	none
Ignition temperature in air, °C	615 - 932
LEL (%)	15 (25 °C)
UEL (%)	20 (25 °C)

Methylene chloride is considered non-flammable but under certain circumstances it may propagate a flame. In the vapor phase and under abnormal conditions (elevated temperatures, flame, sparks etc.), it may be decomposed to give off small amounts of hydrogen chloride, carbon monoxide, and phosgene.

The most likely routes of human exposure will be inhalation and skin contact. Methylene chloride is absorbed through the lungs and through the skin. It can, however also be absorbed through the intestines upon ingestion. It is quite rapidly excreted, mostly through the lungs, without any chemical change. The remainder is metabolised to carbon monoxide (CO), carbon dioxide (CO₂) and inorganic chloride. There are two pathways for this metabolism: a cytochrome P450 pathway, also called "mixed function oxidise (MFO), generating CO and CO₂, and a glutathione-S-transferase (GST) pathway, generating only CO₂.

The MFO route is predominant at relatively low doses; saturation occurs at around 500 ppm. Increasing the dose above the saturation level does not lead to extra metabolism by this route. The GST route seems to be used very little in the human system. In other species (e.g. the mouse) this pathway can become the major route at sufficiently higher doses.

The generation of CO in the body is of significance. It can combine with haemoglobin in the blood, forming carboxy- haemoglobin (COHb) thus reducing the oxygen carrying capacity of the blood.

MC has a relatively low acute toxicity. High exposure (> 1,000 ppm) triggers anaesthetic effects and a depressant effect on the central nervous system (CNS). The CNS effect is additive with those from other CO sources, e.g. cigarette smoking. Some reversible effects on sensory and psychomotor function have been observed from acute exposures to 300-500 ppm, but not to lower concentrations. Little evidence is available on oral toxicity. Swallowing of small splashes is unlikely to have significant effect.

Liquid MC is a slight skin irritant, due to the removal of natural oils in the skin.

Long term behavioural and neurological studies have shown no significant adverse effects. There is no evidence that MC causes the irreversible chronic CNS damage sometimes diagnosed as "Danish Painters Syndrome" (solvent induced encephalopathy).

The potential carcinogenicity of MC is a controversial issue. There is one study, performed for the National Toxicology Program (NTP), that suggests carcinogenic effects of high lifetime

doses in mice. Other bioassays with different animals (rat, hamster) and at lower concentrations did not confirm these findings, indicating that the association between MC exposure and carcinogenicity may be unique to mice and even then concentration related. This was supported by subsequent research, concluding that important species differences exist in metabolism between the mouse on one side, and rats, hamsters, or humans on the other side. Evidence was provided that the GST pathway of metabolism is linked to the carcinogenic response observed in mice. Since humans show a very limited ability to metabolize MC via the GST pathway, the mouse is a poor surrogate for assessing human hazard.

The above mentioned research efforts led to the development of a physiologically based pharmacokinetic (PB-PK) model to evaluate the carcinogenic risk to man from exposure to MC. Application of this model on experimental animal data concludes to no significant risk for man under current hygiene standards.

The U.S. EPA has accepted the PB-PK model, and used in its draft Update to the Health Assessment Document (HAD) for methylene chloride. Also EPA's Science Advisory Board indicated approval. OSHA, however, indicated reservations, and has based its proposed revision of the occupational exposure standard for MC on the before mentioned NTP study. The industry has submitted critical comments to this proposal, and achieved reconsideration by the agency. The effected date for the new standard delayed accordingly.

Industrial mortality studies have shown no evidence of that methylene chloride, even at relatively high concentrations (100-350 ppm, with peaks of up to 10,000 ppm) represents a carcinogenic or cardiovascular ischemic risk to humans.

The US Occupational Safety and Health Administration (OSHA) in January 1997 adopted a comprehensive standard for workplace exposure to methylene chloride. The standard establishes permissible exposure limits (PELs) of 25 ppm as an 8-hour time-weighted average (TWA) and 125 ppm as a short-term exposure limit (STEL). The compliance dates vary by industry sector and size of business; all companies must be in compliance by April 2000 at the latest. The standard also requires medical surveillance and contains a number of other ancillary provisions. The ACGIH threshold limit value (TLV) is 50 ppm for an 8-hour TWA exposure. In 1987, the US Consumer Product Safety Commission (CPSC) published a Statement of Interpretation and Enforcement Policy for household products containing methylene chloride. This policy statement establishes labeling guidance for these products under the Federal Hazardous Substances Act. In addition, the use of methylene chloride in cosmetic and food products is restricted by the Food and Drug Administration (FDA).

The EU classification was established as Carc. Cat. 3 /Xn;R40 in the 23rd ATP in 1997. This classification was implemented by member states by December 1998.

Commercial status

Methylene chloride is a generic chemical and available from numerous manufacturing and trading sources. The use of recycled material in PU foam applications is discouraged because of a possible catalytic effect of dissolved trace metals. Several manufacturers such as Dow Chemical, Solvay and ICI offer product versions that have been specifically stabilized for the use in PU foam.

HFC-134a

Description & Usage

HFC-134a is a non-flammable gas at room temperature. It is the most widely used zero ODP fluorochemical and is an established refrigerant. HFC-134a has been used as a blowing agent in almost all foam sectors, particularly rigid and integral skin foam. It is also being used for extruded polystyrene foam in Europe.

Physical and Chemical properties

Chemical name:	1,1,1,2-Tetrafluoroethane
Formula:	CF ₃ CH ₂ F
Molecular Weight ²² :	102.0314
EC Number (EINECS):	212-377-0
CAS Number:	811-97-2
Density ²³ (g/cm ³)	1.2076 (25 °C)
Boiling Point ²⁴ (°C)	- 26.2
Vapour pressure (bar) (50 °C)	5.72 bar (20 °C), 6.6 (25 °C), 13.18
Gas conductivity (mW/m. K)	12.4 (10 °C), 13.7 (25 °C)
Vapour density (air=1)	4.32 (20 °C)
Solubility (20°C, 1bar)	Slightly soluble in Water (0.15%) Soluble in many organic solvents

HSE properties

Toxicological data:	
TLV or OEL (USA) (ppm)	1000
WEEL, 8 hr. TWA, ppm	1000
Decomposition temperature	no data
Flammable limits in air (vol. %)	None
VOC	No
GWP ²⁵ (100 years)	1410
ODP	0

²² <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.

²³ <http://ull.chemistry.uakron.edu/erd/Chemicals/6000/5742.html>. Consulted July, 2006.

²⁴ <http://ull.chemistry.uakron.edu/erd/Chemicals/6000/5742.html>, <http://chemfinder.cambridgesoft.com/result.asp>, Consulted July, 2006.

²⁵ IPCC TEAP Special Report 2005

Commercial status

Producers:

Arkema, Asahi Glass, Clariant, Honeywell,
Produven, Solvay, Zhejiang Fluorescence
Chemical Co. Ltd., Zhonghao New
Chemical Materials Co. Ltd.

HFC-152a

Description & Usage

HFC-152a is a flammable gas at room temperature. It has limited use in polyurethane foam because it is flammable, and it diffuses out of the foam quickly, preventing it from offering additional long term thermal insulation value. Yet, HFC-152a is widely used as a blowing agent for one component PU foam system where the foam is mostly used to fill a cavity and thermal insulation value is not the most critical parameter.

HFC-152a is used with HFC-134a in XPS boardstock. Although it does not offer long term thermal insulation value for the product, it is mainly used to reduce the foam density of HFC-134a foam, and improve processing conditions. It is also used as blowing agent for extruded polystyrene sheets, mostly used in food packaging applications. It is the only HFC that is approved by US food and drug administration (FDA) for this application.

Physical and Chemical properties

Chemical name:	1,1-Difluoroethane
Formula:	CH ₃ CHF ₂
Molecular Weight ²⁶ :	66.0504
EC Number (EINECS):	200-866-1
CAS Number:	75-37-6
Density (g/cm ³)	0.886 (30 °C)
Boiling Point (°C) ²⁷	- 27
Vapour pressure ²⁸ (mmHg)	4100 (25 °C)
Gas conductivity (mW/m. K)	14.3 (25 °C)

HSE properties

Toxicological data:	
WEEL, 8 hr. TWA (ppm)	1000
Flammable limits in air (vol. %)	3.8 - 21.8
VOC	No
GWP ²⁹ (100 years)	122
ODP	0

²⁶ <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.

²⁷ <http://chemfinder.cambridgesoft.com/result.asp>, <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/32.html>. Consulted July, 2006.

²⁸ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/32.html>. Consulted July, 2006.

²⁹ IPCC TEAP Special Report 2005

Commercial status

Producers:

Asahi Glass, Daikin, ICI, Du Pont, Rivoira,
Shanghai 3F New Materials Co. Ltd.,
Shanghai Sanaifu New Material Co. Ltd.,
Solvay.

HFC-245fa

Description & Usage

HFC-245fa is a non-flammable liquid having a boiling point slightly below room temperature. It is being actively considered for a wide variety of foam blowing applications.

Physical and Chemical properties

Chemical name:	1,1,1,3,3-Pentafluoropropane
Formula:	CF ₃ CH ₂ CHF ₂
Molecular Weight ³⁰ :	134.0487
EC Number (EINECS):	
CAS Number:	460-73-1
Density/Specific gravity	1.32
Boiling Point (°C)	15.3
Freezing Point (°C)	< -160
Vapour Pressure (KPa)	123 (20 °C)
Gas Conductivity (mW/m. K)	12.05 (20 °C)
Water Solubility in HFC-245fa (ppm)	1600

HSE properties

Toxicological data:	
WEEL, 8 hr. TWA (ppm)	300

HFC-245fa is currently listed on the US EPA TSCA inventory, the European EINECS inventory, and the Japanese MITI inventory. Extensive toxicity testing indicates that HFC-245fa is of low toxicity. Overall results from a series of genetic studies indicate that HFC-245fa is non-mutagenic. It was also not a teratogen. The American Industrial Hygiene Association has established a Workplace Environmental Exposure Level (WEEL) of 300 ppm.

Flammable limits in air ³¹ (vol. %)	None
Flash Point ³² (°C)	None
VOC	No
GWP ³³ (100 years)	1020
ODP	0

³⁰ <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.

³¹ Measured at ambient temperature and pressure using ASTM E681-85 with electrically heated match ignition, spark ignition and fused wire ignition; ambient air.

³² Flashpoint by ASTM D 3828-87; ASTM D1310-86.

³³ IPCC TEAP Special Report 2005

HFC-245fa is a fluorinated hydrocarbon. Treatment or disposal of wastes generated by use of this product may be of concern depending on the nature of the wastes and the means of discharge, treatment or disposal. HFC-245fa is not considered a “hazardous waste” by the Resource Conservation and Recovery Act (USA) if discarded unused. Care should be taken to avoid releases into the environment.

The US EPA has given SNAP approval for the use of the HFC-245fa blowing agent as a replacement in all foam applications. Based on a review of toxicity and food migration test results by Keller and Heckman, it was concluded, there is no impediment to refrigerator and freezer manufacturers adopting a self determined GRAS position on HFC-245fa.

Commercial status

Current Producers:

Honeywell, Central Glass, Zhejiang
Sanhuan Chemicals Co. Ltd.

HFC - 365mfc

Description & Usage

HFC - 365mfc is a liquid at room temperature with low gas phase thermal conductivity. It is being used for a wide variety of foam blowing applications.

Physical and Chemical properties

Chemical name:	1,1,1,3,3-Pentafluorobutane
Formula:	CF ₃ CH ₂ CF ₂ CH ₃
Molecular Weight ³⁴ :	148.08
EC Number (EINECS):	430-250-1
CAS Number:	406-58-6
Density/Specific gravity	1.25
Boiling Point (°C)	40.2
Vapour pressure (bar)	0.47 (20 °C)
Heat of vaporization (kJ/mol)	26.2 (boiling point)
Gas conductivity (mW/m. K)	10.6 (25 °C)
Vapour density (air = 1)	5.11
Solubility in Water ³⁵ (mg/L)	26.1 (25 °C)

HFC - 365mfc has a flash point, but the flammability behaviour is much different to hydrocarbons. This is due to the high content of fluorine, which takes away much energy from the molecule. According to the manufacturer, the flammability can be managed by adding 5% of a non flammable HFC, e.g. HFC-134a, HFC-227ea or HFC-245fa. Non flammable blends have been developed to overcome the original flammability of neat HFC - 365mfc.

HSE Properties

Toxicological data:	
WEEL, 8 hr. TWA (ppm)	N/A
Acute toxicity oral route, LD50 rat, mg/kg	> 2000
Acute toxicity inhalation, LC50, 4h, rat, mg/kg	> 2000
No mutagenic effect	
Flammable limits in air (vol. %)	3.6-13.3
Minimum Ignition Energy (mJ)	10.4 (25 °C)
Flash point (°C)	< -27
Auto flammability (°C)	580
GWP ³⁶ (100 years)	782
ODP	0

³⁴ <http://esc.syrres.com/interkow/webprop.exe?CAS=406-58-6>. Consulted July, 2006.

³⁵ <http://esc.syrres.com/interkow/webprop.exe?CAS=406-58-6>. Consulted July, 2006.

³⁶ IPCC TEAP Report 2005

Commercial Status

Current Producers:

Solvay

Geographic Constraints

The use of HFC-365mfc might fall within the scope of European Patent 381 986 and its counterparts, all held by Bayer. Solvay has acquired from Bayer the right to sublicense its customers under these patents in all countries except in the USA and in Canada.

HFC 227ea

Description & Usage

HFC-227ea is used as a component in non-flammable HFC-365mfc blowing agent blends. Its prime purpose is to suppress flammability (flash-point) of the blowing agent and/or of the polyol system. Commercially available are blends with HFC-227ea ratios of 7% and 13% by wt.

Physical and Chemical properties

Chemical name:	1,1,1,2,3,3,3 Heptafluoropropane
Formula:	CF ₃ CHFCF ₃
Molecular Weight:	170
EC Number (EINECS):	207-079-2
CAS Number:	431-89-0
Density/Specific gravity	1.54
Boiling Point (°C)	-16,5
Vapour pressure @ 25 °C (bar)	4,6
Gas Conductivity (mW/m. °K at 10 °C)	11,6
Gas Conductivity (mW/m. °K at 25 °C)	12,7
Vapour density (air=1)	30,2 (25°C)
Solubility in Water	≈ 0,4 g/l (20°C)
Decomposition temperature	425°C
Flammable limits in air (vol. %)	none

HSE properties

Toxicological data:	
AEL TWA	1000 ppm ³⁷
VOC	No
GWP (100 years)	2900 ³⁸
ODP	0

Commercial Status

Current Producers:	Solvay
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³⁷ Manufacturers Information (Solvay Fluor GmbH, Germany)

³⁸ IPCC 2nd assessment report (1996)

Trans-1,2-Dichloroethylene

Description & Usage

Trans-1,2-dichloroethylene is a liquid at room temperature and is recommended for use in a variety of polyurethane foam blowing applications primarily in combination with HFC-134a and HFC-245fa. Studies have shown that trans-1,2-dichloroethylene moderates the frothing effect particularly with HFC-134a and significantly improves its blowing efficiency.

Physical and Chemical Properties

Chemical name:	trans-1,2-dichloroethylene
Formula:	C ₂ H ₂ Cl ₂
Molecular weight:	97
EC Number (EINECS):	205-860-2
CAS Number:	156-60-5
Specific gravity:	1.26
Boiling point (°C)	48
Vapor pressure @ 25°C (bar / mm Hg)	0.45 / 330
Heat of vaporization at boiling point (kJ/mol)	28.22
Vapor density (air = 1) @ 20°C	1.8
Flammable limits in air (volume %)	6.7 – 18
Flash point (°C)	-12°C
Solubility @ 25°C (g trans / 100 g water)	0.63
Minimum ignition energy @ 25°C (mJ)	40.5
Auto-ignition temperature (°C)	460°C

Although trans-1,2-dichloroethylene has a flash point, its flammability behavior is much different from hydrocarbons. Blends of trans-1,2-dichloroethylene and HFC-134a are non-flammable providing the concentration of trans-1,2-dichloroethylene is less than 50%. In addition, it has been found that if the level of trans-1,2-dichloroethylene in the polyol blend is less than 4% by weight, the flash point will be greater than 60°C (140°F), and therefore the polyol blend can be labeled “combustible” according to US DOT regulations.

HSE properties

Toxicological data:

TLV	200 ppm (ACGIH TLV® 8-hr TWA)
Volatile Organic Compound	yes
GWP* (100 years)	negligible
ODP	0

Trans-1,2-dichloroethylene is approved as a replacement for CFCs and HCFCs in rigid polyurethane foams under the US EPA's Significant New Alternatives Policy (SNAP).

Commercial Status

Current Producers/Suppliers:

Arkema

CARBON DIOXIDE

Description & Usage

Carbon Dioxide (chemical formula CO₂) is a gas in normal conditions and exist in the atmosphere in small concentrations. It is a colourless, odourless, non flammable gas, with very low chemical reactivity and toxicity.

Physical and Chemical Properties

Formula	CO ₂
Molecular weight ³⁹	44.0098
CAS Number:	124-38-9
Triple point	
Pressure (bar)	5.11
Temperature (°C)	-56.6
Critical point	
Pressure (bar)	75.2
Temperature (°C)	31
Specific volume (L/kg)	2.156
Density relative to air (air = 1)	1.521 (20 °C)
Vaporisation Heat (Kcal/kg)	83.20 (triple point)
Sublimation Heat (Kcal/kg)	136.40 (1 atm)
Heat of formation of gas (Kcal/kg)	2.137 (25 °C)

HSE Properties

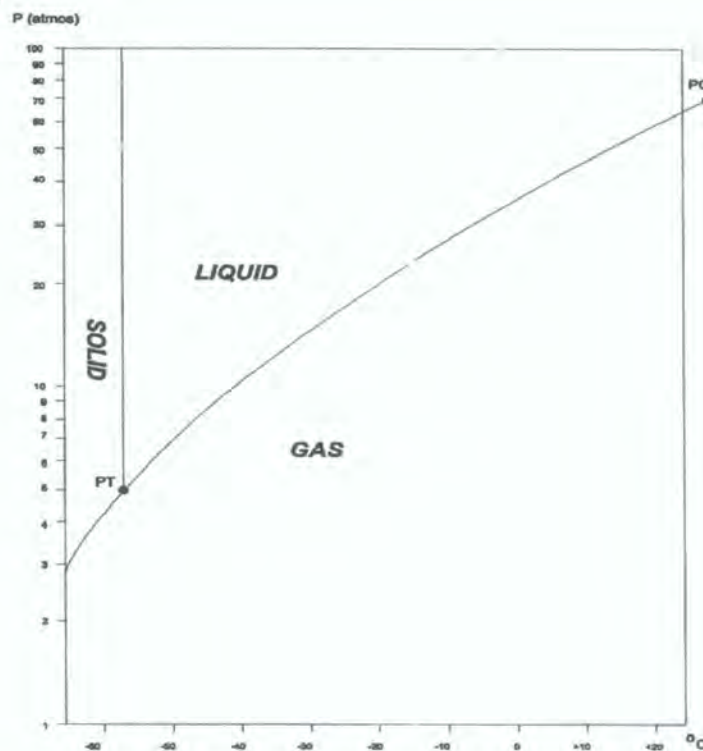
Carbon dioxide is toxic only at very high concentrations (5000 ppm = 9000 mg/m³).

Commercial Data

Carbon dioxide is a generic chemical with numerous suppliers and wide availability in most countries. There are two main supply sources:

- From mining sources (natural CO₂). Carbon Dioxide exists in the underground and is produced by the decomposition of carbonate compounds in presence of steam or by the sudden cooling of magma which release CO₂ as a gas.

³⁹ <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.



Phase diagram for carbon dioxide

- Chemically generated as a by-product of several chemical reactions in the main industrial processes. One of the main sources is the process to produce ammonia and urea. The main impurities are sulphurous products, inert gases and water.

Since CO₂ is normally utilized as an additive in the food industry, it is supplied at very high purity (some suppliers guarantee more than 99,9%).

CO₂ is liquefied to be stored and transported. There are two systems to store carbon dioxide for industrial use: pressurized bottles for small consumption requirements and bulk tanks for high consumptions. All major suppliers of liquid gases provide rental contracts for the mentioned storage solutions.

- Pressurised bottles: Bottles of liquid CO₂ are at pressures of 70 to 100 bar at normal ambient temperature. Two types of pressure bottles are used – bottom feed, with an internal bottom-feed pipe for delivering liquid CO₂ or top-feed, for delivering gaseous CO₂. Avoid any heating of the bottles either by sun light or any heating source. Bottles must be handled with care using gloves and avoiding any hard contact.
- Bulk tanks: CO₂ is stored in insulated, pressurised tanks of capacity from 3 up to 50 m³, at a pressure of about 16-18 bar and temperature about -30 to -24 °C. The tank is normally fitted

with a CO₂ level detector and cooling system to control the pressure within the required limits. It is recommended that the tank is protected from adverse weather conditions and to erect around it a guard rail, to restrict access. Any parts of the electric installation should be placed under a roof or indoors.

Carbon Dioxide as blowing agent for polyurethane foams

In polyurethane flexible foam (slabstock or moulded) the main blowing agent is carbon dioxide generated chemically by the reaction between water and isocyanates.

CYCLOPENTANE

Description and Usage

Cyclopentane is a colorless and flammable liquid with a gasoline-like odor. It is a blowing agent for polystyrene and polyurethane foam processes.

Physical and Chemical properties

Chemical name :	Cyclopentane
Formula	C ₅ H ₁₀
Molecular Weight ⁴⁰	70.134
EC Number (EINECS)	206-016-6
CAS Number	287-92-3
Density ⁴¹ (g/cm ³)	0.746 (20 °C)
Boiling Point ⁴² (°C)	49
Melting point ⁴³ (°C)	-93.3
Vapour pressure (mmHg)	318 (20 °C)
Gas Conductivity (mW/m.K)	11.0 (10 °C)
Vapour density (air=1)	2.42 (20 °C)
Solubility in Water	Insoluble

HSE properties

Toxicological data ⁴⁴	
TLV (as TWA) (ACGIH 1993-1994)	600 ppm, 1720 mg/m ³
TWA (NIOSH REL)	600 ppm, 1720 mg/m ³
Flammable limits in air ⁴⁵ (%)	1.5 – 8.7
Autoignition Temperature ⁴⁶	380 °C
Flash Point ⁴⁷ (°C)	-42
VOC	Yes ⁴⁸
GWP (100 years)	<25 ⁴⁹
ODP	0

⁴⁰ <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.

⁴¹ <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6360.html>. Consulted July, 2006.

⁴² <http://chemfinder.cambridgesoft.com/result.asp>, <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6360.html>. Consulted July, 2006.

⁴³ <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6360.html>. Consulted July, 2006.

⁴⁴ <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6360.html>. Consulted July, 2006.

⁴⁵ <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6360.html>. Consulted July, 2006.

⁴⁶ <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6360.html>. Consulted July, 2006.

⁴⁷ <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6360.html>. Consulted July, 2006.

⁴⁸ Subject to regulations that can vary from country to country and within a country even from region to region

⁴⁹ Subject of on-going investigation at time of publication

Commercial Status

Producers⁵⁰

Chevron Phillips Chemical Company LLC.,
ExxonMobil, Haltermann, Maruzen, Haldia
Petrochemicals Ltd., Yixing City Changjili
Chemical Industry Company Limited,
Productos Quimicos Coin. S.A. de C.V.

⁵⁰ <http://www.chemchannels.com>. Consulted July, 2006.

CYCLOPENTANE

Description and Usage

Cyclopentane is a colorless and flammable liquid with a gasoline-like odor. It is a blowing agent for polystyrene and polyurethane foam processes.

Physical and Chemical properties

Chemical name :	Cyclopentane
Formula	C ₅ H ₁₀
Molecular Weight ⁴⁰	70.134
EC Number (EINECS)	206-016-6
CAS Number	287-92-3
Density ⁴¹ (g/cm ³)	0.746 (20 °C)
Boiling Point ⁴² (°C)	49
Melting point ⁴³ (°C)	-93.3
Vapour pressure (mmHg)	318 (20 °C)
Gas Conductivity (mW/m.K)	11.0 (10 °C)
Vapour density (air=1)	2.42 (20 °C)
Solubility in Water	Insoluble

HSE properties

Toxicological data ⁴⁴	
TLV (as TWA) (ACGIH 1993-1994)	600 ppm, 1720 mg/m ³
TWA (NIOSH REL)	600 ppm, 1720 mg/m ³
Flammable limits in air ⁴⁵ (%)	1.5 – 8.7
Autoignition Temperature ⁴⁶	380 °C
Flash Point ⁴⁷ (°C)	-42
VOC	Yes ⁴⁸
GWP (100 years)	<25 ⁴⁹
ODP	0

⁴⁰ <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.

⁴¹ <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6360.html>. Consulted July, 2006.

⁴² <http://chemfinder.cambridgesoft.com/result.asp>, <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6360.html>. Consulted July, 2006.

⁴³ <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6360.html>. Consulted July, 2006.

⁴⁴ <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6360.html>. Consulted July, 2006.

ISOPENTANE

Description and Usage

Isopentane is a colorless and flammable liquid with a gasoline-like odor. It is a blowing agent for polystyrene and polyurethane foam processes.

Physical and Chemical properties

Chemical name :	2-Methylbutane
Formula	C ₅ H ₁₂
Molecular Weight ⁵¹	72.1498
EC Number (EINECS)	201-142-8
CAS Number	78-78-4
Density ⁵² (g/cm ³)	0.620 (20°C)
Boiling Point ⁵³ (°C)	28
Melting point ⁵⁴ (°C)	-159.9
Vapour pressure ⁵⁵ (mmHg)	727 (25 °C)
Gas Conductivity (mW/m.K)	13.0 (10 °C)
Vapour density (air=1)	2.48 (20 °C)
Solubility in Water	< 0.1 g /100ml (23°C)

HSE Properties

Toxicological data ⁵⁶	
TWA (ACGIH)	600 ppm
Odor threshold ⁵⁷ (ppm)	10
Flammable limits in air ⁵⁸ (%)	1.4 – 8.3
Autoignition Temperature ⁵⁹ (°C)	420
Flash Point ⁶⁰ (°C)	-57
VOC	Yes ⁶¹
ODP	0
GWP (100 years)	<25 ⁶²

⁵¹ <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.

⁵² <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/45.html>. Consulted July, 2006.

⁵³ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/45.html>. Consulted July, 2006.

⁵⁴ <http://chemfinder.cambridgesoft.com/result.asp> Consulted July, 2006.

⁵⁵ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/45.html>. Consulted July, 2006.

⁵⁶ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/45.html>. Consulted July, 2006.

⁵⁷ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/45.html>. Consulted July, 2006.

⁵⁸ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/45.html>. Consulted July, 2006.

⁵⁹ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/45.html>. Consulted July, 2006.

⁶⁰ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/45.html>. Consulted July, 2006.

⁶¹ Subject to regulations that can vary from country to country and within a country even from region to region

⁶² Subject of on-going investigation at time of publication

Commercial Status

Producers⁶³

ExxonMobil, Haltermann, Chevron Phillips Chemical Company LLC., Shell, Productos Quimicos Coin. S.A. de C.V., Jilin Jinlong Industrial Company (Subsidiaries As Jinlong Fine Chemical factory & Longyan Chemical Factory)

⁶³ <http://www.chemchannels.com>

n-PENTANE

Description and Usage

N-pentane is a colorless and flammable liquid with a gasoline-like odor. It is a blowing agent for polystyrene and polyurethane foam processes.

Physical and Chemical properties

Chemical name :	n-pentane
Formula	C ₅ H ₁₂
Molecular Weight ⁶⁴	72.1498
EC Number (EINECS)	203-693-4
CAS Number	109-66-0
Density ⁶⁵ (g/cm ³)	0.62 6 (20 °C)
Boiling Point ⁶⁶ (°C)	36.1
Melting point ⁶⁷ (°C)	-129.7
Vapour pressure ⁶⁸ (mmHg)	512 (25 °C)
Gas Conductivity (mW/m.K)	14.0 (10 °C)
Vapour density (air=1)	2.48 (20 °C)
Solubility in Water	0.04 g /100ml (23 °C)

HSE Properties

Toxicological data ⁶⁹	
TWA (OSHA PEL)	1000 ppm, 2950 mg/m ³
TWA (NIOSH REL)	120 ppm, 350 mg/m ³
C (NIOSH REL)	610 ppm, 1800 mg/m ³ (15-minute)
LEL (NIOSH IDLH)	1500 ppm
Flammable limits in air (%)	1.4 – 8.0
Autoignition Temperature ⁷⁰ (°C)	285
Flash Point ⁷¹ (°C)	- 49
VOC	Yes ⁷²
ODP	0
GWP (100 years)	<25 ⁷³

⁶⁴ <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.

⁶⁵ <http://ull.chemistry.uakron.edu/erd/Chemicals/8000/7313.html>. Consulted July, 2006.

⁶⁶ <http://chemfinder.cambridgesoft.com/result.asp>, <http://ull.chemistry.uakron.edu/erd/Chemicals/8000/7313.html>. Consulted July, 2006.

⁶⁷ <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.

⁶⁸ <http://ull.chemistry.uakron.edu/erd/Chemicals/8000/7313.html>. Consulted July, 2006.

⁶⁹ <http://ull.chemistry.uakron.edu/erd/Chemicals/8000/7313.html>. Consulted July, 2006.

⁷⁰ <http://ull.chemistry.uakron.edu/erd/Chemicals/8000/7313.html>. Consulted July, 2006.

⁷¹ <http://ull.chemistry.uakron.edu/erd/Chemicals/8000/7313.html>. Consulted July, 2006.

⁷² Subject to regulations that can vary from country to and from region to region

⁷³ Subject of on-going investigation at time of publication

Commercial Status

Producers⁷⁴

Beijing Yanshan Petrochemical Co. Ltd.,
ExxonMobil, Haltermann, Maruzen
Petrochemical Co. Ltd., Chevron Phillips
Chemical Company LLC., Shell, Productos
Quimicos Coin. S.A. de C.V.

⁷⁴ <http://www.chemchannels.com>

ISOBUTANE

Description and Usage

Isobutane is a colorless gas with a faint petroleum-like odor. It is a blowing agent for polyethylene and polyurethane foam processes.

Physical and Chemical properties

Chemical name :	Isobutane
Formula	C ₄ H ₁₀
Molecular Weight ⁷⁵	58.123
EC Number (EINECS)	200-857-2
CAS Number	75-28-5
Density/Specific gravity	0.557
Boiling Point ⁷⁶ (°C)	-11.7
Melting point ⁷⁷ (°C)	-255.3
Vapour pressure ⁷⁸ (mmHg)	2580 (25 °C)
Gas Conductivity (mW/m.K)	15.9 (20 °C)
Vapour density (air=1)	2.01 (20 °C)
Solubility in Water ⁷⁹	Slightly soluble

HSE properties

Toxicological data ⁸⁰	
TWA (NIOSH REL)	800 ppm, 1900 mg/m ³
Flammable limits in air ⁸¹ (%)	1.8 – 8.4
Flash Point ⁸² (°C)	-107
Autoignition Temperature ⁸³ (°C)	460
VOC	Yes ⁸⁴
GWP	<25 ⁸⁵
ODP	0

⁷⁵ <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.

⁷⁶ <http://chemfinder.cambridgesoft.com/result.asp>, <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/24.html>. Consulted July, 2006.

⁷⁷ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/24.html>. Consulted July, 2006.

⁷⁸ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/24.html>. Consulted July, 2006.

⁷⁹ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/24.html>. Consulted July, 2006.

⁸⁰ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/24.html>. Consulted July, 2006.

⁸¹ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/24.html>. Consulted July, 2006.

⁸² <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/24.html>. Consulted July, 2006.

⁸³ <http://ull.chemistry.uakron.edu/erd/Chemicals/1000/24.html>. Consulted July, 2006.

⁸⁴ Subject to regulations that can vary from country to country and within a country even from region to region

⁸⁵ Subject of on-going investigation at time of publication

Commercial Status

Producers⁸⁶

Chevron Phillips Chemical Company
LLC., Huntsman Petrochemical
Corporation, Quhua Yonghe Chemical
Trade Co. Ltd., Refinery of Jinling
Petrochemical Corporation

⁸⁶ <http://www.chemchannels.com/chemchannel/Advance/directory/directory.asp>

n-BUTANE

Description and Usage

n-Butane is a colorless gas with a faint disagreeable odor. It is used as blowing agent for polyethylene and extruded polystyrene processes.

Physical and Chemical properties⁸⁷

Chemical name :	n-butane
Formula	C ₄ H ₁₀
Molecular Weight ⁸⁸	58.123
EC Number (EINECS)	203-448-7
CAS Number	106-97-8
Density ⁸⁹ (g/cm ³)	0.579 (20 °C)
Boiling Point ⁹⁰ (°C)	-0.45
Melting point ⁹¹ (°C)	-138.35
Vapour pressure ⁹² (mmHg)	1556 (20 °C)
Gas Conductivity (mW/m.K)	13.6 (0°C)
Vapour density (air=1)	2.046
Solubility in Water ⁹³	61mg/L (20 °C)

HSE properties

Toxicological data	
TWA ⁹⁴ (ACGIH TLV)	800 ppm
TWA ⁹⁵ (OSHA PEL)	800 ppm
Odor threshold ⁹⁶ (ppm)	50000
Flammable limits in air ⁹⁷ (%)	1.8 – 8.5
Flash Point ⁹⁸ (°C)	-60
Autoignition Temperature ⁹⁹ (°C)	405
VOC	Yes ¹⁰⁰
GWP	<25 ¹⁰¹

⁸⁷ <http://ull.chemistry.uakron.edu>

⁸⁸ <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.

⁸⁹ <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6193.html>. Consulted July, 2006.

⁹⁰ <http://chemfinder.cambridgesoft.com/result.asp>, <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6193.html>. Consulted July, 2006.

⁹¹ <http://chemfinder.cambridgesoft.com/result.asp>. Consulted July, 2006.

⁹² <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6193.html>. Consulted July, 2006.

⁹³ <http://chemfinder.cambridgesoft.com/result.asp>, <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6193.html>. Consulted July, 2006.

⁹⁴ http://www.cpcchem.com/enu/msds_unsecured/Import_3448_MSDS_O_ENGLISH_A_ENGLISH_A_N.pdf

⁹⁵ http://www.cpcchem.com/enu/msds_unsecured/Import_3448_MSDS_O_ENGLISH_A_ENGLISH_A_N.pdf

⁹⁶ <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6193.html>. Consulted July, 2006.

⁹⁷ <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6193.html>. Consulted July, 2006.

⁹⁸ <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6193.html>. Consulted July, 2006.

⁹⁹ <http://ull.chemistry.uakron.edu/erd/Chemicals/7000/6193.html>. Consulted July, 2006.

¹⁰⁰ Subject to regulations that can vary from country to country and within a country even from region to region

ODP

0

Commercial Status

Producers

Chevron Phillips Chemical Company
LLC., Huntsman Chemical Corp,
Petrobras, Shanghai Petrochemical Co.
Ltd.

¹⁰¹ Subject of on-going investigation at time of publication

Methyl Formate (Ecomate®)

Description & Usage

Ecomate® is a colourless, flammable liquid with an ethereal odour. It is a registered trademark of Foam Supplies, Inc. protected by Patent No. 6753357. It is being promoted as blowing agent for PU rigid foams mainly but also for flexible foams and microcellular elastomers with zero ODP. Use has been reported in commercial refrigeration.

Physical and Chemical properties¹⁰²

Chemical composition:	Methyl Formate 97.5 %, Methanol 2.5 %
Molecular Weight	60
EC Number (EINECS):	203-481-7
CAS Number:	107-31-3
Density (g/cm ³)	0.97 (20 °C)
Boiling Point (°C)	31.5
Melting Point (°C)	-100
Vapour pressure ¹⁰³ (mm Hg)	710 (25 °C)
Gas conductivity (mW/m. K)	10.7 (25 °C)
Water solubility	Not miscible or difficult to mix

HSE Properties¹⁰⁴

Toxicological data:

WEL	
Short Term Value, mg/m ³	333
Long Term Value, mg/m ³	266
TWA, OSHA, ppm,	100
Explosion limits (vol. %)	5.0 - 23.0
Flash point (°C)	-32
Autoignition Temperature (°C)	450
VOC	No
GWP (100 years)	<25 ¹⁰⁵
ODP	0

¹⁰² Ecomate MSDS, BOC, reviewed on 10/11/2005. Product and Package Handling Guidance, BOC, 2006. "Ecomate: The new blowing agent for Europe", presentation by John Murphy, Foam Supplies Inc. at UTECH 2006.

¹⁰³ <http://www.ecomatesystems.com>. Consulted July, 2006.

¹⁰⁴ Ecomate MSDS, BOC, reviewed on 10/11/2005. Product and Package Handling Guidance, BOC, 2006. "Ecomate: The new blowing agent for Europe", presentation by John Murphy, Foam Supplies Inc. at UTECH 2006.

¹⁰⁵ Subject of on-going investigation at time of publication

Commercial Status

Current Supplier:

BOC

APPENDIX 3: DESCRIPTION OF TECHNICAL OPTIONS

RIGID PU FOAM TECHNICAL OPTIONS

DOMESTIC REFRIGERATOR AND FREEZER INSULATION

Performance Requirements

Rigid polyurethane foam is the dominant insulation material used in refrigerators and freezers. The foam serves as a key element in the structure of the appliance, as well as a very effective insulation. It must have adequate compressive and flexural strength to ensure the integrity of the product under extreme temperature conditions during shipping, as well as heavy loading during usage of the appliance. It must maintain both its insulation effectiveness and structural properties throughout the design life of the product. Using CFCs, foam manufacturers were successful in developing formulations which met all of these requirements. As substitutes are developed, care has been taken to ensure that properties are not compromised to the extent that the overall performance of the appliance is degraded.

Although the basic requirements for refrigerator/freezer foam insulation are similar for most manufacturers, unique manufacturing facilities, local market conditions and regulatory requirements result in a situation where unique requirements exist for specific markets. For example, the importance of energy consumption has influenced manufacturers in the USA to use foams giving lower conductivities than those required in the European market. Nevertheless, energy regulations control the energy consumption of the complete unit and the foam thermal conductivity is only one of several factors.

In the EU stringent energy consumption requirements have now been put into place since September 1999. Developments to reduce energy consumption have continued. For example, the ability of some of the current European models to surpass the current best rating of class A by a considerable margin has been highlighted in a report¹⁰⁶ prepared for the European Commission in 2001. This level of performance has been achieved with hydrocarbon blowing agents. The report recommends a new labeling and minimum energy performance system from 2005/6 in which the minimum energy performance allowed would be today's class A.

New and more stringent US energy efficiency standards set by the DOE were implemented in July 2001. These require, on average, a 30% reduction in energy consumption compared to existing models. Cabinet design, flammability, capital conversion cost, and potential liability issues moved the industry towards a HFC solution in contrast to the hydrocarbon solution preferred in most other regions.

¹⁰⁶ COLD II 'The revision of energy labelling and minimum energy efficiency standards for domestic refrigeration appliances'

Technical Options

There are two main technology streams in use. Hydrocarbon technology has been in use since 1993 and has been under continuous development to deliver improvements in foam properties. This technology stream is seen as a long-term option. The other current technology is an intermediate one based on HCFC-141b, also in wide scale use since 1993, and is expected to be replaced by, mainly, "liquid" HFC blowing agents. There is some use of the HCFC-141b/HCFC-22 blend and minor use of the HCFC-142b/HCFC-22 blend and of HFC-134a.

- Low ODP Technologies

The foams based on HCFC-141b show the best insulation performance of any CFC 11 substitute used so far. The increase in initial thermal conductivity is about 7-10% relative to an optimised full CFC-11 foam (measured at 10°C) or equivalent to slightly lower than for a 50%-reduced CFC-11 foam. There has been an increase in density because of the solvent effect on the foam matrix of the blowing agent - this amounts to 4-7% on overall density compared to a full CFC foam. Work with blends containing up to 50% HCFC-22 shows that this effect can be reduced (see below).

There are many solutions in use to counter the solvent effect of HCFC-141b on the plastic liner. Most show an economic penalty of up to 15 % on the cost of the liner material depending on product design and foam system characteristics. For those designs where voids (which contain pockets of HCFC-141b) can be avoided, there may be no need to take special measures to protect "standard chemically resistant" grades of HIPS. For other designs, a barrier layer may be required to protect the liner or a special grade of ABS may be used with an economic penalty that can be a major issue for all producers. High-pressure dispensers are recommended to obtain the best foam quality.

The thermal insulation properties of foams based on HCFC-142b/HCFC-22 are about 5% poorer than for HCFC-141b but this blowing agent combination is less aggressive to the plastic liner. Pre-blenders capable of blending-in the gaseous blowing agent mixtures are required.

The technology based on blends of HCFC-141b with HCFC-22 has been extended up to 50/50 blends. These give advantages in terms of reduced density and cost, reduced effect on liners, good dimensional stability and minimal effect on thermal conductivity and energy consumption.

Another blowing agent being considered is HCFC-124 but little information is available on its performance in appliance foams.

- Zero ODP Technologies

Hydrocarbon technology has been mostly based on cyclopentane, either "pure" grade (95%) or "technical" grade (75%). There is no significant difference in their performance in practice. Both are easy to process in formulations that have been developed around them.

Because of their flammability, extensive but now well established modifications to the foaming part of the factory to meet appropriate safety requirements are essential. These include a dedicated storage tank for the cyclopentane, pre-mixers, adapted high pressure dispensers, suitable moulds (often water-cooled) plus process exhaust, hydrocarbon detectors, appropriate classification of electrical equipment, avoidance of static electricity and, above all, training of operating staff. See Appendix 4 for a more detailed outline of standard hydrocarbon process safety procedures. These requirements make economic conversion to this technology, particularly in the cases of small factories, a difficult issue. However, in this sector most of the production units, even in developing countries, are large enough to make conversion to hydrocarbons an economic proposition. To extend the use of this technology to some areas, including some regions in the USA, precautions would be necessary to comply with limits on the emissions of VOCs.

Conventional liner systems, as used with CFC-11, are suitable for use with any of the hydrocarbon blowing agents.

The conventional cyclopentane-based foams show an overall density of, typically, 38 kg/m³ or 15-18% above the 50%- reduced CFC-11 foams which they replaced and, typically, the initial thermal conductivity is increased by 12-13% to about 20.8 mW/m²K (at 10°C). Optimisation of the foam systems has reduced these deficiencies to 36 kg/m³ (an increase of 10-13%) and 20.2 mW/m²K (an increase of 7-10%) respectively. The latter figure equates to an increase of cabinet energy consumption of about 5% relative to the reduced CFC- 11-based foams.

Further development of hydrocarbon systems involves the use of blends which reduce the economic density penalty without affecting the insulation performance and may even enhance it at refrigerator and, particularly, at freezer operating temperatures. For example, an optimised cyclo/iso pentane-based foam shows the overall density reduced to about 35 kg/m³ (an increase of 6-8% compared to 50%-reduced CFC 11-foams) with similar thermal insulation performance to the best cyclopentane systems. Another approach, using cyclopentane/isobutane blends, achieves the same improvement plus improvement in low temperature thermal insulation because of the higher gas vapour pressure in the foam cells. There is minor use of iso/normal pentane blends. This is in markets where cyclopentane is not available locally and the iso or normal isomers are used despite their deficiencies in terms of thermal conductivity.

The technologies that have been actively evaluated as non-hydrocarbon replacements for the HCFCs are those based on HFC-134a and HFC-245fa.

Foams based on HFC-134a are seen as a safeguard against the non-availability of liquid HFCs. They have been used in appliances, for short periods, already and are being used in a few production lines today. The main issues are: processing because HFC- 134a is a gas and has poor solubility in polyol formulations; and the thermal conductivity penalty of the foam - which is 15-20% compared to CFC-11-based foam.

In contrast, the evaluation of HFC-245fa shows it to be a technically viable blowing agent for this application, giving similar densities to those of CFC-11-based foams. The thermal

conductivity of the foam, at about 18.5 mW/m²K (at 10°C) and the energy consumption of the appliance are equivalent to those of HCFC-141b-based products and up to 10% lower than for current hydrocarbon-blown foams. The boiling point of 15.3°C may mean that pressurised blending equipment will be necessary for its use, although evaluations reported to date suggest that HFC-245fa can be processed through foam equipment designed for use with CFC-11 and HCFC-141b in many cases. The very good solubility in polyol formulations is a significant factor in its use. The liner materials used with CFC-11 are suitable for use with HFC-245fa with the exception of some ABS compositions.

To date, there has been little evaluation of HFC-365mfc in this application.

Vacuum insulation panels continue to be developed and are used in limited quantities. They are not, strictly, CFC-11-replacement technologies but allow insulation efficiency to be maintained or improved when using foam technologies of inferior insulation compared to that based on CFC-11. There is now production of refrigerators and freezers using open-celled polyurethane rigid foam-based vacuum panels. These allow, for example, a reduction of either 20% in energy consumption or, in another example, an increase of 25% in internal volume at the same energy consumption. Such advances are obviously strongly dependent on model design.

OTHER APPLIANCES

Performance Requirements

This category encompasses all "appliance" applications other than domestic refrigerators and freezers. The main performance requirements are:

- **Water Heaters** - Where foam insulation leads to a significant saving in energy consumption, particularly in designs where the space for insulation is limited. There is a trend towards energy consumption controls in some regions. For example, the US DOE has implemented energy efficiency standards for water heaters that will require approximately a 15% improvement in energy efficiency beginning in 2004. There are also controls on energy consumption in the EU.
- **Commercial Refrigerators and Freezers (including display units)** - These are typically much larger than domestic units and include open top display units. Vending machines are also included and there have been requirements for zero ODP and low GWP blowing agents from large manufacturers of soft drinks. Basic performance requirements are as for domestic refrigerators.
- **Picnic Boxes (Coolers)** - With a premium on insulation value and strong lightweight structures.
- **Flasks and Thermoware** - Several types of articles which require the same characteristics as picnic boxes.

Technical Options

- Low ODP Technologies

The main option to replace CFC-11 in these sectors is HCFC-141b. This is because of the low capital investment required by the manufacturers - many of these are small enterprises with limited production capacity. The "drop-in" nature of this liquid blowing agent is of paramount importance. In addition, for the reefer application, the excellent thermal insulation performance of HCFC-141b-based foams is important for this application in which there are stringent requirements in terms of wall thickness and energy efficiency.

- Zero ODP Technologies

Cyclopentane is used for commercial refrigerators and freezers in those areas where the market demands a zero ODP, low GWP option.

Some vending machines and water heaters are produced with CO₂ (water). For water heaters the comparatively poor thermal insulation properties of the foam can be compensated by increased thickness in some cases.

For the replacement of HCFC-141b the blowing agents being considered are HFC-245fa and HFC-365mfc. The question of whether HFC-245fa can be supplied pre-blended into formulations will be an important factor in its wide scale use in temperate and tropical climates and this issue is being studied.

The various forms of pentane are also technically suitable, but the cost of appropriate safety measures and the difficulty in supplying pre-blended formulations may rule out wide scale use as many of the manufacturers in this sector are comparatively small enterprises.

INSULATED TRUCKS AND REEFERS

Performance Requirements

This is a very stringent application with emphasis on durability and minimum wall thickness whilst maintaining insulation value. Most products for this market are produced by the discontinuous sandwich panel technique (see below) although reefers can also be produced by foaming section by section into a large pre-assembled jigged structure.

Technical Options

The technical options available for insulated truck bodies are the same as for discontinuous panels for other applications and these are dealt with later in this section. For the manufacture of reefers, the situation is rather different since the skins are much thicker and are often jigged differently. The basic technologies can be set out as follows:

- Low ODP Technologies

Historically, HCFC-141b has been widely used in this sector and with the transfer of much of the global manufacture to Article 5(1) countries such as China, the use of HCFC-141b is likely to be maintained for a considerable time to come.

- Zero ODP Technologies

Although thermal insulation requirements can be onerous, there is sufficient leeway in the design of reefers to allow the use of foam systems based on hydrocarbons. These are usually based on linear pentanes and other similar blowing agents.

BOARDSTOCK/FLEXIBLE-FACED LAMINATION

Performance Requirements

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

- **Low thermal conductivity** - High values of energy efficiency can be achieved by using comparatively thin layers of foam insulation. Laminated foams with impermeable facers offer the highest degree of long-term insulation value. The low thermal conductivity was originally derived from the fine, closed-cell polymer structure combined with an ODS as the main blowing agent. Retention of low thermal conductivity is a key concern when considering alternatives.
- **Fire performance** - PIR and fire retarded PUR foams provide excellent fire test results under a variety of test procedures. The impact on fire performance is another factor when considering alternative blowing agents;
- **Compressive strength** - This property is very important in roofing applications because of the construction and maintenance traffic that a roof system, including the insulation, must bear. Some alternatives can plasticise the foam and reduce the compressive strength and result in the need to increase density;;
- **Ease of processing** - One advantage of the product is its ease of manufacturing combined with its excellent adhesion to a whole range of facing materials; and,

- **Ease of use and handling** - Laminated products are lightweight, offered in a variety of thicknesses, provide excellent structural rigidity, and, in the case of PIR when used on roofs, can be sealed with hot bitumen and be used without separation technology.

Technical Options

There are two main blowing agent technologies in use. Both HCFC-141b and n-pentane (and isopentane) have been in use since 1992. HCFC-141b (and the HCFC-141b/HCFC-22 blend) provide the best insulation value of the CFC-11 replacements, and these boards satisfy a wide range of building codes. N-pentane, iso-pentane and cyclopentane plus blends are used in markets, which require a zero ODP option.

- Low ODP Technologies

HCFC-141b processes in a very similar fashion to CFC-11. There are two main differences in terms of foam properties. The density is usually increased by up to 10% in order to obtain a satisfactory dimensional stability and the initial and aged thermal conductivities of the foam are increased by up to 5% and 10% respectively.

The dimensional stability problem arises because of the plasticisation effect of the blowing agent and its higher boiling point (32°C) compared to CFC-11 (24°C). There have been problems in both US and European markets with dimensional instability of roof boards based on HCFC-141b (also with n-pentane in Europe). These effects were not predicted by the then existing standard dimensional stability tests. Some manufacturers had also reduced density, for economic reasons, to a borderline level. There have been several actions to ameliorate the problem. Foams based on HCFC-141b/HCFC-22 blends with, typically, 10% of the gaseous blowing agent are in use - these give an increase in cell vapour pressure and hence avoid shrinkage. New, more severe, test methods have been introduced and adopted by the industry.

Boards/foam based on HCFC-141b can be produced to meet the same flammability requirements as were achieved with CFC-11. However, changes in building codes in both the USA and the EU are constantly introducing new challenges.

- Zero ODP Technologies

N-pentane/isopentane requires changes in the processing area of the factory to ensure safe operation because of its flammability. In addition, there are issues of dimensional stability, thermal conductivity and formulating to satisfy fire codes.

There have been dimensional stability problems in the European market with shrinkage of installed roof boards, particularly in winter conditions. This has arisen because of the high boiling point (36°C) of the n-pentane and is similar, in some respects, to the problems seen with HCFC-141b. Industry has addressed the issue by assuring that the density is maintained and through the introduction of the new test methods mentioned above.

The initial and aged thermal conductivities are about 10% higher than with CFC-11 but the rate of aging is no more than with CFC-11 and with isopentane it is slower than with CFC-11. Some code standards, such as the DIN 020 classification, cannot be met. This is a considerable penalty in the market.

The need to meet fire codes means that the potential economic advantage of using a cheap blowing agent is not realised in practice. The inherent flammability of the blowing agent is counteracted, in practice, by the use of flame retardants. Preferably, these are of the reactive type because non-reactive fire retardants can lead to plasticisation of the foam matrix. By these means most small scale tests can be met, as can some of the larger scale tests. However, the increasing stringency of both the developing EU harmonised tests and those of the insurance companies' results in pentane-based boards being unable to meet all market requirements. However, progress is being made and recent developments in the USA have achieved ASTM E-84 Class 1 and FM Calorimeter ratings.

For several markets the HCFC-141b replacement options are HFC-245fa and HFC-365mfc. Current evaluation indicates that processing, insulation, physical property and most flammability requirements would all be met by these blowing agents. Initial insulation properties would be similar to those of HCFC-141b with the advantage of reduced rates of aging.

The key issue relating to the acceptance of these blowing agent in this sector are their prices and the resulting costs of the boards in an extremely cost sensitive market in which there are several potential substitution products. This is currently an open question.

CONSTRUCTION: SANDWICH PANELS

Performance Requirements

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

- light industrial steel construction
- residential buildings
- cold stores - for frozen and fresh food storage;
- doors entrance and garage;
- retail stores - including the cold rooms for food storage within them; and
- factories - particularly where hygienic and controlled environments are required such as in electronics, pharmaceuticals, and food processing.

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

In all applications, the insulating property of the foam is used in conjunction with its strength and bonding capability. The panels are components of high quality modular construction techniques and their use is growing rapidly in developed and developing countries.

There has been particularly strong growth for continuously produced sandwich panels in Europe. This market has grown at the expense of built-up wall and roof systems with mineral fibre insulants. By developments such as the use of PIR foam and attention to edging and joint detail the fire performance of these panels has improved to a level close to those of panels based on mineral fibre core materials.

Technical Options – Continuous Panels

The main CFC-11 replacement blowing agent in this sector is HCFC-141b with additional use of n-pentane, HCFC-142b/HCFC-22, HCFC-22 alone and HFC-134a. This sector does not sell on thermal conductivity alone and this results in a range of options being used.

Low ODP Technologies

HCFC-141b gives most of the property and processing advantages of CFC-11 with few penalties. The dimensional stability is not an issue because the core density is about 40 kg/m³ to endow the panel with adequate structural properties. Flammability performance is also similar to that obtained by CFC-11.

HCFC-142b/HCFC-22 and HCFC-22 alone are also in use. The processing equipment has to be modified to include pre-blenders. These can be of the in-line type. The impervious steel facers counteract the rather more rapid diffusion out of the foam cells of HCFC-22.

Zero ODP Technologies

N-pentane is used where a zero ODP-blowing agent is required. The production equipment has to be modified to counter its flammability.

HCFC-134a is also in use in markets where a zero blowing agent is required. The poor solubility of HFC-134a in polyols is less of an issue in this application. This is because of the low level of blowing agent required at the higher density of the foam used in structural panels. Another factor is that the HFC-134a is used as a co-blowing agent with CO₂ (water), thus reducing the amount of HFC-134a required.

This market is facing ever more stringent flammability requirements and this has, so far, favoured HCFC options, particularly HCFC-141b, and it inhibits the wider scale use of n-pentane.

This sector also sees HFC-245fa and HFC-365mfc as the most significant future options (together with n-pentane). Evaluations have shown them to be technically suitable but, as in the case of boardstock, the industry is uncertain about the economics of their use.

Technical Options - Discontinuous Panels

The options and market requirements are basically similar to those for continuously produced panels. There is often the requirement for non-flammable pre-blended systems for the smaller producers in both developed and developing countries.

- Low ODP Technologies

The most widely used alternative is HCFC-141b. It gives a performance almost equivalent to CFC-11 and is usually supplied in pre-blended formulations.

- Zero ODP Technologies

Pre-blended HFC-134a formulations have been introduced in the European market. The latter is possible despite the low solubility of this blowing agent in polyol formulations because the mixed CO₂ (water)/HFC-134a systems only require about 2% of the gaseous blowing agent.

HFC-245fa and HFC-365mfc are seen as replacements for HCFC-141b.

Because of safety considerations, there is a strong reluctance to market pre-blends containing pentane. Accordingly, these systems are virtually not marketed. However, both cyclopentane and n-pentane have been used in the European and some developing country markets for several years where direct supplies of blowing agent can be handled.

SPRAY POLYURETHANE FOAM INSULATION

Performance Requirements

Sprayed foams are used for in situ application of rigid polyurethane foam thermal insulation. Worldwide, sprayed foams are used for residential and commercial buildings, industrial storage tanks, piping and ductwork, and refrigerated transport trailers and tanks. A major use is in roofing applications, especially in North America. There are strongly growing markets in other countries such as Spain and in several countries in the Asia Pacific region. Spray foam is generally applied by contractors in the field in accordance with the instructions of manufacturers of spray foam systems. In view of these requirements, spray foams have to demonstrate the following characteristics:

- High resilience (e.g. to foot traffic)
- Low moisture absorption and transmission (closed cell requirement in some cases)
- Good thermal properties
- Sufficient fire performance to meet relevant building codes
- Application capability in a variety of climatic conditions
- Ease of use and operation
- Multi-layering capability

Technical Options

The main CFC replacements in current use are HCFC 141b and CO₂ (water). Neither gaseous HCFCs and HFCs, nor the pentanes are suitable for this sector. All formulations are preblended and a gaseous blowing agent would not give the required foam quality because of frothing and would result in unacceptable losses of the blowing agent. The flammability of pentanes would make their on-site applications unacceptable.

- Low ODP Technologies

The major CFC-11 replacement is HCFC-141b. It gives equivalent processing and foam properties to its predecessor. There may be a density penalty depending on the choice of the system.

- Zero ODP Technologies

The use of CO₂ (water) is in applications where the higher (about 50%) foam thickness to give equivalent insulation value can be accommodated. There is also a penalty of a density increase of about 30% for the lower, 32 kg/m³ density, foams but this penalty does not apply to those higher density foams used for example in roofing applications. The processing equipment can be modified to cater for stream ratios of about 1.5:1.

In Japan, at least two suppliers have launched technologies based around the use of super-critical CO₂, although it is still not clear how widely applicable this technology may be outside of the country.

Systems based on both HFC-245fa and HFC-365mfc have been developed as replacements for HCFC-141b. These include systems based on HFC 245fa and water (CO₂).

PIPE-IN-PIPE

Performance Requirements

These pipes are used, mostly underground, to transport hot water over long distances.

The foam in this sector has a high density of 70-80 kg/m³ and is well protected by a thick high density polyethylene cover. However, it must last for a specified 50 years (CEN 253) at an operating temperature of 80°C. The main markets are in Northern Europe and in China.

Technical Options

In the pipe-in-pipe sector, the main CFC-11 replacements are HCFC-141b, cyclopentane and CO₂ (water).

All the above options meet the performance requirements of the application. The only significant difference is that thicker walls are required with CO₂ (water) to achieve the same insulation value.

The two "liquid" HFC options, HFC-245fa and HFC-365mfc, have not yet been evaluated in this application.

SLABSTOCK/PREFORMED PIPE

Performance Requirements

The performance of foam required will depend heavily on the application envisaged. Slabstock production tends to be the method of producing foam for many low-volume standard and non-standard applications. In many cases, these niche markets can be highly demanding and hence the potential range of performance criteria needs to be kept in mind when selecting blowing agent alternatives. A significant application is for the low volume manufacture of panels in which the metal or other facing materials are glued onto the foam. These are used for trucks and other applications.

In the case of preformed pipe section, it is common that these are used in exposed internal and external environments and particular care needs to be taken in ensuring that fire properties and moisture performance requirements can be met.

Technical Options

The options to replace CFC-11 are the same as those in the boardstock sector. The major replacement blowing agent is HCFC-141b and there is minor use of pentane and CO₂ (water). The options tend to be similar for both continuous and discontinuous processes, although particular care is required in designing plant for hydrocarbon use (see below).

Low ODP Technologies

Because of the thick sections and range of densities required the processing requirements in this sector are quite stringent and HCFC-141b gives equivalent processing to that obtained with CFC-11.

Zero ODP Technologies

Pentane can also be used but only after process development to ensure safe operation despite the propensity of the high temperature exotherms being generated in this application.

The use of CO₂ (water) also has the penalty of difficult processing because of the high exotherm temperature. Care has to be taken to ensure safety, especially in the post application storage phase.

Both HFC-245fa and HFC-365mfc have been evaluated for this sector and process well. The foam properties are acceptable.

ONE COMPONENT POLYURETHANE FOAM

Performance Requirements

One component foams have rather unusual performance requirements which are associated with its prime end-use (gap filling) and the fact that its usage is shared between the DIY sector and the professional building industry. Accordingly, the following characteristics become important:

- Rapid foaming and curing characteristics independent of climatic conditions
- Safety in use (low level of flammable blowing agents/propellants)
- Low surface spread of flame for cured foams (a legal requirement in some markets)
- Good foam adhesion

Technical Options

A gaseous blowing agent/propellant is required to replace CFC-11/CFC-12. The thermal conductivity of the foam is not a critical requirement. The gaseous HCFCs, HFC-134a and HFC-152a, the hydrocarbons, propane and butane plus dimethyl ether (DME) are all technically suitable and are in use. These are frequently used in blends, for example, a blend of HFC-134a/DME/propane/ butane is widely used in Europe. Flammable blends are used in about 80% of the total European market for cost-effectiveness reasons.

Considerable modifications are required in the production and storage areas to ensure safe operation with hydrocarbons.

FLEXIBLE PU FOAM TECHNICAL OPTIONS

SLABSTOCK

Performance Requirements

The use of ODS technologies in this sub-sector has been driven historically by the need to generate lower density and hardness combinations and, by providing a heat sink, to lower the process heat generation. The majority of the foams are TDI-based—which is relatively volatile at prevalent process temperatures (80-150 °C)—and virtually all blowing agent is released within twenty-four hours after production. This makes control of process emissions together with potential flammability and toxicity issues a major factor in the choice of CFC replacement—

which is inert, non-toxic and non-flammable. However, while these issues limit the replacement choices, the fact that there are no requirements for thermal insulation, allows more latitude and makes it feasible to select from non-ODP/non-transitional substances alone.

Technical Options – Slabstock (Continuous)

Available technologies can be classified into

- Conservation Methods
- Alternative Substances
- Chemical Modifications
- Process Modifications

- Conservation

Conservation techniques are those technologies and procedures, understood to reduce the use of CFCs through best management practices, reformulation and recovery/recycling. Proper housekeeping and formulation management can save a plant up to 10 % of its use of ABAs. Some recommendations—not only for CFCs, but for any blowing agent:

- Use closed loop unloading systems
- Do not leave drums open
- Store at reduced temperature and out of the sun
- Avoid using CFCs for non-essential applications (flushing, viscosity adjustments)

Recycling/Recovery: Has been practiced in several foam plants but lost in significance after because of costs, low efficiencies and unwanted side effects. In this process, the ABA is first adsorbed to activated charcoal, and subsequently desorbed through steam or nitrogen. Precondition is a reduction of the process ventilation, which can lead to exposure problems for production workers. Recovery of curing emissions is hardly feasible, reducing the obtainable overall efficiency to less than 50 %. Investment and operational costs are high.

"E-MAX"TM: The E-Max process combines the production and curing steps by encapsulating the developing foam in a mold as the foaming mixture is introduced to the foam line. The foam mold allows all emissions from the process to be captured and collected, using relatively low airflow. The costs are high; retrofitting is not possible and the enclosure of the lay-down and expansion process complicates process control. Only one facility has been constructed and is believed not to be in operation anymore.

- Alternative Substances

Methylene Chloride (MC): Methylene chloride's combination of properties, such as a low boiling point, relative inertness and virtual non-flammability have led to its use as an auxiliary blowing agent in the foam industry. It does not contribute significantly to atmospheric pollution through formation of tropospheric ozone, to the depletion of stratospheric ozone, or to

global warming. MC is a widely used industrial chemical and its health effects have been studied extensively both in animals and through epidemiological studies. It is considered "possibly carcinogenic to humans" (Group 2B) by the International Agency for Research on Cancer (IARC). MC's volatility can result in high concentrations in the production area, requiring careful handling to avoid overexposure. Local and regional exposure and emission regulations vary and may affect the use of this auxiliary blowing agent. MC is capable of replacing CFCs without any significant limitations, at lower costs. The "learning curve", however, can be considerable, as the process is less forgiving. Also, contamination of MC with metals can cause severe scorching. It is recommended to use only a stabilized version ("Urethane Grade"). MC is currently the preferred replacement technology in many countries. However, some countries limit its use based on toxicity concerns.

Acetone: Acetone has been proven fully capable in replacing CFC-11. Precautions must be taken in view of its flammability. Only about 60% is needed compared to CFC-11. Capital outlays and license fees may put the costs close or equal to those of MC.

AB Technology: This technology utilizes the reaction between TDI and formic acid to create an ABA, consisting of equal amounts of carbon monoxide (CO) and CO₂. As this reaction is exothermic, a complete replacement of CFCs is not feasible. Substantial equipment adjustments are needed and monitoring of CO is highly recommended. This technology has been used in a few European plants, but has found no acceptance elsewhere, due to safety concerns and limited applicability. It is believed that most users have in the mean time changed--or are in the process of changing--to other technologies.

Pentane: While proven capable, the flammability of pentane would require extensive safety precautions when used in flexible polyurethane foam. There is currently very limited use of this technology.

Liquid Carbon Dioxide (LCD) Technology: The basic principle of LCD technology is the blending of liquidized CO₂ with other foam components under pressure prior to the initiation of the chemical reaction. This blend is then released and, triggered by the decompression, releases the CO₂, resulting in froth. This froth further expands because of the CO₂ released from the water/isocyanate reaction. While the "wet end" (storage, metering and blending of chemicals) of the process requires considerable modifications to allow the storage and processing of liquefied/pressurized CO₂, the "dry end" (conveyor) remains essentially unchanged. The application of LCD requires the resolution of a number of challenges, which include limited solubility in the PU chemical mixture, controlled decompression, and distribution of the unavoidable froth. Several approaches—ranging from pre-blending to co-blending—are offered. All LCD equipment suppliers have developed patented technologies to manage these issues. Three distinct, proprietary technologies through four manufacturers are currently offered. LCD technology has proven to be commercially viable for a significant variety of foam grades in the 15-35 kg/m³ density range and applicability to densities as low as 10 kg/m³ has been claimed (albeit a density associated with high exotherms and not recommended by industry trade associations). Each individual foam manufacturer faces challenges specific to equipment design and product range. Typical problems include achieving high hardness at low density, control of

cell structure (pinholes), achievement of optimum block profile, and producing foams with solid particles. Storage can also be an issue and bulk facilities will generally be more appropriate for slabstock processes than bottled supplies. Economically, the use of LCD offers potential savings compared to the use of CFCs based on a lower cost price and higher blowing index. These advantages are to an extent negated by higher cost of other chemicals, energy and maintenance as well as license fees. In addition, a significant learning curve can be expected when introducing this technology. About 100 slabstock production units are currently operating with LCD technology with about 20-30 more in planning or in construction stages. LCD is also widely used where toxicity controls inhibit methylene chloride use.

- Chemical Modifications

Chemical modifications allow water technologies to be more widely used. These modifications have been effectively applied in foam softening, but fall short in density reduction.

Extended Range Polyols: These polyols are able to provide a larger range of foam hardness, and consequently, partially replace CFC-11 as a softening agent. Some do also allow the use of lower TDI indexes, and will therefore lower the exotherm. This allows in addition a reduction of the foam density. However, a complete replacement of CFC-11, while maintaining the full production range is not (yet) possible. Additional metering systems and tanks are needed, and the price of an extended range polyol is higher than conventional polyol. Application is relatively limited.

Additives: Several additives have been developed to modify the chemistry of the flexible PUF production process. These additives are predominantly for softening and do not allow very low densities. Some additives can be used in addition with extended range polyols and reduced TDI index. A special variant of additive technology is the so-called "Low Index/Additive (LIA) Technology", in which the use of certain additives is combined with a lower TDI index. The application of additive technologies is limited by the relatively high price.

Exotherm Modifiers: one of the functions of an auxiliary blowing agent (ABA) is to reduce the process temperature, in other words, act as a heat sink. "Exotherm Management Technology™" introduces the use of an organic additive with excellent heat sink properties. The powdered additive allows up to a 25 °C reduction in process temperature and therefore to use of all-water-based formulations in densities over 15 kg/m³ while reducing significantly the use of ABAs in densities lower than that.

MDI Technology: Water-blown MDI technology is widespread in the manufacture of molded flexible foam because of its inherent softness and lower exotherm, which allows higher water formulations. Several chemical suppliers offer MDI-based flexible PUR systems also for slabstock. Some interesting environmental features are:

- no need for auxiliary blowing agents to achieve softness,
- significant lower isocyanate emissions,
- rapid curing,

- lower exotherm, allowing higher water formulations.

The technology is, however not capable to produce low densities without sacrifices to physical performance. Its use is therefore more focused on achieving better hardness combinations.

- Process Modifications

Several technologies have surfaced, that could be classified as "mechanical" replacement technologies for the use of CFCs in flexible PUR, predominantly slabstock. The "mechanical" technologies allow the integration of the curing area in the emission control, or allow elimination the use of auxiliary blowing agents altogether.

Forced Cooling Systems: The process is based on an accelerated dissipation of process energy, which allows increasing the amount water up to a level that permits complete elimination of the use of ABAs for the purpose of density reduction. The chemical costs are reported to be very close to those of MC-blown foams. Capital costs are highly dependent on local layout. There are several proprietary systems on the market that apply this technology in several variations, sometimes including treatment of process emissions. The emergence of LCD technology has decreased the attractiveness of forced cooling technology considerably and the application of this technology has virtually stopped.

Variable Pressure Systems: It is well known that the blowing efficiency increases with decreased atmospheric pressure. This allows at higher altitudes the manufacture of lower density foams with less or no ABAs through a higher effectiveness of the water/TDI generated CO₂. This principle can be applied at lower altitudes by encapsulating the foam production line and then reducing process pressure. Conversely, the increase of pressure reduces the effectiveness of the water/TDI induced gas generation and in this way allows the generation of higher urea levels (a by product of this reaction). Two equipment manufacturers market this technology as proprietary technology. Six production units are currently in operation with good results and several more in the planning. The capital requirements are high - approximately 2 to 5 million U.S. dollars, depending on the configuration.

Technical Options (Slabstock – Discontinuous)

Chemically, slabstock foams made through a discontinuous process—also called “Boxfoams”—are identical to product made through the continuous process and application of the previously mentioned CFC replacement technologies is only limited by different—more simple—manufacturing equipment.

Methylene chloride is the prevalent CFC replacement technology applied in boxfoam operations. In cases where the use of MC is subject to regulatory limitations or poses process problems, additive technologies are applied, often with a restricted production program, as these technologies do not provide for a full range replacement and are less economical.

LCD technology, while theoretically capable of being applied in boxfoam operations is not (yet) offered for this production process.

The use of forced cooling has been applied but the prevalent production of rather close-celled foams—a method to provide an initial increase in hardness—interferes with the cooling operations and has rendered the introduction of forced cooling in boxfoam operations less than successful.

Several variable pressure technology (VPT) systems target the boxfoam market following essentially the same technology as described before—but in a drastically reduced complexity. There are currently VPT facilities in the USA, Spain, Brazil and several African countries. In total, in excess of 25 plants are installed, but some of the earlier ones may not be operating. VPT provides the only option in boxfoam application to avoid the use of methylene chloride—a substance that is increasingly under regulatory scrutiny and restrictions. Capital outlays are considerable—US\$ 300,000-500,000. The process provides significant operational savings because of the elimination of the need for an auxiliary blowing agent, without replacing this by other chemicals.

EMT technology is very well suited for box foams and, while not in frequent use, has met large interest in several countries. A project for 20 companies in Brazil is currently under implementation.

MOULDED FOAMS

Performance Requirements

Densities of moulded foams are higher than slabstock foams, and there is consequently no concern of excessive process heat. This reduces the need for ABAs and facilitates the application of CFC-free options. Moulded foams can be produced using either "hot cure" or "cold cure" technology. In hot cure and cold cure/primarily TDI-based formulations, CFCs reduce the hardness. In cold cure/MDI-based formulations, CFCs perform also a function in density reduction.

Technical Options – ‘Hot Cure’

For hot cure molded PU foams, established replacement technologies include methylene chloride systems, water-blown systems (with the use of an additive) or substitution by water-blown cold cure foams. The use of HCFCs, although technically feasible, is not considered necessary as sufficient technically feasible zero ODP options exist.

Technical Options – ‘Cold Cure’

For cold cure foams, established technologies include water-blown systems and auxiliary carbon dioxide. The use of HCFCs, although technically feasible, is not considered necessary, as sufficient technically feasible zero ODP options exist.

The advantages of CO₂ (water) based systems include superior environmental performance (no ODP or GWP), no health and safety hazard, almost unlimited commercial availability and low/no capital outlays. Disadvantages include the potential of increased densities and reduced flow properties of the foam mixture due to higher viscosity. These disadvantages can be overcome by equipment, chemical and process modifications.

Technology based on carbon dioxide—liquefied (LCD) or gaseous (GCD)—as an auxiliary blowing agent is the most important replacement option to have recently emerged. Whilst there are 20-30 LCD units in operation, only a few GCD plants are known to be in operation. This technology provides significant economic and environmental benefits (no ODP, very low GWP or health hazards) and lower foam densities, while essentially maintaining quality. Disadvantages are relatively high initial investment and more complicated process control. The technology can be applied in two ways:

- First, directly through injection in or just prior to the mixing head. This allows instantaneous formulation change and in this way very flexible manufacturing. The maximum amount of CO₂ that can be injected is 3% of the foam mixture. This is equivalent to almost 10% CFC-11 replacement and sufficient to cover most replacement scenarios. The technology is only offered as LCD.
- Second, indirectly through premixing in one of the foam components. This is done preferably in the isocyanate to avoid potential hydrolysis that would occur in the polyol component. As this is in principle a "batch" system—even when effected in the day-tank on a continuous base, no instantaneous formulation change is possible. The tank has to be emptied and refilled with another CO₂ concentration. Also, the control on the CO₂ concentration is more critical as this concentration has to be maintained over a longer period against a tank atmosphere. LCD as well as GCD can be applied. The maximum amount of CO₂ that can be added to the foam formulation is restricted—less than 1%—and this may reduce the technology co-replacement option.

The application of LCD/GCD in flexible molded foams has not shown the rapid development seen in slabstock. This may be related to the fact that the current major CFC replacement technology—the use of CO₂ (water)—does not face regulatory restrictions and requires significantly lower investment.

INTEGRAL SKIN FOAMS

Performance Requirements

This category can be sub-divided in

- Flexible Integral Skin Foams
- Rigid Integral Skin Foams

The major performance requirements in both sectors relate to the following:

- Processability
- Skin formation
- Density
- Cost of processing (e.g. pre-mould coating)

Technical Options – Flexible Integral Skin

The choice of technology is frequently regulation and specification driven. Zero ODP technology is mandated in most industrialized countries, despite drawbacks in performance such as skin quality and density. In countries where no regulations limit the choice, the use of HCFCs (mainly HCFC-141b, which mirrors closely the performance of CFC-11) remains important.

Several specifications, particularly in the EU, favor water-based formulations. Such technology is now available for all applications but may require in-mold coatings (IMC) to be first injected into the mold.

HFC-134a is also used in this application and may also require the use of an IMC to give the required skin quality.

There is also use of n-pentane blown foams for applications such as shoe soles, exercise equipment and steering wheels/instrument panels in trucks, where a very durable skin is required.

Technical Options – Rigid Integral Skin

Water-blown systems are available and commonly used where available. There is minor use of HCFC-141b where water-based systems are not commonly available or where water-based systems do not perform—mostly based on skin problems.

NON-INSULATING RIGID FOAMS

These applications are met by foams manufactured from a variety of processes including spray, pour-in-place, moulding and slabstock. Accordingly, it is difficult to categorise specific alternative technologies for each application.

Performance Requirements

For similar reasons, technical categorization is challenging and difficult in view of the many different and highly individualized requirements. The following breakdown is an approximation:

- Semi-Rigid Foam
 - Packaging Foam
 - Floral Foam
 - Energy Absorbing Foam
- Rigid Foam
 - Low Density (i.e. floatation devices)
 - Medium Density (i.e. cornices)
 - High Density (i.e. wood imitation)

Technical Options

All applications have moved predominantly to all-water-base systems with minor applications of HCFCs in low-density rigid foams for floatation devices (HCFC-22) and floral foam (HCFC-141b), and some methylene chloride in packaging foams.

SUMMARY

The following table provides a summary of the current status and future trends for technologies in the Flexible PU Foam sector.

SECTOR	TECHNOLOGIES	
	CURRENT	TREND
SLABSTOCK	MC, Acetone, VPT, LCD, LIA	LD, VPT
BOXFOAM	MC, VPT, LIA	MC, VPT
MOLDED FOAM – HOT CURE	MC, Water/CO ₂	Water/CO ₂
MOLDED FOAM - COLD CURE	Water/CO ₂ , LCD/GCD	Water/CO ₂
INTEGRAL SKIN – RIGID	Water/CO ₂ , HCFC-141b	Water/CO ₂
INTEGRALSKIN – FLEXIBLE	Water/CO ₂ , HCFC-141b, HFC-134a, Hydrocarbons	Liquid HFCs, HFC-134a, Water/CO ₂
NON-INSULATION RIGID	Water/CO ₂ , HCFC-22, -141b, MC	Water/CO ₂

EXTRUDED POLYSTYRENE

EXTRUDED POLYSTYRENE SHEET

Performance Requirements

The major uses of extruded polystyrene sheet are in the food packaging sector, where there is a requirement for basic thermal insulation and resilience. However, as these are not difficult to attain with extruded polystyrene sheet, there is little dependence on the blowing agent to contribute in final product performance. Accordingly, if processing characteristics can be maintained, there are several other blowing agents available for use.

Technical Options

Use of CFCs or HCFCs, is considered technically unnecessary in both non-Article 5(1) and Article 5(1) Countries and have been banned by a significant number of these countries. A wide range of alternative blowing agents have been evaluated for use in polystyrene sheet foam including atmospheric gases (carbon dioxide, nitrogen), hydrocarbons (butane, isobutane, pentane, isopentane), HFCs (HFC-134a, HFC-152a), and hydrocarbon/CO₂ (LCD) blends.

- Zero OPD Technologies

Atmospheric Gases--CO₂ (LCD) is considered a technically proven, licensable technology and remains as a viable alternative. Some have claimed it to be a higher cost alternative to hydrocarbons when the license package costs are included. Nitrogen gas is very insoluble, produces small-celled, high density foam that is not dimensionally stable. It is difficult to process and very difficult to make high quality foam. For these reasons, nitrogen is not recommended as a viable zero-ODP option.

Hydrocarbons (butane, isobutane, pentane, and isopentane)--Hydrocarbons produce good quality foam sheet and are relatively low in cost. Due to their high flammability, stringent safety precautions in manufacturing, storage, handling, transport and customer use are imperative. These safety measures should include periodic safety audits to ensure continued compliance by all. Hydrocarbons are volatile organic compounds (VOCs), contribute to ground level ozone and smog and are regulated in many regions. Capital (emission control, safety equipment) is a usual requirement to convert to this category of alternative.

Hydrofluorocarbons (HFC-134a, HFC-152a)--HFCs have been implemented by some foam sheet manufacturers. HFC-152a is flammable requiring equipment modification and safety precautions. No VOC emission controls are necessary. This classification of alternative is significantly higher in cost than CO₂ or hydrocarbons.

Hydrocarbon / CO₂ (LCD) blends -- Although blends are definitely viable, few manufacturers are employing them. Difficulties of additional equipment for storage, transfer and emission control are a few of the drawbacks of this alternate technology.

EXTRUDED POLYSTYRENE BOARD

Performance Requirements

As the major application for extruded polystyrene board is in thermal insulation for buildings, there is a distinct requirement to optimise thermal conductivity at all times. This is particularly the case in the highly competitive domestic markets served by the product in the United States. As an additional challenge, the blowing agents are of much greater processing significance in board production and the right solubility characteristics are a key factor in successful production. Finally, density needs to be carefully controlled to avoid undue influence on cost and fire loading. All in all, the performance requirement of a blowing agent in extruded polystyrene board is greatly contrasting to that in its 'sheet' counter-part.

Technical Options

- Low ODP Technologies

HCFC-142b and HCFC-22 remain the primary transitional blowing agents for extruded polystyrene boardstock insulation across most of the world because of their important contribution as insulating gases in the product. The high insulation value obtained helps to reduce and mitigate the amount of carbon dioxide (CO₂) produced from fossil fuel combustion in the home and commercial heating contribution sectors of the global climate change challenge. Although some zero-ODP alternatives are commercially available, performance requirements, inability to produce a wide enough product mix, loss of insulation value, poor processability, dimensional instability, low density foam capability, economic viability and commercial availability cannot be met for all products in all markets at this time.

- Zero ODP Technologies

Potentially viable zero-ODP alternatives for extruded polystyrene boardstock are the following: HFC-134a, HFC-134, HFC-152a, HFC / CO₂ (LCD) blends, CO₂ (LCD)/ Organic Blowing Agents (i.e. ethanol), 100% CO₂ (LCD) and hydrocarbons in limited applications.

Technical advantages / disadvantages of each of these systems include:

HFC-134a--Availability and comparative economic viability versus other zero-ODP alternatives will cause HFC-134a to be seriously considered as an HCFC replacement. Lack of solubility during manufacture (causing inability to produce a full product mix along with higher densities), along with higher raw material prices compared to other HCFC alternatives will be deterrents. Flammability is of little concern during manufacture, storage and use. Equivalent

insulation performance to HCFCs can likely be maintained. Work continues on processability and the ability to make cost effective insulation.

HFC-134--As an isomer of 134a, HFC-134 possesses greater solubility in polystyrene. It diffuses from the foam more rapidly than HFC-134a, consequently greater starting concentrations must be used to achieve equivalent long-term insulation values. HFC-134 is more expensive to produce and when coupled with the need for higher concentration makes this option unattractive economically. No producer has planned to commercialise this product at this time.

HFC-152a--HFC-152a as an alternative in extruded polystyrene boardstock holds no technical advantages over HFC-134a. Limited producer activity will cause this alternative to be higher cost than HFC-134a. HFC-152a is flammable, requiring capital expenditure for storage, processing and safety considerations.

HFC / CO₂ blends--CO₂ (LCD) when combined with either HFC-134a or HFC-152a has potential to reduce overall blowing agent system costs. CO₂ itself has poorer solubility than HFCs in polystyrene consequently production of a wide-enough product mix at low densities is even further challenged. It will however continue to be explored by industry because of its' potential as an attractive economic zero-ODP alternative.

CO₂ / Organic Blowing Agent blends (i.e. ethanol)--Organic blowing agents combined with CO₂ (LCD) produce lower density, full cross-section products. The organic blowing agents (i.e. ethanol) are usually flammable (requiring capital electrical upgrades), are volatile organic compounds (VOCs), requiring emission controls in many regions and produce foam having 10-15% lower R-values than those containing HFCs.

100% CO₂--While this option is the most environmentally preferred, it is the most difficult technically to perfect and commercialise. Today, product mix breadth is limited and foam densities are higher than producers can tolerate economically. Significant capital investment is required to convert to CO₂ (LCD) capability. In addition to capital investment, heavy research and development time is needed to work on these formulation disadvantages. Thermal efficiency is also reduced by 10-15% over conventional HCFC technology.

Hydrocarbons (butane, isobutane,)--Hydrocarbons produce exhibit good processability, because of their solubility in polystyrene and are relatively low in cost. Due to their high flammability, stringent safety precautions in manufacturing, storage, handling, transport and customer use are imperative. These safety measures should include periodic safety audits to ensure continued compliance by all. Hydrocarbons are volatile organic compounds (VOCs), contribute to ground level ozone and smog and are regulated in many regions. Capital (emission control, safety equipment) is a usual requirement to convert to this category of alternative. Their largest drawback resides in product performance; - namely flammability and loss in thermal efficiency.

HFCs will likely remain an important option for parts of the product mix where flammability, dimensional stability constraints and thermal performance are key properties that must be met.

POLYOLEFIN FOAM

Performance Requirements

One of the primary criteria in blowing agent selection is the ability to match the diffusion rate of blowing agents out of the foam with the diffusion rate of air into it. This match is necessary because the polyolefin resins are resilient. If the diffusion rates are not sufficiently matched, the foam will either shrink or expand while ageing. This is unacceptable in all three product types: sheet, plank and tubular. Permeability modifiers can sometimes be used to help match these diffusion rates where they are reasonably close but not acceptably so.

Technical Options

- Low ODP Substitutes

Initially the sole option for polyolefin foam producers was to move to hydrocarbons either via HCFC-142b or HCFC-142b/22 blends, in an attempt to preserve, especially in the cushion packaging area, traditional physical properties, or, as typically the case for new entrants to the market, directly. With the experience which now exists, it is possible to convert directly from CFCs to hydrocarbons. This will be further discussed in the next section.

- Zero ODP Substitutes

The usual choice is a blend of normal and isobutane. Some pentane is also used.

Hydrocarbons are flammable. For example, isobutane flammability limits are about 1.8 to 8.4 volume percent in air with an extremely low energy of ignition. This situation requires the careful consideration of proper processing equipment upgrades along with appropriate safety procedures and equipment in manufacturing, storage, handling, and shipment of the product. Periodic safety audits should be performed to ensure full worker compliance. Removal of flammable gases (e.g. through perforation) from the foam in order to ensure safe transport, storage and use in an economically viable time period represents "best available technology" that is patented and licensable. In addition, hydrocarbons are volatile organic compounds (VOCs) that are regulated in certain regions. Emission controls would be required in these areas.

It is very difficult to make extruded polyolefin foams using HFCs 152a and 134a alone. To facilitate meeting VOC emission requirements, HFC-152a is sometimes used in combination with hydrocarbons.

- Other Theoretical Options

Carbon dioxide, nitrogen and other inorganic gases have very low solubility in the resins and have only very limited use in extruded polyolefin foams. In addition, process pressures will be very high, typically beyond the capability of most processes without significant or prohibitive capital expenditure. These volatile gases are, however, being used in some mouldable bead products where the process pressure problem can be overcome.

Carbon dioxide diffuses rapidly out of polyolefin foams and causes massive dimensional stability problems. Without some, as yet unidentified, enabling technology, carbon dioxide, except as a very minor component of the blowing agent system, is simply not an option.

CO₂, nitrogen and other inorganic gases thus remain theoretical options only for the bulk of today's polyolefin foams applications.

PHENOLIC FOAM

Performance Requirements

Phenolic foams are differentiated by three key criteria:

- Good reaction to fire properties
- Very low thermal conductivities (arising from the use of emulsion technologies)
- Extremely low inherent smoke generation.

The selection of alternative blowing agent therefore has to maintain these properties in both continuous and discontinuous processes.

Technical Options – Continuous Processes

- Low ODP Technologies

The use of HCFC-141b in continuously laminated phenolic foams has virtually been phased out in the key global markets.

One European continuous laminate technology makes use of 2-chloropropane as the blowing agent. Although this does not provide such good thermal conductivity properties as HFC-based formulations it has a significantly lower cost. There is a finite but minor ozone depletion potential of 0.002. This technology has been in the market place since the early 1990s and is not likely to be more widely used in future because of a trend towards stricter fire requirements in the sector served by laminated products.

- Zero ODP Technologies

With the phase-out of HCFC-141b in Europe, the main continuous lamination technology options are HFCs and hydrocarbons. In general, hydrocarbons are now more acceptable in phenolic core materials than envisaged in previous reports because of the significant influence of the foam matrix. However, for the highest fire performance requirements, HFCs will continue to have a significant place. In the fast growing market of Japan, hydrocarbons are nearly universally used for laminate products.

Within the period of this Assessment, a new process technology has been introduced allowing the continuous production of pipe section. This has been commercialised in the UK and is based on a hydrocarbon blowing agent.

Technical Options – Discontinuous Processes

- Low ODP Technologies

As with continuously-produced foams, the use of HCFC-141b has virtually been eliminated in this sector.

- Zero ODP Technologies

Again, the situation is the same as for continuously laminated foams. However, the possibility of using blends (HFC-245fa, HFC-365mfc and other HFCs or hydrocarbons) is more important in this sector because of process sensitivity to boiling point.

For hydrocarbon-based technologies, the comments are as for continuously laminated foam with the exception that the fire issues are even more critical for both product and process reasons. Foam fabricated from blocks is often used for heating and ventilating applications in exposed locations within public buildings or for petrochemical plants. The maintenance of product fire properties is therefore critical.

APPENDIX 4: ALLOCATION OF COUNTRIES TO REGIONS

Latin America and the Caribbean (LAC)

Antigua and Barbuda
Argentina
Bahamas
Barbados
Belize
Bolivia
Brazil
Chile
Colombia
Costa Rica
Cuba
Dominica
Dominican Republic
Ecuador
El Salvador
Grenada
Guatemala
Guyana
Haiti
Honduras
Jamaica
Mexico
Nicaragua
Panama
Paraguay
Peru
Saint Kitts and Nevis
Saint Lucia
Saint Vincent and The Grenadines
Suriname
Trinidad and Tobago
Uruguay
Venezuela

Middle East/North Africa (MENA)

Algeria
Bahrain

**Sub-Saharan Africa
(SSA)**

Egypt
Iran, Islamic Republic of
Iraq
Israel
Jordan
Kuwait
Lebanon
Libyan Arab Jamahiriya
Mauritania
Morocco
Oman
Palestine
Qatar
Saudi Arabia
Syrian Arab Republic
Tunisia
Turkey
United Arab Emirates
Yemen

Angola
Benin
Botswana
Burkina Faso
Burundi
Cameroon
Cape Verde
Central African Republic
Chad
Comoros
Congo
Congo, Democratic Republic of
Cote d'Ivoire
Djibouti
Equatorial Guinea
Eritrea
Ethiopia
Gabon
Gambia
Ghana

Guinea
Guinea-Bissau
Kenya
Lesotho
Liberia
Madagascar
Malawi
Mali
Mauritius
Mozambique
Namibia
Niger
Nigeria
Rwanda
Sao Tome and Principe
Senegal
Seychelles
Sierra Leone
Somalia
South Africa
Sudan
Swaziland
Tanzania, United Republic of
Togo
Uganda
Zambia
Zimbabwe

**South/Central Asia
(SCA)**

Afghanistan
Bangladesh
Bhutan
India
Maldives
Nepal
Pakistan
Sri Lanka

**South-East Asia
(SEA)**

Brunei Darussalam
Cambodia

**North-East Asia
(NEA)**

Japan

Europe

Indonesia
Lao People's Democratic Republic
Malaysia
Myanmar
Philippines
Singapore
Thailand
Viet Nam

China (incl. Taiwan)
Mongolia
North Korea
South Korea

Japan

Albania
Andorra
Austria
Bosnia and Herzegovina
Belgium
Bulgaria
Croatia
Cyprus
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Holy See
Hungary
Latvia
Iceland
Ireland
Italy
Liechtenstein
Lithuania

Luxembourg
Macedonia
Malta
Moldova
Monaco
Netherlands
Norway
Poland
Portugal
Romania
San Marino
Slovakia
Slovenia
Spain
Sweden
Switzerland
United Kingdom
Yugoslavia

North America

Canada
USA

Australia, New Zealand & The Pacific (ANZP)

Australia
Cook islands
Fiji
Kiribati
Marshall Islands
Micronesia
Nauru
New Zealand
Niue
Palau
Papua New Guinea
Samoa
Solomon Islands
Tonga
Tuvalu
Vanuatu

Countries with Economies in Transition (CEIT)

Armenia
Azerbaijan
Belarus
Georgia
Kazakhstan
Kyrgyzstan
Russian Federation
Tajikistan
Turkmenistan
Ukraine
Uzbekistan

APPENDIX 5: UNEP FOAMS TECHNICAL OPTIONS COMMITTEE

Committee Member	Affiliation	Country
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